TWAP
TRANSBOUNDARY WATERS ASSESSMENT PROGRAMME

The Open Ocean

Status and Trends

VOLUME 5: OPEN OCEAN

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Intergovernmental
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Status and Trends

UNESCO
United Nations Educational, Scientific and Cultural Organization
Intergovernmental Oceanographic Commission

GOOS
Global Ocean Observing System

GEOWOW
EC FP7 GEOWOW Project

CERMES
Centre for Resrouce Management and Environmental Studies

Sea Around Us Project

esa

WCRP
World Climate Research Programme

GACS
Global Alliance of Continuous Plankton Recorder Surveys

Ångstrom Group
science facilitation

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PML | Plymouth Marine Laboratory

CMAP
Center for Marine Assessment and Planning

American Chemistry Council

GESAMP

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Administrative Boundaries

Source of administrative boundaries used throughout the assessment: The Global Administrative Unit Layers (GAUL) dataset, implemented by FAO within the CountrySTAT and Agricultural Market Information System (AMIS) projects.

Preface

The GEF Full Size Project (FSP) "A Transboundary Waters Assessment Programme: Aquifers, Lake/Reservoir Basins, River Basins, Large Marine Ecosystems, and Open Ocean to catalyze sound environmental management", was approved in December 2012, following the completion of the Medium Size Project (MSP) "Development of the Methodology and Arrangements for the GEF Transboundary Waters Assessment Programme" in 2011. The TWAP FSP began in 2013 and was envisioned to fill two major objectives: (1) to undertake the first global assessment of transboundary water systems that will assist GEF and other international organizations improve the setting of priorities for funding; and (2) to formalise the partnership with key institutions so that transboundary considerations are incorporated in regular assessment programmes.

The TWAP FSP has been implemented by UNEP as Implementing Agency, UNEP's Division of Early Warning and Assessment (DEWA) as Executing Agency, and the following lead agencies for each of the water system categories: the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) for transboundary aquifers including groundwater systems in small island developing states (SIDS); the International Lake Environment Committee Foundation (ILEC) for lake basins; UNEP-DHI Partnership – Centre on Water and Environment (UNEP-DHI) for river basins; and the Intergovernmental Oceanographic Commission (IOC) of UNESCO for large marine ecosystems (LMEs) and the open ocean.

The five water-category specific assessments cover 199 transboundary aquifers and groundwater systems in 43 small island developing states, 206 transboundary lakes and reservoirs, 286 transboundary river basins; 66 large marine ecosystems; and the open ocean, a total of 758 international water systems. The assessment results are organized into five technical reports and a sixth volume that provides a cross-category analysis of status and trends:

Volume 1 -- ***Transboundary Aquifers and Groundwater Systems of Small Island Developing States: Status and Trends***
Volume 2 – ***Transboundary Lakes and Reservoirs: Status and Trends***
Volume 3 - ***Transboundary River Basins: Status and Trends***
Volume 4 – ***Large Marine Ecosystems: Status and Trends***
Volume 5 – ***The Open Ocean: Status and Trends***
Volume 6 – ***Transboundary Water Systems: Crosscutting Status and Trends***

A Summary for Policy Makers accompanies each volume.

Volume 5 presents the results of a baseline review of issues linking human well-being with the status of the open ocean, prepared in partnership with the Intergovernmental Oceanographic Commission of UNESCO (IOC/UNESCO, lead), the European Commission FP7 GEOWOW project, American Chemistry Council, Angstrom Group, Center for Marine Assessment and Planning (CMAP) at UCSB, European Space Agency; Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP); Plymouth Marine Lab; SAHFOS/Global Alliance of Continuous Plankton Recorder Surveys Global Assessment; Univ. British Columbia Sea Around Us project; University of the West Indies, Centre for Resource Management and Environmental Studies; WMO-ICSU-IOC World Climate Research Programme and individual experts.

Figures

Tables

Acronyms

General

ASCOBANS	Agreement on the Conservation of Small Cetaceans in the Baltic, North East Atlantic, Irish and North Seas
GEOSS Data-CORE	GEOSS Data Collection of Open Resources for Everyone
IT	Intergovernmental Oceanographic Commission
PML	Plymouth Marine Laboratory
ABNJ	areas beyond national jurisdiction
ACCOBAMS	Agreement on the Conservation of Cetaceans in the Black Sea Mediterranean Sea and Contiguous Atlantic Area
AIMS	Australian Institute of Marine Science
AOSIS	Alliance of Small Island States
APEC-OFWG	Asia-Pacific Economic Cooperation (APEC) Oceans and Fisheries Working Group (OFWG)
ASEAN	Association of Southeast Asian Nations
AWNJ	Areas within national jurisdiction
BBNJ	UN Working Group on Marine Biodiversity beyond Areas of National Jurisdiction
BCC	Benguela Current Commission
BIMSTEC	Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC) Working Committee on Fisheries
BON	Biodiversity Observation Network
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CARICOM	Caribbean Community and Common Market
CARPHA	Caribbean Public Health Agency
CBD	Convention on Biological Diversity
CBSS	Council of the Baltic Sea States
CCAD	La Comisión Centroamericana de Ambiente y Desarrollo
CERMES	Centre for Resource Management and Environmental Studies, University of the West Indies
CIESIN	Center for International Earth Science Information Network
CMAP	Center for Marine Assessment and Planning
CMIP5	Coupled Model Inter-comparison Project Phase 5
CO_2	Carbon dioxide

COBSEA	Coordinating Body on the Seas of East Asia
COFI	FAO Committee on Fisheries
COREP	Convention Concerning the Regional Development of Fisheries in the Gulf of Guinea and the Regional Fisheries Committee for the Gulf of Guinea (COREP)
CPPS	Permanent Commission of the South Pacific
CRFM	Agreement establishing the Caribbean Regional Fisheries Mechanism (CRFM)
CROP	Council of Regional Organisations of the Pacific
CSW	Catalogue Service for the Web
DDT	Dichlorodiphenyltrichloroethane
DHM	Digital Height Model
DIN	Dissolved Inorganic Nitrogen
DPSIR	Drivers-pressures-state-impact-response
Dugong MOU	Memorandum of Understanding on the Conservation and Management of Dugongs and their Habitats throughout their Range
EBSAs	Ecologically and Biologically Significant Areas
EBVs	Essential Biodiversity Variables
ECVs	Essential Climate Variables
eEOVs	ecosystem Essential Ocean Variables
eEOVs	ecosystem Essential Ocean Variables
EEZs	Exclusive Economic Zone
EO	Earth Observations
EOS	Essential Ocean Samples
EOVs	Essential Ocean Variables
ESA	European Space Agency
ESGF	Earth System Grid Federation
EU Maritime Policy	European Union Integrated Maritime Policy
EU-CFP	European Union Common Fisheries Policy
EuroGOOS	The European GOOS
EVs	Essential Variables
FAO	Food and Agriculture Organisation of the United Nations
FAO	UN Food and Agricultural Organisation
FAQ	Frequently Asked Questions
FCWC	Convention for the establishment of Fishery Committee of the West Central Gulf of Guinea
FiB	Fishing in Balance Index
FOO	Framework for Ocean Observing

FP7 EC	Seventh Framework Programme of the European Commission
GACS	Global Alliance of Continuous Plankton Recorder Surveys
GCI	GEOSS Common Infrastructure
GCOS	Global Climate Observing System
GDP	Gross Domestic Product
GEF	Global Environment Facility
GEO	Group on Earth Observations
GEOBON	Group on Earth Observations Biodiversity Observation Network
GEOSS	Global Earth Observation System of Systems
GEOSS DataCORE	GEOSS Data Collection of Open Resources for Everyone
GEOWOW	GEOSS interoperability for Weather, Ocean and Water
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GIS	Geographic Information System
GOODS	Global Open Oceans and Deep Seabed
GOOS	Global Ocean Observing System
GRA	GOOS Regional Alliances
HABs	Harmful Algal Blooms
HCH	Hexachlorocyclohexanes
HELCOM	Baltic Marine Environment Protection Commission
IAEA	International Atomic Energy Agency
IASC	International Arctic Science Committee
ICEP	Indicator for Coastal Eutrophication Potential
ICES	International Council for the Exploration of the Sea
ICSU	International Council for Science
IGBP	International Geosphere Biosphere Programme
IMO	International maritime Organisation
IMOS	Australian Integrated Marine Observing System
IOC	Intergovernmental Oceanographic Commission
IOC	Intergovernmental Oceanographic Commission
IOCCG	International Ocean Colour Co-ordinating Group
IOCCP	International Ocean Carbon Coordination Project
IODE	International Oceanographic Data and Information Exchange
IOSEA	The Memorandum of Understanding on the Conservation and Management of Marine Turtles and their Habitats of the Indian Ocean and South-East Asia
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change

ISO	International Organisation for Standardisation
LME	Large Marine Ecosystems
MAP	Marine Affairs Programme, Dalhousie University
MEA	Millennium Ecosystem Assessment
MEPC	IMO Marine Environmental Protection Committee
MPAs	Marine Protected Areas
MTI	Marine Trophic Index
MTL	Mean Trophic Level
NASA	National Aeronautics and Space Administration of the US Government
NOAA	US Government National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre of the UK
NODC	US Government National Oceanographic Data Center
NOWPAP	North West Pacific Action Plan
NOWPAP	Action Plan for the Protection, Management and Development of the Marine and Coastal Environment of the Northwest Pacific Region
NSIDC	US National Snow and Ice Data Center
O_2	Oxygen
OBIS	Ocean Biogeographical Information System
OC–CCI	Ocean Colour Climate Change Initiative
OECS	Organisation of Eastern Caribbean States
OGC	Open Geospatial Consortium
OLDEPESCA	Agreement instituting the Latin American Organization for Fisheries Development
OSPESCA	Central America Fisheries and Aquaculture Organization
PCB	Polychlorinated Biphenyls
PEMSEA	Partnerships in Environmental Management for the Seas of East Asia
PICES	North Pacific Marine Science Organization
PICO	GOOS Panel for Integrated Coastal Observation
PIF	Pacific Islands Forum
PML	Plymouth Marine Laboratory
POPs	Persistent Organic Pollutants
PRCM	Regional Marine and Coastal Conservation Programme for West Africa
RACMED	Regional Advisory Council for the Mediterranean
RCP	Representative Concentration Pathway Scenarios
RECOFI	Agreement for the establishment of the Regional Commission for Fisheries
SAARC	South Asian Association for Regional Cooperation
SACEP	South Asian Cooperative Environment Programme

SADC	South African Development Community
SBAs	Societal Benefit Areas
SBSTA	UNFCC Subsidiary Body for Scientific and Technological Advice
SCOR	Scientific Committee on Oceanic Research
SEA	Sea Education Association
SEO	Search Engine Optimisation
SICA	Sistema de la Integración Centroamericana
SIDS	Small Island Developing States
SLD	Styled Layer Descriptor
SOCAT	Surface Ocean CO_2 Atlas
SOKI	Southern Ocean Knowledge and Information wiki
SOOS	Southern Ocean Observing System
SOPAC	Pacific Islands Applied GeoScience Commission
SPAW Protocol	Specially Protected Areas and Wildlife Protocol, Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region
SPTO	South Pacific Tourism Organisation
SRES	Special Report Emission Scenario
SRFC	Sub-Regional Fisheries Commission
SST	Sea Surface Temperature
TCHP	Tropical Cyclone Heat Potential
TWAP	Transboundary Waters Assessment Programme
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme
UNESCO	United Nations Education, Science and Cultural Organization
UNESCO-IOC	Intergovernmental Oceanographic Commission of UNESCO
UNFCCC	UN Framework Convention on Climate Change
URL	Universal Resource Locator
URL	Universal Resource Locator
US IOOS	United States Integrated Ocean Observing System
US NMFS-NOAA	United States National Marine Fisheries Service of the National Oceanic and Atmospheric Administration
USP	University of the South Pacific
VOS	Volunteer Observing Ships
WCRP	World Climate Research Programme
WCS	Web Coverage Service
WHO	World Health Organisation

WIOSEA	Western Indian Ocean Sustainable Ecosystem Alliance
WMO	World Meteorological Organisation
WMS	Web Map Service
WOA	World Ocean Assessment

Governance

(CN = constituting, OP = operational, P = pollution, F = Fisheries, B = biodiversity, C = climate change

Abidjan Convention	Abidjan Convention for Co-operation in the protection and Development of the Marine and Coastal Environment of the West and Central African Region	CN	P
Abidjan Convention - Emergency Protocol	Protocol on Cooperation in Combating Pollution in Cases of Emergency and the associated Action Plan for the Protection and Development of the Marine Environment and Coastal Areas of the West and Central African Region	OP	P
Abidjan Convention - LBS Protocol	Protocol concerning Cooperation in the Protection and Development of the Marine and Coastal Environment from land-Based Sources and the Activities	OP	P
ACAP	Agreement on the Conservation of Albatrosses and Petrels	OP	B
Anti-fouling convention	The International Convention on the Control of Harmful Anti-fouling Systems on Ships	OP	P
Antigua Convention	Convention for Cooperation in the Protection and Sustainable Development of the Marine and Coastal Environment of the Northeast Pacific	CN	FPB
APFIC	Asia Pacific Fisheries Commission	OP	F
Arctic Council	Arctic Council	OP	FPBC
ATS	Antarctic Treaty System	CN	FP
ATS Environment Protocol	Protocol on Environmental Protection to The Antarctic Treaty	OP	P
Barcelona Convention	Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean	CN	P
Barcelona Convention - Dumping Protocol	Protocol for the Prevention of Pollution in the Mediterranean Sea by Dumping from Ships and Aircraft	OP	P
Barcelona Convention - Hazardous Wastes Protocol	Protocol on the Prevention of Pollution of the Mediterranean Sea by Transboundary Movements of Hazardous Wastes and their Disposal	OP	P
Barcelona Convention - LBS Protocol	Protocol on the Protection of the Mediterranean Sea against Pollution from Land-Based Sources	OP	P
Barcelona Convention - Offshore Protocol	Protocol for the Protection of the Mediterranean Sea against Pollution Resulting from Exploration and Exploitation of the Continental Shelf and the Seabed and its Subsoil	OP	P

(CN = constituting, OP = operational, P = pollution, F = Fisheries, B = biodiversity, C = climate change

Barcelona Convention - Prevention and Emergency Protocol	Protocol Concerning Cooperation in Preventing Pollution from Ships and, in Cases of Emergency, Combating Pollution of the Mediterranean Sea	OP	P
Barcelona Convention - SPA and Biodiversity Protocol	Protocol Concerning Specially Protected Areas and Biological Diversity in the Mediterranean	OP	B
BOBP-IGO Agreement	Agreement on the Institutionalisation of the Bay of Bengal Programme as an Inter-Governmental Organisation	OP	F
Bucharest Convention	Convention on the Protection of the Black Sea against Pollution	CN	P
Bucharest Convention - Dumping protocol	Protocol on dumping of waste	OP	P
Bucharest Convention - Emergency Protocol	Protocol on joint action in the case of accidents (such as oil spills)	OP	P
Bucharest Convention - LBS Protocol	Protocol on the control of land-based sources of pollution	OP	P
BWMC	International Convention for the Control and Management of Ships' Ballast Water and Sediments (Ballast Water Management Convention)	OP	P
Cartagena Convention	Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region (Cartagena Convention)	CN	P
Cartagena Convention - LBS Protocol	Cartagena Convention Protocol Concerning Pollution from Land-Based Sources and Activities	OP	P
Cartagena Convention – Oil Spills Protocol	Cartagena Convention Protocol Concerning Co-operation in Combating Oil Spills	OP	P
CBD	Convention on Biological Diversity	CN	B
CCAMLR	Convention for the Conservation of Antarctic Marine Living Resources	OP	FB
CCAS	Convention for the Conservation of Antarctic Seals	OP	B
CCBSP	Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea	OP	F
CCSBT	Convention for the Conservation of the Southern Bluefin Tuna	OP	F
CECAF	Fishery Committee for the Eastern Central Atlantic	OP	F
CITES	Convention on International Trade in Endangered Species	OP	FB
CMS	Convention on Migratory Species	CN	FB
COMHAFAT	Ministerial Conference on Fisheries Cooperation among African States Bordering the Atlantic (COMHAFAT or ATLAFCO)	OP	F

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FAO Compliance Convention	The Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas - 1993	OP	F
FFAC	Pacific Islands Forum Fisheries Agency/South Pacific Forum Fisheries Agency Convention	OP	F
GFCM Agreement	Agreement for the establishment of the General Fisheries Commission for the Mediterranean	OP	F
GPA	Global Programme of Action for the Protection of the Marine Environment from Land-based Activities	CN	P
HELCON	Convention on the Protection of the Marine Environment of the Baltic Sea Area - Helsinki Convention	OP	PB
Hong Kong Convention	Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships	OP	P
HSDN	United Nations Resolution on High Seas Drift Netting	OP	F
IAC	Inter-American Convention for the Protection and Conservation of Sea Turtles	OP	B
IATTC	Convention for the Strengthening of the Inter-American Tropical Tuna Commission	OP	F
ICCAT	International Convention for the Conservation of Atlantic Tunas	OP	F
ICES	International Council for the Exploration of the Sea	OP	FPBC
IOTC	Agreement for the establishment of the Indian Ocean Tuna Commission	OP	F
IPHC	International Pacific Halibut Commission (IPHC)/Convention for the Preservation of the Halibut Fishery	OP	F
IWC	International Convention for the Regulation of Whaling	OP	F
Jeddah Convention	Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment	CN	P
Jeddah LBS Protocol	Protocol Concerning the Protection of the Marine Environment from Land-Based Activities in the Red Sea and Gulf of Aden	OP	P
Jeddah Oil Pollution Protocol	Protocol concerning Regional Cooperation in Combating Pollution by Oil and Other Harmful Substances in cases of Emergency	OP	P
Kuwait - Continental Shelf Exploitation Protocol	Protocol Concerning Marine Pollution Resulting from Exploration and Exploitation of the Continental Shelf	OP	P
Kuwait Convention	Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution – Kuwait Convention	CN	P
Kuwait Convention - Hazardous Wastes Protocol	Protocol on the Control of Marine transboundary movements and disposal of hazardous wastes and other wastes, 1998	OP	P
Kuwait Convention - LBS Protocol	Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution – Kuwait Convention	OP	P
Kuwait Convention - Oil Spills Protocol	Protocol concerning regional cooperation in combating pollution by oil and other harmful substances in cases of emergency, 1978	OP	P
Lima Convention	Convention for the Protection of the Marine Environment and Coastal Areas of the South-East Pacific	CN	P

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Lima Convention - Hydrocarbons Protocol	Lima Agreement on Regional Cooperation in Combating Pollution in the South East Pacific by Hydrocarbons and other Harmful Substances in cases of Emergency	OP	P
Lima Convention - LBS Protocol	Lima Protocol for the Protection of the South East Pacific Against Pollution from Land- Based Sources	OP	P
Lima Convention - Radioactive Pollution Protocol	Lima Protocol for the Protection of the South East Pacific from Radioactive Pollution	OP	P
London Convention	London Convention (1975)	OP	P
London Convention - Protocol	London Convention Protocol (2006)	OP	PC
MARPOL	International Convention for the Prevention of Pollution from Ships (MARPOL) Annexes I - VI	OP	P
Montreal Protocol	The Montreal Protocol on Substances that Deplete the Ozone Layer	OP	P
NAFO	Convention on Future Multilateral Cooperation in the Northwest Atlantic Fisheries	OP	F
Nairobi Convention	Nairobi Convention for the Protection, Management and Development of the Marine and Coastal Environment of the West Indian Ocean	CN	P
Nairobi Convention - Emergency Protocol	Protocol Concerning Co-operation in Combating Marine Pollution in Cases of Emergency in the Eastern African Region	OP	P
Nairobi Convention - LBS Protocol	Protocol for the Protection of the Marine and Coastal Environment of the Western Indian Ocean from Land-Based Sources and Activities	OP	P
NAMMCO	Agreement on Cooperation in Research, Conservation and Management of Marine Mammals in the North Atlantic	OP	FB
NASCO	Convention for the Conservation of Salmon in the North Atlantic Ocean	OP	F
NEAFC	North-East Atlantic Fisheries Commission	OP	F
Niue Treaty/NTSA	Niue Treaty on Cooperation in Fisheries Surveillance and Law Enforcement in the South Pacific Region and Multilateral NTSA Agreement on Strengthening Implementation of the Niue Treaty	OP	F
Noumea Convention	Convention for the Protection of the Natural Resources and Environment of the South Pacific	CN	PBC
Noumea Convention - Dumping Protocol	Protocol for the Prevention of Pollution of the South Pacific Region by Dumping	OP	P
Noumea Convention - Emergency Protocol	Protocol Concerning Co-operation in Combating Pollution Emergencies in the South Pacific Region	OP	P
NPAFC	Convention for the Conservation of Anadromous Stocks in The North Pacific Ocean	OP	F
OPRC 90	International Convention on Oil Pollution Preparedness, Response and Co-operation 1990	OP	P

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OSPAR Convention	Convention for the Protection of the Marine Environment of the North-East Atlantic	OP	BP
PICES	The North Pacific Marine Science Organization	OP	FPBC
PIF/POF/PIROP	Pacific Islands Forum/Pacific Oceanspace Framework/Pacific Islands Regional Oceans Policy	OP	FPBC
PNA	Nauru Agreement Concerning Cooperation in the Management of Fisheries of Common Interest	OP	F
Polar Bear	Agreement on the Conservation of Polar Bears	OP	B
PSC	Treaty Between the Government of the United States of America and the Government of Canada concerning Pacific Salmon	OP	F
SCAR	Scientific Committee on Antarctic Research	OP	FPBC
SEAFDEC	South East Asian Fisheries Development Center	OP	F
SEAFO	The Convention on the Conservation and Management of Fishery Resources in the South East Atlantic Ocean	OP	FB
SIOFA	South Indian Ocean Fisheries Agreement	OP	FB
SPC	Secretariat of the Pacific Community (initially South Pacific Commission)	OP	F
SPRFMO	Convention on the Conservation and Management of High Seas Fishery Resources in the South Pacific Ocean	OP	F
Stockholm Convention	Stockholm Convention on Persistent Organic Pollutants	OP	P
UNCLOS	United Nations Convention on the Law of the Sea	CN	FPB
UNCLOS – Seabed Agreement	Agreement relating to the implementation of Part XI of the United Nations Convention on the Law of the Sea.	OP	PB
UNFCC	United Nations Framework Convention on Climate Change	CN	C
UNFCC - Kyoto Protocol	Kyoto Protocol to the United Nations Framework Convention on Climate Change	OP	C
UNFSA	UN Fish Stocks Agreement	CN	FB
Vienna Convention	The Vienna Convention for the Protection of the Ozone Layer	CN	P
WCPFC	Convention on the Conservation and Management of High Migratory Fish Stocks in the Western and Central Pacific Ocean	OP	F
WECAFC	Western Central Atlantic Fisheries Commission	OP	FB
Wellington Convention (SP Drift Nets)	Convention for the Prohibition of Fishing with Long Drift Nets in the South Pacific	OP	F

Pollution

BTBPE 1,2-bis(2,4,6-tribromophenoxy)ethane	PBEB pentabromoethylbenzene
CFC clhorofluorocarbons	PBT Persistent, Bioaccumulating and Toxic
decaBDE decabromodiphenylether (BDE congener 209)	PBrT pentabromotoluene
EESC equivalent effective stratospheric chlorine	PCN polychlorinated naphthalenes
HBCD hexabromocyclododecane	PFC perfluorocarboxylates
HCB hexachlorobenzene	PFOA perflourooctanoate (C8)
HCFC hydrochlorofluorocarbon	PFOS perfluorooctane sulphonate
HCH hexachlorocyclohexane	PFOSA perfluorooctane sulfonamide
HxBBz hexabromobenzene	PFNA perfluorononoate (C9)
OC organochlorine	PFUnA perfluoroundecanoate (C11)
ODP ozone depleting potential	SCCP short-chain chlorinated paraffin
PBB polybrominated biphenyl	TBBPA tetrabromobisphenol A
PCB polychlorinated biphenyl	TBECH tetrabromoethylcyclohexane
PBDE polybrominated diphenylether	vPvB very Persistent, very Bioaccumulating

Glossary

Large Marine Ecosystems (LMEs) – Large Marine Ecosystems are vast regions of coastal ocean space of 200,000 km^2 or more, extending from river basins and estuaries seaward to the continental shelf break or slope or to the outward margins of major current systems. Unique defining ecological criteria of LMEs include bottom depth contours, currents and water mass structure, marine productivity, and food webs.

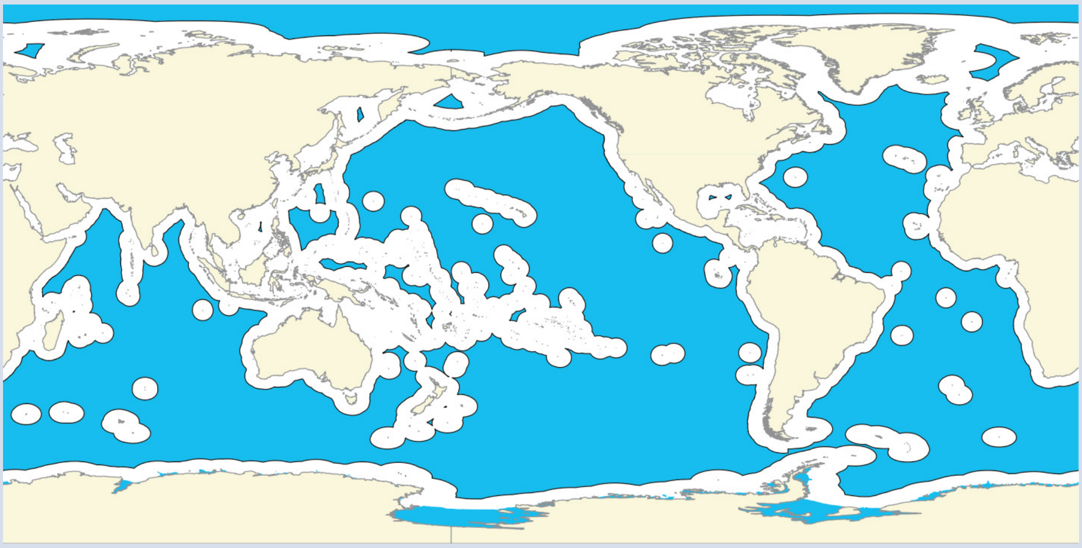
OneSharedOcean.org – The web portal that contains the data and results for both the Open Ocean and Large Marine Ecosystem Components of the Transboundary Waters Assessment Programme, and which was co-financed by the European Commission's FP7 GEOWOW Project (www.geowow.eu) under Grant Agreement 282915.

Transboundary Full Size Project (FSP) – The Full Size Project in which the Transboundary Water's Assessment Programme was funded (by GEF) and implemented from 2013 to 2015.

TWAP OO – The Transboundary Waters Assessment Programme's assessment of the Open Ocean

Box 1: Defining the 'Open Ocean'

The 'open ocean' is the largest areas of global commons, vital to life on the planet, and under the legal jurisdiction of no single nation, but the common stewardship of all in 'areas beyond national jurisdiction' (ABNJ). The area equates to marine waters beyond exclusive economic zones (EEZs). By international convention, the open ocean is the Earth's largest transboundary space covering about half of the surface of the planet. Ocean 'areas within national jurisdiction' (AWNJ) cover a further 20 per cent. The 'high seas' is an international legal term used by the UN Convention on the Law of the Sea (UNCLOS) which refers to the area of the ocean not included in the EEZ, territorial sea or internal water of any State. Essentially, this is the same as the 'open ocean' and the term is often inter-changed. Due to the strong connections between the open ocean and coastal areas, in some aspects of the assessment, a global ocean scope has been taken.



The Open Ocean (or 'area beyond national jurisdiction') is blue. The white areas depict exclusive economic zones (EEZs) (or 'areas within national jurisdiction').

Box 2: Explaining Projected Climate Change Scenarios and RCPs

The IPCC Fifth Assessment Report 2014 (AR5) provides the most up to date review of scientific information on climate change and the ocean and an overview of impacts already observed or expected from a range of climate change scenarios in socio-economic sectors. The *Open Ocean Assessment* focuses on some of the climate change aspects which are relevant either to human settlements near the ocean or to biological balance of the oceans, making use, to a large extent, of AR5 material and complemented by a few other recent articles.

Where possible and relevant, projections of the future state of the open ocean ecosystems have been modeled using the scenarios outlined in the **IPCC 5th Assessment Report (2014),** for the time periods 2030 and 2050, and in one instance, for 2090.

Representative Concentration Pathways (RCP) are tools used by researchers to predict different greenhouse gas emission scenarios. There is a range of scenarios but mostly, this Assessment uses two:

- **RCP8.5 'Business As Usual'** – where nothing changes from the current situation, there is continuing growth of greenhouse gas concentrations in the atmosphere.
- **RCP4.5 ' two degree stabilization scenario' (or 'Moderate Mitigation') –** where there is a rapid initial growth of greenhouse gas concentrations, but stabilizing concentrations from 2070 onward.

Box 3: Explaining 'Certainty' and 'Risk' Terms

Projections are based on models, which provide a 'trend' for any given situation. Because models show 'trends', language to describe these trends needs to reflect the level of 'certainty' with respect to the outcome of the calculations.

Throughout this assessment, language of **'certainty'** is based on the IPCC's *'Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties' (2010)* where categories of 'certainty' are considered:

Term*	Likelihood of the Outcome
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33 to 66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

Similarly, when referring to the **'risk'** of occurrence or change, language reflecting the approximation of a risk level has also been used with the categories:

Low, Medium, High, Extreme, Critical

For a full detailed glossary see onesharedocean.org/glossery

Earth is the ocean planet, with 70 per cent of its surface covered by oceans, and 50 per cent covered by ocean areas beyond national jurisdiction. Photo courtesy NASA.

Executive Summary

The open ocean is remote from human society, and usually remote from our thinking. Our ability to monitor it is constrained, and humans directly in contact with the high seas are limited to a small community of fishers, commercial shipping vessels, navies, and the occasional recreational vessel.

But the open ocean deserves a higher profile when examining and trying to improve our management of the relationship between human society and the environment.

Global impacts on the ocean such as pollution and fishing come from human drivers on land and at sea. And global impacts on human society can be driven by the global open ocean through its role in the climate system. The oceans have a role in mediating patterns of rainfall and drought (an important input for the other TWAP water systems), global climate change is leading to sea-level rise and ocean acidification with growing impacts on ocean ecosystems and on tourism and fisheries. Communicating these impacts remains a challenge.

The open ocean is by international convention the largest transboundary space, with ocean areas beyond national jurisdiction covering about half of the surface of planet Earth (ocean areas under national jurisdiction cover a further 20 per cent), under the ultimate governance of the UN General Assembly. Governance of the open ocean is mediated largely through global international treaties based on particular themes (climate change, fisheries, pollution, biodiversity), as well as some regional conventions.

Challenges of assessing global open ocean issues

There are numerous challenges to assessing how human wellbeing and stakeholder behaviour are affected by and linked to changes in the open ocean. A primary challenge relates to the limited natural science data on the state of the ocean: its physical state, chemical state, the state of ocean ecosystems and living marine resources. Monitoring systems of the state of the physics of the upper ocean, and the ocean carbon system related to climate are not fully implemented and have gaps in their adequacy. Monitoring of the state of ocean ecosystems in particular is lacking. However a lack of sufficient monitoring and scientific understanding should not rule out an assessment of the *high* uncertainty, long timescale, and yet potentially *very high* impact environmental problems associated with the global ocean. Indicators are key to communicating problems and tracking progress. The assessment provides a scoping analysis for looming future problems through development of indicators and as well, an expert assessment of the latest scientific literature. It acts as an analogue to the WMO-UNEP Intergovernmental Panel on Climate Change (IPCC) assessment of the human relationship to climate, and as well, complements the UN Regular Process and the World Ocean Assessment.

Quantifying uncertainty will always be a key part of the natural science assessment of the ocean to support its management. The open ocean assessment has focussed on where data are available, making extrapolations, assumptions and projections based on best scientific knowledge to generalize where data are lacking. The assessment has also addressed key gaps for research and observations to point to a future path towards reducing uncertainties about our knowledge.

The cost of management action to limit human impact on the open ocean, and of the open ocean on human lives, is often difficult to establish when the threats and benefits are not clearly monetized. Of the many ecosystem services (regulatory services, provision of food, energy, recreational and cultural services) provided by the open ocean, the only one that is traded on markets is fish. An assessment of changes in the valuation of natural capital with changes in the ocean could help inform debate.

The global governance arrangements for the open ocean are complex and and it is therefore deemed a priority, through this assessment, to better understand them. In deciding where future interventions can help to mediate this relationship between human and natural systems and increase human wellbeing, the Global Environment Facility (GEF) and other stakeholders will need to target these global conventions, and work to ensure that links to lower-level policy cycles (including regional and local scales) are fully appreciated.

The assessment

The TWAP Open Ocean Assessment has addressed these challenges through a globally-scoped analysis that directly considered six broad themes: governance, climate, ocean ecosystems, fisheries, pollution and an integrated assessment of these impacts on marine ecosystems. Rather than carving the open ocean into units based on natural system criteria (which can vary depending on the scientific discipline consulted, and whether the surface, mid, or deep ocean is being considered), the analysis took the cue from the human system side and the global governance arrangements already in place to focus on a global thematic assessment.

The assessment aimed to clearly link human vulnerabilities on land to the open ocean, as well as ecosystem vulnerabilities in the ocean to human threats.

This assessment addressed the political need for clear, high-level messages about the issues raised, and points towards interventions in governance that can help mediate the relationship between humans and the ocean, improving human wellbeing. A Conceptual Framework was used to organize the necessary simplifications and assumptions rising from the scientific work to achieve this goal.

The Conceptual Framework links human and natural systems, puts human wellbeing at the centre of concerns, but allows a focus on where data is available, in particular on indicators of human-related stress on ocean systems. For this Assessment, the Framework allowed clarity on where simplifications and assumptions were being made in the causal chain, and emphasized the vulnerability of human and natural systems. It put a broad definition of governance at the centre of the human system side to help guide future interventions.

To communicate messages at a high level, a global mapping approach with a limited number of metrics was taken, linking as far as possible stresses on the natural or human system with vulnerabilities. Projections of these stresses and vulnerabilities have been used wherever possible. To support an eventual regional focus, the mapping approach was scaled to smaller spatial domains, where regional governance arrangements existed or interventions on a regional scale were decided. This also acts as a complement in coastal regions to parts of the Large Marine Ecosystem (LME) assessment methodology, which focused on fixed assessment units.

This global mapping approach was accompanied by expert assessment of the latest scientific literature wherever available, particularly with an eye to addressing *high* uncertainty but potentially high-impact problems. The key research and monitoring needs in each thematic area have been identified, as a bridge between the scientific need for exactness and the political need for clear direction. Embedded in the assessment methodology is a expert assessment of the global governance arrangements in place in each thematic area, with a view to identifying gaps in the policy cycle and links with regional and national levels

The results provide a baseline of information of the state of the open ocean ecosystems, alongside projections of potential changes in the future through to 2050, and in some cases 2090. They also compliment the *Summary of the First Global Integrated Marine Assessment (2015)* as part of the *UN Regular Process for Global Reporting and*

Assessment of the State of the Marine Environment, including Socio-Economic Aspects (Regular Process) (otherwise known as the *Summary for the World Ocean Assessment (2015)).*

It is clear from the results of the TWAP Open Ocean Assessment and considering the *Summary for the World Ocean Assessment (2015),* that urgent attention is required to sustainably manage the open ocean ecosystems and services now and into the future. Understanding the impact of climate-ocean-human interconnections will help inform and improve decisions for sustainable management. To do this however, ongoing and improved monitoring of essential ocean variables (including physical, chemical and biological) is necessary. The UN's Global Ocean Observing and Climate Systems (GOOS and GCOS) can assist drive this forward. Future monitoring and management/policy interventions can be improved, guided by these results and the recommendations (outlined in the accompanying *TWAP Open Ocean Summary for Policy Makers – Status and Trends (2015).* In particular, issues linked to complex governance arrangements (and with many gaps), climate change impacts such as ocean acidification, de-oxygenation, and ocean warming are threatening the health of open ocean ecosystems and related services and human wellbeing. Urgent reduction in greenhouse gas emissions along with improved regulations for reducing pollution sources and over-exploitation of fish stocks, could significantly improve the future health and sustainability of the open ocean ecosystems, services and human wellbeing.

The TWAP Open Ocean Assessment provides a holistic overview of the state of the open ocean ecosystems and their inter-connections with wellbeing. This can be used to guide a system of monitoring goals that could be set out within the Sustainable Development Goal framework, and should also be used to support future rounds of the World Ocean Assessment and subsequent targeted transboundary assessments for the ocean. Indeed, an ongoing and robust scientific support enterprise is essential in providing confidence to policy and decision makers that resources are being appropriately allocated for improved sustainable management and use of the ocean and its ecosystem services.

Chapter 1
Introduction

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Chapter 1 Introduction

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Introduction

The TWAP

The Transboundary Waters Assessment Programme (TWAP) was established to assess – for the first time - the state of the global transboundary waters system. It aimed to guide the Global Environment Facility (GEF) to identify priority areas for intervention in the management of shared water systems. The results should also help governments in managing their shared water bodies. The project has been carried out using a scientifically credible methodology for a global assessment of transboundary water systems (groundwater, lakes/reservoirs, river basins, Large Marine Ecosystems (LMEs), and open ocean areas). It has also catalysed partnerships and established arrangements for conducting the global assessment. The assessment methodology has allowed the monitoring of evolving trends in these water systems, and the identification of the impacts of GEF International Waters programmes and those of other agencies and actors.

For the Open Ocean component, the assessment methodology was developed to decipher the complex interaction of the natural system with human systems, speaking to a high level policy and decision making audience, and pointing to environmental problems related to the 'open ocean'. For the purpose of this assessment, 'open ocean' was defined to include areas beyond national jurisdiction. However, also acknowledging that the open ocean is connected to and has direct impacts on areas within national jurisdiction, the assessment covers a global scope. (see Glossary Box 1 for an explanation). Whilst focused on the open ocean, the assessment maintained a high level of scientific credibility, making the best use of sometimes very sparse data about the open ocean, and identifying uncertainties driven from gaps in knowledge and in data.

The open ocean as global commons

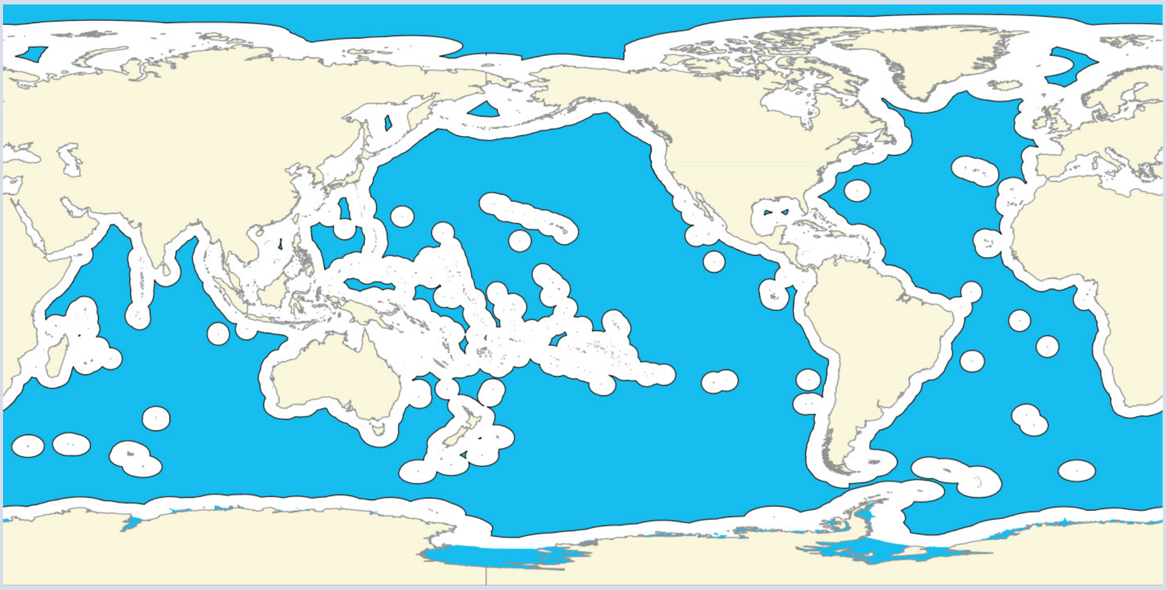
The open ocean is the largest area of global commons, vital to life on the planet, and under the legal jurisdiction of no one nation but the common stewardship of all. About half of the entire surface of our planet is open ocean in areas beyond national jurisdiction (Figure 1.1).

While most of the human population of the planet may feel remote from the open ocean - it influences lives in profound ways. The ocean holds 97 percent of all the water on Earth, most of it in the open rather than coastal ocean. Open ocean dynamics play a key role in regulating and modulating the Earth system and hydrological cycle. The ocean has absorbed about one quarter of human emissions of greenhouse gases and prevented stronger warming of the planet, but as a consequence they are acidifying, with future potential impacts on marine ecosystems. The ocean provides some key ecosystem services to the human population - they produce the majority of oxygen through ocean primary productivity, hold the major part of the planet's biodiversity, and while the significant fraction of fish catch is in LMEs / coastal waters, the open ocean provides a source of food and economic gain from fish and a habitat to highly mobile species, as well as the transport of nutrients into coastal waters. More than 90 per cent of goods in international trade are transported by sea, and the Global Ocean Observing System (GOOS) estimates the value of marine activities globally (including open ocean and coastal areas) to be about 5 per cent of global GDP.[1]

1 http://ioc-goos.org/spm

Defining the 'Open Ocean'

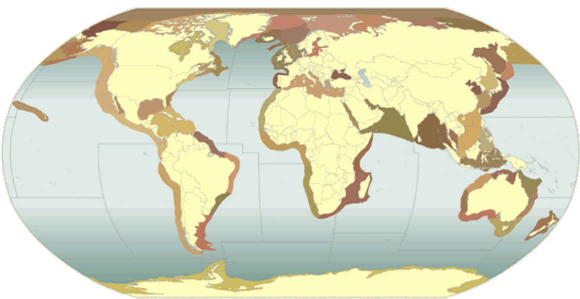
The 'open ocean' is the largest areas of global commons, vital to life on the planet, and under the legal jurisdiction of no single nation but the common stewardship of all in 'areas beyond national jurisdiction' (ABNJ). The area equates to marine waters beyond exclusive economic zones (EEZs). By international convention, the open ocean is the largest transboundary space covering about half of the surface of planet Earth. Ocean 'areas within national jurisdiction' (AWNJ) cover a further 20%. The 'high seas' is an international legal term used by the UN Convention on the Law of the Sea (UNCLOS) which refers to the area of the ocean not included in the EEZ, territorial sea or internal water of any State. Essentially, this is the same as the 'open ocean' and the term is often inter-changed.

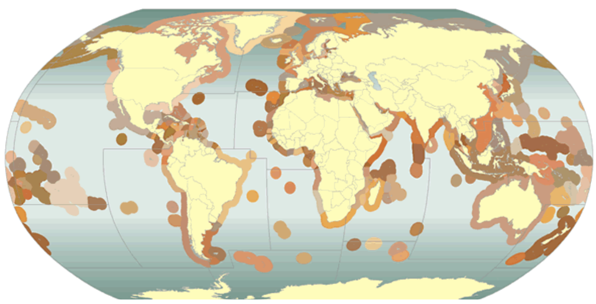


The Open Ocean (or 'area beyond national jurisdiction') is blue. The white areas depict exclusive economic zones (EEZs) (or 'area within national jurisdiction').

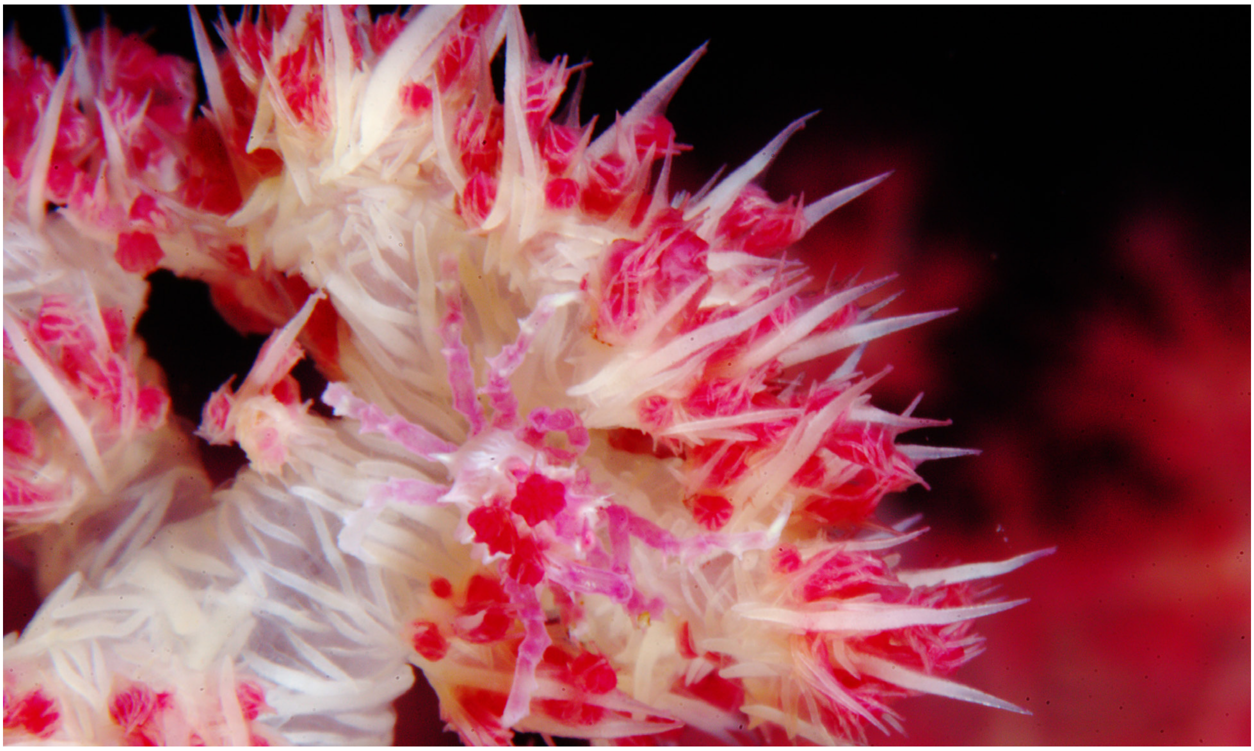
The legal framework governing the uses of the ocean and its resources is defined by the UN Convention on the Law of the Sea (UNCLOS), which entered into force in 1994. It defines internal waters; territorial seas; rights of Coastal States in EEZs over natural resources, certain economic activities, marine scientific research and environmental protection; and rights of coastal States on their continental shelf (limited to the seabed) for exploration and exploitation. Areas beyond the internal waters and EEZs are the high seas, where all states enjoy freedoms of navigation, over-flight, scientific research and fishing.

Figure 1.1. Large Marine Ecosystem areas (left) and Exclusive Economic Zones (EEZs, right). About 50 per cent of the surface of the earth is legally beyond national jurisdiction, the open ocean is the largest transboundary space on the planet.





Source: Sea Around Us project



For the purposes of TWAP, the open ocean is defined as the ocean area beyond the defined LME areas[2] (Figure 1.1). However the open ocean assessment has taken a global approach, complementary to the LME fixed assessment unit approach. While this definition of open ocean is similar to the high seas of UNCLOS, there is a notable addition of many island EEZs in the large ocean basins, particularly in the tropical Pacific. Conditions in the open ocean have impacts on the natural system and particularly on human systems beyond this strict geographic zone, and in assessing the vulnerability and impact of environmental problems associated with the open ocean, the methodology and scope was global.

Principles guiding the global partnership for the environment and development are encapsulated in the Rio Declaration of the 1992 Earth Summit (the United Nations' Conference on Environment and Development), and they are worth noting in the context of the open oceans. These principles include:

- putting human beings at the centre of concerns for sustainable development,
- the responsibility of states not to cause damage to the environment of areas beyond their national jurisdiction,
- the equitable meeting of the needs of present and future generations should be a goal of development,
- that states shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystems,
- environmental issues are best handled with the participation of all concerned citizens, at the relevant level,
- the precautionary approach shall be widely applied.[3]

Under UNCLOS, all states are obliged to adopt, or cooperate with other states in adopting measures to manage and conserve living marine resources. Highly migratory species of fish and marine mammals are accorded special protection. States are bound to prevent and control marine pollution and are liable for damage caused by violation of their international obligations to combat such pollution.

2 Sea Around Us Programme
3 Full text of the Rio declaration: http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

There are a variety of governance arrangements for the open ocean in addition to UNCLOS, detailed in Section 3, which are generally thematic: for managing fisheries, climate change, or ocean-based pollution. They are based on State consensus and cooperation, and generally have weak or no enforcement mechanisms. The TWAP Open Ocean Assessment has evaluated governance arrangements related to open ocean environmental problems as a basis to understand where potential interventions are required to manage these. In some cases, interventions point to areas of management and governance that are not directly related to the open ocean, because of geographic links between human systems, other natural systems, and open ocean systems. In the context of GEF these may not fall under the International Waters focal area, but might cut across other GEF focal areas.

Previous and ongoing assessment efforts and lessons learned

TWAP is not the only assessment focused on the open ocean or international waters. In conducting the assessment, it has been important to learn from previous efforts, and align with ongoing ones, for example with the World Ocean Assessment, to maximize the synergies between efforts and improve their chances of being sustained by local and international involvement.

Previous Global approaches

The Global International Waters Assessment (GIWA) published in 2006 was a previous effort by GEF and implemented by UNEP to assess international freshwater and coastal ocean systems in a holistic and globally comparable manner, but it did not address the open ocean. Four major concerns were addressed: freshwater shortage, pollution, overfishing, and habitat modification, along with the overarching concern of global change. In 66 sub-regions, building on strong local involvement, GIWA assessed the concerns above, and proposed policy options. Whilst GIWA built local ownership from a strong bottom-up approach, it was hampered by a lack in many cases of social scientists and policy expert involvement, and limited stakeholder involvement. The GIWA approach to assessment will not be repeated by GEF. GIWA provided an interesting background to the TWAP Open Ocean Assessment Methodology, in emphasizing the importance of social science and policy in assessing management options for environmental problems, and in pointing out the geographic areas of current and future water stress - since rainfall and drought are controlled mainly by open ocean processes.

The UN General Assembly is currently implementing the *Regular Process for Global Reporting and Assessment of the State of the Marine Envrionment, including Socio-Economic Aspects (Regular Process,* or otherwise known as the *'World Ocean Assessment).* In its start-up phase, a group of experts led by UNESCO-IOC and the United Nations Environment Programme (UNEP) conducted an Assessment of Assessments that identified best practices for an influential assessment, published in 2009. TWAP had a different main client (GEF) from the Regular Process (the Member States of the UN), and therefore had a different scope and objectives. Nevertheless, the TWAP Open Ocean and LME Assessments have maintained communication with the Regular Process and hope to contribute relevant results to it in future rounds.

The Open Ocean Methodology also took note of some other global assessment initiatives with some relevance:

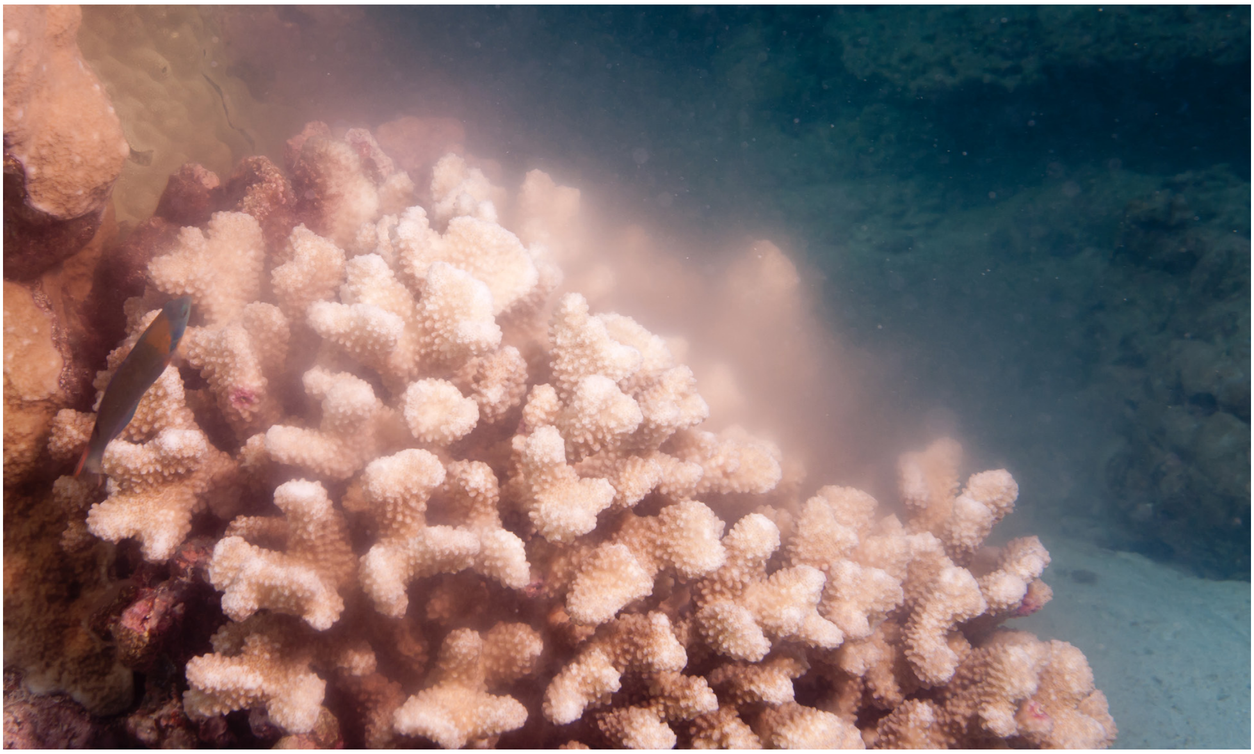
- The UN Global Ocean Observing System (GOOS, a joint project with the UNESCO-IOC, World Meteorological Organization (WMO), UNEP, and the International Council for Science (ICSU)) has been developing and working with partners to publicize indicators of open ocean variability and change, and is developing further information on the impacts related to these indicators. Its multilateral network of ocean observations is key for monitoring change in the ocean. While originally developed as a climate observing system, the open ocean extent of GOOS has now expanded into biological and biogeochemical variables, and is working with additional partners to expand to sustained observations of these into 'ecosystem Essential Ocean Variables' (eEOVs). Indeed, the GOOS Biology aspect has been set up, under the guide of *A Framework for Ocean Observing (2012),* during the course of the Open Ocean Assessment.

The IOC's International Oceanographic Data and Information Exchange (IODE) programme coordinates the management of open ocean data, including the Ocean Biogeographical Information System (OBIS), a key output of the decade-long Census of Marine Life which ended in 2010.

- One of the most extensive scientific assessment efforts that include the open ocean is thematic: the one performed by the Intergovernmental Panel on Climate Change (IPCC). It was based on the assessment of peer-reviewed published scientific articles, and included the open ocean in assessing the role of the ocean in changing climate, and the vulnerabilities to and impacts of the changing climate on natural marine systems.
- The UNEP Global Environmental Outlook (GEO) is a consultative, participatory, capacity-building process for global assessment and reporting on the state of the environment, trends and future outlooks. It aims to facilitate the interaction between science and policy. The Conceptual Framework of GEO is consistent with the one proposed for the TWAP Open Ocean and LME Assessments.

Regional approaches

The European Union's Marine Strategy Framework Directive (MSFD) adopted in 2008 aims to achieve good environmental status of the EU's marine waters by 2020. It requires each EU Member State to conduct a detailed assessment of the state of the marine environment based on definitions of 'good environmental status' and to establish targets and monitoring programmes. The descriptors of 'good environmental status' are now being developed through scientific advice, and are focused on biodiversity, non-indigenous species, healthy fish stocks, marine food webs, human-induced eutrophication, sea-floor integrity relating to ecosystems, hydrographic conditions, pollution, contaminants in seafood, marine litter, and underwater noise. The assessment will include open ocean portions of the northeast Atlantic Ocean, and the descriptors and methodology are relevant to both the Open Ocean and the LME Components of TWAP.



Some regional and national efforts of note:

- Cooperation Across the Atlantic for Marine Governance Integration was a project to rationalize indicators in the coastal zones and open ocean across the Atlantic, and had links to other ocean health index projects.
- The US Government's National Oceanic and Atmospheric Administration (NOAA) is developing Integrated Ecosystem Assessments[4] for marine ecosystems with indicators to track ecosystem health.
- The OSPAR Quality Status Report 2010[5] provides a thematic assessment of the level of human threats and ecosystem health in the Northeast Atlantic.

Development of the TWAP Open Ocean Assessment

The UNESCO-IOC coordinated the development of the TWAP Open Ocean Assessment with wide consultation from 2010, including with GEF. The methodology was finalised in July 2012 (UNESCO-IOC 2012, http://www.geftwap.org/publications/methodologies-for-the-gef-transboundary-assessment-programme-1/volume-6). The approval of the Project Document in December 2012 paved the way for the Open Ocean Assessment, which was carried out from April 2013 until December 2015. This Technical Report presents the results of the work, and is supplemented by the *'OneSharedOcean.org'* web portal, which provides access to the underlying data and interactive graphics. The key results in relation to policy guidance have been summarised into the *Open Ocean Summary for Policy Makers – Status and Trends (2015).*

4 http://www.st.nmfs.noaa.gov/st7/iea/
5 http://qsr2010.ospar.org/

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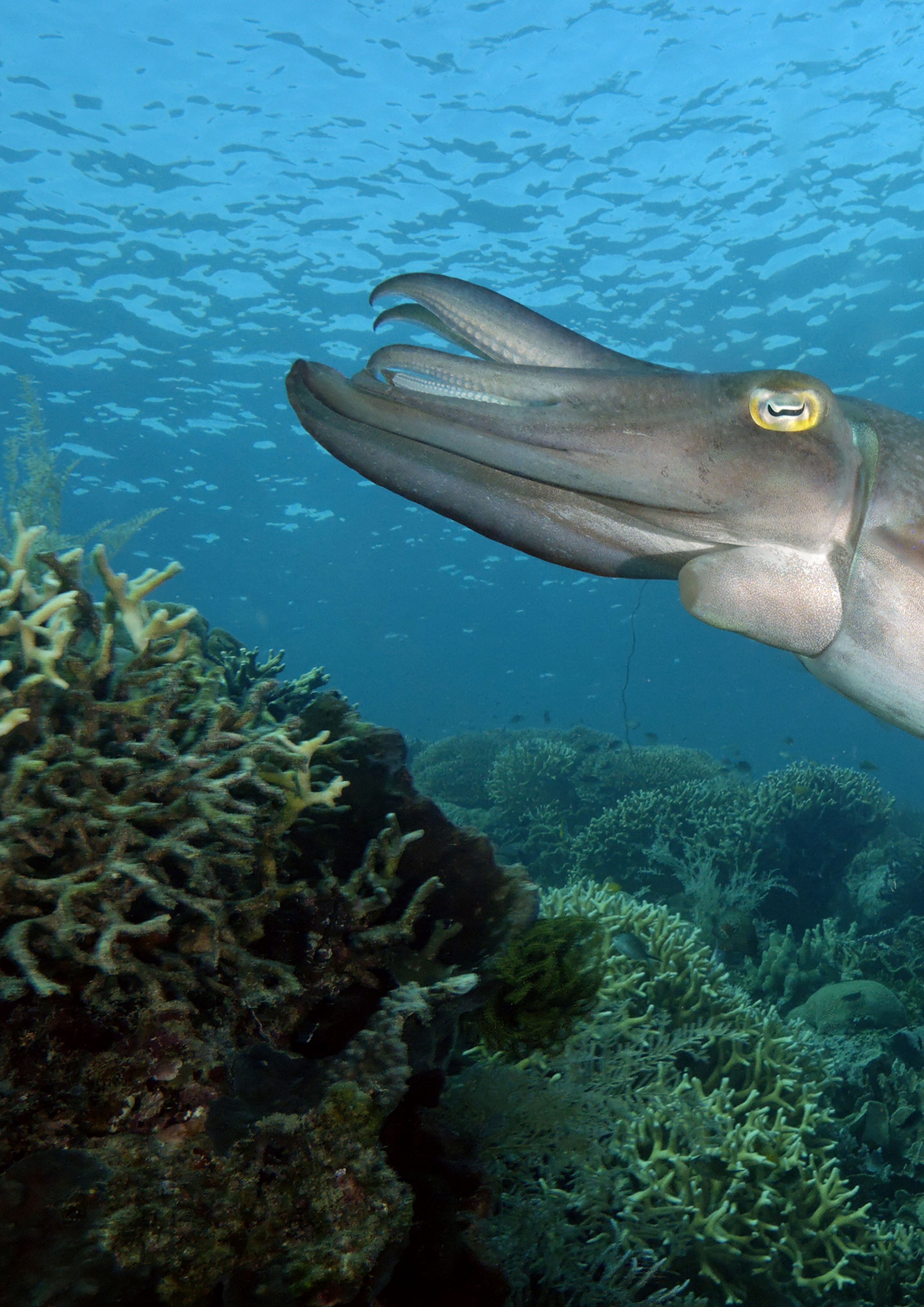
UNESCO 2012 A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing, IOC/INF-1284, doi: 10.5270/OceanObs09-FOO

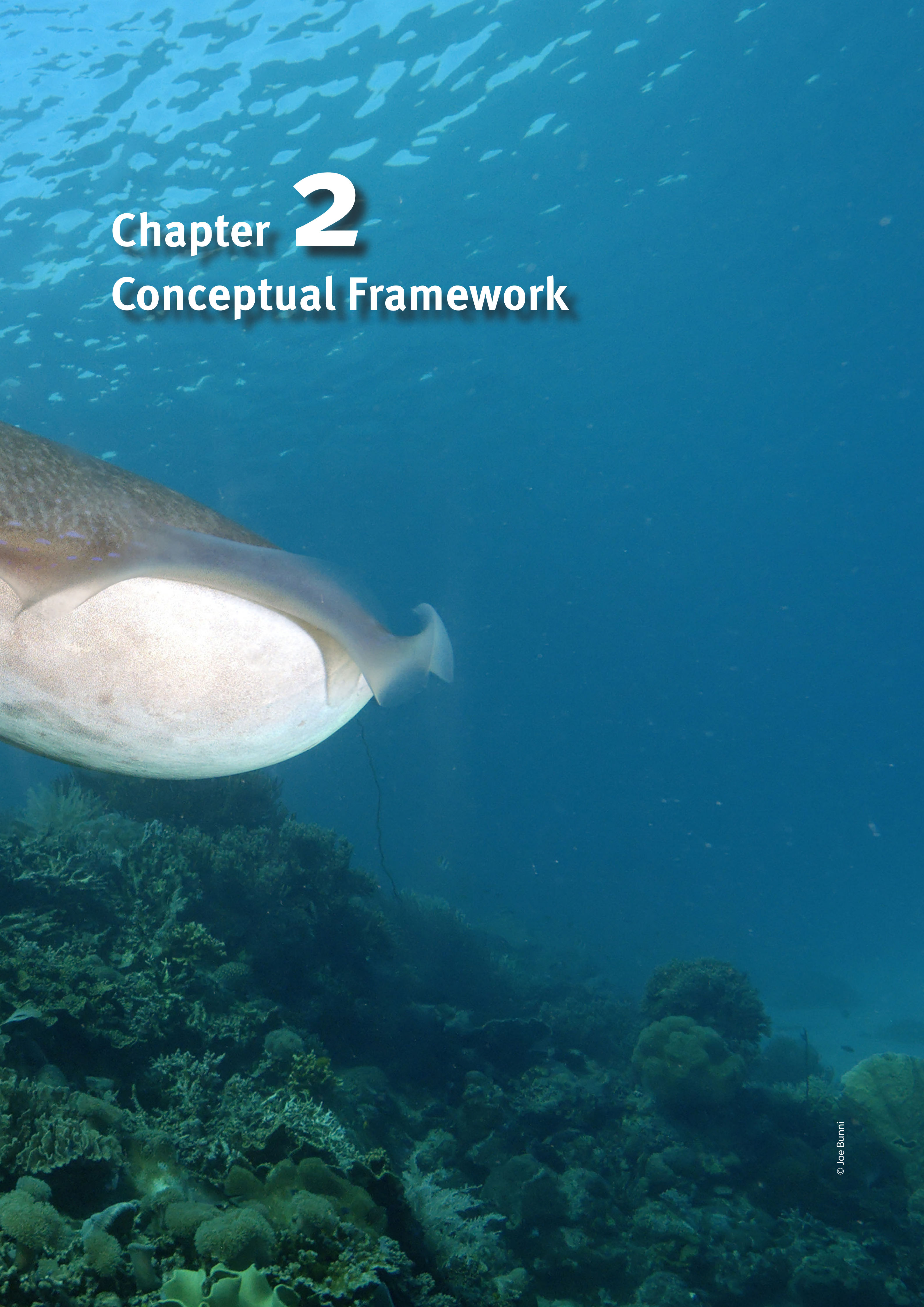
UNESCO-IOC 2015'OneSharedOcean.org' web portal

UNESCO-IOC 2015 Open Ocean Summary for Policy Makers – Status and Trends, UNEP

2012 Summary for the World Ocean Assessment



Chapter 2
Conceptual Framework



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Chapter 2. Conceptual Framework

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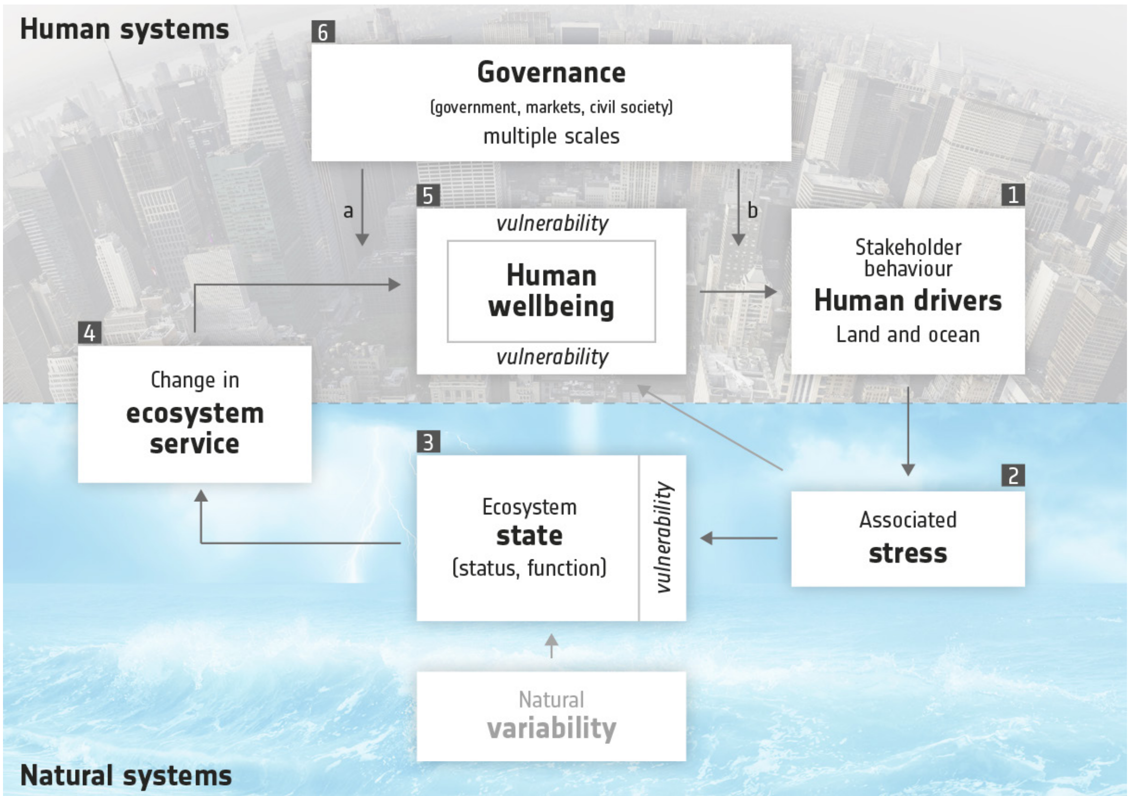
Conceptual Framework

2.1 Overall Conceptual Framework

The Conceptual Framework of the TWAP Open Ocean Assessment (similar to the TWAP LME assessment) displays the relationship between human and natural systems, to help identify why particular indicators are proposed and their relevance, where assumptions have been made, and where there are gaps in knowledge and data (Figure 1). The Framework draws on assessment efforts that focus on the idea of 'causal chains'. In short, human activities have associated stressors that in turn impact natural systems and this in turn affects the delivery (and value) of services to people (starting in Box 1 below and going clockwise). Ultimately the Open Ocean Assessment investigates how people are affected (Box 5 in bold), but these ultimate responses may not have easy indicators to develop and may take time, so there is value in having rapid 'early indicator' metrics that are earlier in the causal chain. Understanding and modelling this causal chain allows one to assess the relationship between indicators earlier in the causal chain while keeping in mind the ultimate goal.

Figure 2.1. Conceptual Framework for the Open Ocean Assessment, describing the relationship between human and natural systems from the point of view of ecosystem services and its consequences for people expressed as human well-being. Within TWAP this allows an identification of data sources and gaps, of assumptions made, of some factors peripheral to the central framework that may come into play, and of natural points of intervention for management.



Source: UNESCO-IOC and European Space Agency

The Framework tried to merge several existing conceptual frameworks: the Driving force-Pressure-State-Impact-Response (DPSIR) framework, indicator science, an emerging focus on ecosystem services, and cumulative impact modelling, all with a strong focus on governance and socio-economics - on how to manage the human-natural system interaction.

The top half of the diagram is the human system, the bottom half the natural system.

On the human system side, all the interactions between boxes were strongly mediated by socio-economic factors. Governance was defined broadly as including government, markets, and civil society, operating at global, regional, national, and local scales. Governance factors influence each other across scales, including through personal behaviour, and determine, for example, which people benefit from the delivery of ecosystem services (for example: equity) and what kinds of activities people engage in (regulations, social norms, etc.). One could reasonably and conceivably have indicators for any of these boxes, but the ideal indicators would connect directly to 'human well-being' (Box 5).

Effective governance is fundamental to achieving healthy ecosystems (inclusive of people), and in this context, should focus on sustaining ecosystem services (Box 4) in addition to other politically-negotiated goals. Governance affects the activities people pursue and with what intensity (Arrow b), and if or how value derived from natural systems reaches human communities and is or is not distributed equitably among community members (Arrow a).

On the natural system side, the framework concentrated on stresses associated with human activities (Box 2, which on the ocean side can come from both ocean-based activities like fishing and land-based activities like carbon emissions or plastics pollution), how they affect the state of the ecosystem under consideration (Box 3, modulated by the ecosystem vulnerability), which may lead to changes in the ecosystem services (Box 4, for example: fish catch). Finally, crossing the natural-human system boundary, the changes can lead to consequences for people, buffered or exacerbated by their vulnerability (surrounding Box 5). Natural variability, whether a regular seasonal change or more complex nonlinear interaction within the natural system, was evaluated separately from the interaction with the human system, so that the impact of a change in the human system - through a change in governance or

a particular GEF intervention, can be separately identified. It is also important to characterize natural variability in order to understand which ecosystem state changes require or can be subjected to management.

There are a few additional pathways depicted that were peripheral to this central framework, but should also be mentioned. Depending on the problem being examined, an associated stress may have a direct consequence for people without being mediated through an ecosystem service (Arrow connecting Box 2 to Box 5 directly), such as in the case of human-induced sea-level rise and its direct physical impact displacing populations.

While this conceptual framework identifies the protection of ecosystem services as the main pathway to mitigate consequences for people, under some other internationally-recognized value systems for management (protection of biodiversity, endangered species, natural heritage sites), the goal of management is not focused on sustaining ecosystem services but on directly conserving ecosystem state. In systems where thresholds might exist but uncertainty is *high*, and where future benefits are unknown, such a conservative approach has been politically negotiated.

2.2 Indicators in the Framework

The way that indicator science fits into this Framework is via the need to select indicators that serve specific prioritized needs'. Ultimately, the Open Ocean Assessment is aimed at improving human well-being, so that the long-term indicators that are assessed should focus on the human well-being and vulnerability box (Box 5). But all the preceding Boxes can give insights into likely outcomes for people, and often respond on much shorter time frames. Therefore, on the human system side, management goals and the reasons for wanting to track particular information was clearly articulated. Indicators were then, designed to meet these goals. Making clear all these assumptions and how directly or indirectly an indicator connects to the ultimate goal of the Open Ocean Assessment is critical so that there is a sense of the amount of uncertainty in how well indicator tracks the ultimate concern and whether the indicator is appropriately tracking a concern within the broader Framework.

The Framework allows and is useful for assessing the potential consequences of different management scenarios within a context of changing human activities and associated stressors (through the addition of new stressors and the changing intensity of existing stressors). A given management decision (or change in the intensity of a stressor due to other reasons) will lead to a changing suite of human activities and stressor intensities, which in turn will alter the attributes of the following boxes in the Framework. These changes can be predicted, and then monitored to test the validity of the predictions.

There is an implicit temporal component to this framework, in that it takes time to move from Box to Box, and the time it takes will vary depending on which human activity and which ecosystem service is of interest. For political and practical reasons, GEF may need to focus primarily on attributes within this framework that respond more quickly, but it is important to keep the longer timeframe and relevant consequences in mind, particularly for the large and common spaces of the open ocean.

Within the context of the TWAP Assessment, indicators for all elements of the human and natural systems cannot be developed - as the systems and their interrelationships on different time and spatial scales are complex. In this context, the Framework has brought clarity to the TWAP regarding where data is available to be captured in an indicator, and what assumptions are required to link this indicator with human wellbeing and societal impacts or benefits. In many cases for the open ocean, data on the state of the natural ecosystem is localized or non-existent, and we may know more about the stressor (for example: fishing) than the state itself.

In the context of future GEF interventions, the full Framework could be useful in determining the main points of intervention in the human system to help manage a positive outcome via the environment (the natural system). These assumptions and scenarios will have to be scientifically tested and validated.

2.3 Inventory and characterization of the open ocean—assessment approach

2.3.1 Thematic approach

The TWAP open ocean assessment is thematic, primarily because governance and management arrangements for the open ocean are largely thematic (IOC-UNESCO 2012).

This differed from the traditional approach to an assessment methodology, which is to divide the surface of the area of the zone to be assessed into polygons, assess the same quantities in each, and do a comparative analysis. This was the approach taken by the other components of TWAP (rivers, lakes, groundwater, and LMEs). In the context of a web of regional, national and local management arrangements that are place-based, this type of geographic assessment unit makes sense.

For the open ocean, this approach made less sense, for a number of reasons. As mentioned above, the management of the open ocean is multilateral and largely global and thematic. The ocean is also relatively deep, harbouring very different surface pelagic and benthic ecosystems for example. While they have some links, they are very different and cover distinct regions, as a recent biogeographical mapping exercise for the world oceans (Global Open Oceans and Deep Sea-habitats [GOODS]) shows[6]. Previously, many different assessment units have been used for the open ocean, but these were often political and non-homogeneous: the FAO fishing areas, the Regional Fisheries Management Organizations, the IMO high seas regions, the UNEP and non-UNEP Regional Seas Conventions and Action Plans, the Assessment of Assessment regions; others are more geographical and based on ocean variables, such as the ocean basins, surface wind-driven gyres, and Longhurst polygons[7] that identify key pelagic ocean ecosystems. Each of these assessment units were developed for a different purpose, and none specifically for the purposes of TWAP. Therefore, the Open Ocean Assessment approach in TWAP was for a global governance solution in both time and space that was projected onto local impact and variability.

2.3.2 Identifying key areas of concern

The assessment as far as possible developed mapping approaches for visualization of key indicators and natural and human system vulnerabilities, which directs geographic interest toward areas with current or future problems. Where relevant, scientifically-based projections identified future consequences under relevant scenarios.

In order to speak to a high level with a simple, clear, but scientifically grounded voice, the assessment was based on a small number of indexes or indicators. On the natural system side these words were often interchanged, but to avoid confusion a few definitions guided the process: *indicators on the natural system side* were defined as key natural system or stress variables, averaged over spatial scales of relevance, which helped track the state of the natural system or the stress placed on it. If there were *reference levels* put on these indicators, they reflected natural features intrinsic to the ecosystem and its response to stress. *Indicators on the human systems side* are generally associated with societal goals, are also key social system variables or a combination of variables averaged over the scales of relevance. If there were *targets* for these indicators, they often reflected a political process that has decided a societal goal. An *index* for the open ocean TWAP was a combination of these indicators that exposed the central question being asked, linking as far as possible the human and natural systems.

6 Vierros, M., Cresswell, I., Briones, E.E., Rice, J., Ardron, J. (Eds.), 2009. Global Open Oceans and Deep Seabed (GOODS) biogeographic classification. International Oceanographic Commission, IOC Technical Series No. 84. UNESCO, Paris, 87 pp.
7 Longhurst, A.R., 2006. Ecological Geography of the Sea, 2nd edition. Academic Press, NY, 560 pp.

Due to a lack of data about the natural systems in the open ocean, the assessment also pointed to gaps in observations, in scientific knowledge linking human stressors to changes in ecosystem state and services, and in the governance of human interaction with the open ocean. These allowed for a bridging between scientific exactitude and a management desire for simplicity, highlighting gaps in knowledge and uncertainty, and helped to define whether effective environmental management is possible based on the current state of knowledge.

The assessment was also based, for a number of themes and sub-themes, on expert assessment of the scientific literature. Some issues identified by the open ocean working group experts have *high* uncertainty but potentially *high* impact, with potential ecosystem thresholds, or in the case of governance issues, subjective judgments, and the only way to assess these was through expert judgment.

With the GEFs desire to identify the results of their interventions over time using repeat assessments – the approach used for the Open Ocean Assessment will to some extent help in doing this, but will be complicated by the fact that there are likely to be many actors in the management of the open ocean. Future assessments will have to respond directly to the question of the impact of particular GEF interventions by trying to identify specifically the indicators best suited to this purpose among those proposed here. Future elaboration of the Conceptual Framework will help with this.

2.3.3 Priority issues

The Open Ocean Assessment focused on four major themes, and two cross-cutting aspects on governance and the adequacy of observations and research:

- Climate change and variability in the global ocean, and global and local impacts, related to:
    - changes in temperature, stratification, and sea ice and their impacts on extreme weather, corals, and primary productivity,
    - rainfall and drought changes on land linked to the oceans,
    - ocean deoxygenation,
    - the fate of continued ocean CO_2 uptake,
    - ocean acidification.

- Ocean ecosystems, habitats, and biodiversity, in particular related to:
  - chlorophyll changes due to climate change and their downstream impact,
  - zooplankton changes,
  - pteropod changes (representative of polar ecosystems)
- Open-ocean fisheries
  - as a stress, including bottom fishing,
  - its sustainability, looking at the marine trophic index and projected catch potential, and tuna fishing trends
  - and its equity by looking at the distribution of fish catch value in the high seas.
- Pollution as a stressor of the marine environment, with indicators for
  - ship traffic as a proxy for ocean-based pollutants and stress,
  - plastics, focused on the convergent subtropical gyres,
  - and a clear need for a scientific literature-based assessment to address high uncertainty potentially high-impact issues.
- A cross-cutting governance assessment that looks at the policy cycle at the global level, and its links with regional and national arrangements.
- Underlying all: how adequate are the observational, understanding, and management/governance capabilities? This aspect of the assessment is of key value to the Intergovernmental Oceanographic Commission and the global ocean observing system.

In a thematic approach, the priority ordering of issues for the open ocean was not immediately evident at the commencement of the Assessment. This was addressed by tools for assessment of cumulative impact, which can geographically pinpoint estimates of the stresses on open ocean ecosystems (see Section 8).

2.3.4 Linking knowledge of human and natural systems for management

Ultimately, identifying where interventions should take place will depend on good monitoring and knowledge of the natural system side as well as the human system side. GEF is part of the human system and its interventions will be focused there - on improving governance to mitigate human activities that cause stress to key natural systems, and improving the resilience of human systems to reduce vulnerability. Both of these however will require a good understanding of the interactions and assumptions embodied by the conceptual model, which in turn will require scientific information and knowledge of both the natural systems and social systems.

The TWAP Open Ocean Assessment sought above all to interpret natural and social science with clear and understandable messages that will spark action for management of the environment.

The understanding of the human and natural systems are unavoidably imperfect, but taking a pragmatic approach, the results improve this understanding through scientific monitoring. The open ocean is under-observed and under-explored, and its full impact on present and future human society imperfectly known. However, this should not prevent GEF and others from acting despite this lack of information, as imperfect scientific information can still point to key concerns and management needs, and management goals can be refined iteratively as scientific understanding from research and monitoring improves. The governance of the open ocean is generally poor, and action is needed to prevent adverse consequences to people, and to the environment that provides key ecosystem services.

For the open ocean, a robust scientific support enterprise will continue to be needed to help GEF and others to have confidence that they are directing resources and energy correctly.

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Chapter 3
Governance

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Chapter 3. Governance

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Governance

3.1 Ocean Governance in Areas Beyond National Jurisdiction

3.1.1 Summary and Key Messages

Several recent high-level meetings and reports have concluded that poor governance is a root cause of unsustainability of ecosystem services from the global ocean. Current thinking about governance suggests that addressing this root cause will require much more than the conventional historical focus on regulatory processes and enforcement. The recognition that governance is much broader than this and encompasses the private sector, civil society and resource users of all kinds has led to increased attention to the institutional arrangements and structures within which governance processes play out.

This chapter examines the plethora (over 100) of international agreements comprising the global ocean governance architecture for the key issues, fisheries, pollution, biodiversity and climate change, in areas beyond national jurisdiction (ABNJ). The global governance architecture for the ocean is often referred to as fragmented and having significant gaps. This study confirms that there is indeed considerable room for improvement in integration at the global and regional levels, and that there are significant gaps in coverage of issues, especially biodiversity. It provides indications of where interventions may be needed and proposes an overall structure to make ocean governance architecture more approachable. The chapter is based on a full report by Mahon et al. (2015) which provides further information on the conceptual basis for the assessment and on the assessment methods. The full report is considered to be a companion volume to this chapter which aims primarily to communicate the key findings in a limited space. Examination of the policy processes associated with the 100 agreements found for ABNJ, reveals weaknesses at several policy cycle stages, particularly decision-making and implementation. The decisions made under the processes for agreements are often only suggestions which countries may choose not to implement. There are seldom repercussions for non-compliance. Implementation is also weak, as in most cases it is left up to the countries to ensure that agreed measures are put in effect and monitored. The analysis indicates where interventions can be made to improve these processes, and provide the means of tracking improvements.

Viewing the entire set of agreements as an entire ABNJ governance system, there is an apparent network structure amongst them, which could provide a useful framework for building and strengthening the interactions required to overcome fragmentation. There are several global agreements for key issues such as fisheries, pollution and biodiversity which, together with any associated regional agreements, form separate silos. These are referred to as 'global-regional, issue-based networks'. Integration across these at the global level should be a priority. It is the responsibility of UN-Oceans, a mechanism to link the UN agencies involved in ocean governance; but UN Oceans has no staff or resources to do the job.

Complementing the 'global-regional, issue-based networks' are 16 crosscutting regional clusters or networks found where regional agreements for several issues coincide spatially. These provide the opportunity for integration among issues needed for ecosystem-based management at the regional level. These clusters are generally weak with only a few having any overarching integration mechanism and many lacking an agreement for biodiversity. These regional clusters should be the focus of strengthening activities that target the policy processes of individual agreements, establish new regional agreements to fill gaps, and develop regional integration mechanisms.

This assessment has focused on ABNJ, but the global and regional networks of agreements described above either apply to areas within national jurisdiction (AWNJ) as well, or have linkages to agreements that focus on them. The assessment concludes that it is probably most appropriate to deal with ocean governance as a whole rather than separating it into ABNJ and AWNJ, while recognising that there are substantial jurisdictional differences, and that arrangements for ABNJ are much further behind.

The study has assessed the extent to which provision has been made for practices thought to reflect 'good governance' in the policy processes associated with individual agreements. The study has also sought to assess the overall relations and structure among the many agreements for governance of the world's ocean. These assessments have been based on the text of the agreements and associated documents such as rules of procedure. The limitation that this study reflects largely 'rules on paper' rather than 'rules in practice' is fully acknowledged. Nonetheless, it provides a significant basis for discussion of what is, and what should be, taking place in practice.

The objectives of this Assessment

The objective of this study was to assess global governance architecture for ABNJ governance and global governance aimed at mitigation of global environmental issues related to the ocean. Specifically, the assessment aimed to:

- Address the four themes of the open ocean assessment (climate, biodiversity and ecosystems, fisheries, and pollution);
- Focus on identifying the governance architecture (networks) and the roles of organisations and institutions in the policy cycle, identifying gaps and overlaps;
- Pay particular attention to science-policy interfaces;
- Note links to regional governance architectures; and
- Incorporate emerging global governance concepts and their application to the ocean.

It is important to note that the assessment intended to look only at governance arrangements and architecture. Due to limitations in time and resources, it did not examine governance effectiveness, important as an assessment of effectiveness may be.

Key Messages

There is considerable scope for strengthening the policy processes associated with more than 100 agreements found for ABNJ, particularly with regard to decision-making;

- There is an apparent networking structure amongst ABNJ governance arrangements that could provide a useful framework for building and strengthening the interactions required to overcome fragmentation;
- There are 'global-regional, issue-based networks' for which integration at the global level should be a priority;
- There are crosscutting 'regional clusters' or networks where regional agreements for several issues coincide spatially. These regional clusters should be the focus of strengthening activities that target the policy processes of individual agreements, establish new regional agreements to fill gaps, and to develop regional integration mechanisms; and
- Ocean governance should be dealt with as a whole rather than separating it into ABNJ and AWNJ, while recognising that there are substantial jurisdictional differences and arrangements for ABNJ are much further behind.

3.1.2 Main Findings, Discussion and Conclusions

The ocean area beyond national jurisdiction (ABNJ) covers about half of the surface of planet Earth, with those within national jurisdiction (AWNJ) covering a further 20 per cent See Figure 1.1 in Introduction. ABNJ provide many important ecosystem services (UNEP 2006, UNESCO-IOC et al. 2011). These ecosystem services are increasingly under threat from a diversity of anthropogenic impacts arising from fisheries, land and marine-based sources of pollution, and climate change (GESAMP, 2001). The monetary value of ecosystem services from ABNJ is poorly known; especially for nonmarket services such as their role in moderating climate change (Murillas-Maza 2011) but are thought to be huge (IPCC 2014). This lack of understanding of the value of the ocean, the vastness and remoteness of ABNJ as well as issues of jurisdiction, have resulted in inadequate attention to the protection and preservation of the ocean's capacity to deliver these services.

The global governance arrangements for the ocean fall under the constitutive framework of the 1982 United Nations Convention on the Law of the Sea (UNCLOS). The preamble to UNCLOS acknowledges that 'the problems of ocean space are closely interrelated and need to be considered as a whole'. This perception of the need to manage ocean issues in an integrated and coordinated manner runs throughout the Convention. However, despite the large array of global and regional conventions, treaties and other arrangements for governance of the major ocean issues, coordination and integration among issues such as biodiversity, fisheries, pollution and climate are often weak (Freestone 2010, Rothwell and Stephens 2010).

As with other social-ecological systems, governance of the ocean involves much more than these global conventions. It includes governmental structures, markets, and civil society arrangements. Thus, in deciding where future interventions can help to mediate the relationship between human and natural systems and increase human wellbeing, both the existing global legal framework and linkages with other critical components and actors of the system will need to be fully appreciated by the Global Environment Facility (GEF) and other stakeholders. Given the interconnectedness of the world's ocean, linkages to national and even local level governance processes will also play critical roles in the governance of ocean ABNJ. This chapter examines global and regional agreements and associated arrangements for governance of ABNJ. It is based on a more comprehensive report by Mahon et al. (2015) of the analyses carried out which can be consulted for additional information. The focus is on governance agreements for the key sustainability issues facing ABNJ: fisheries, pollution, biodiversity and habitats, and climate change/variability. Indeed these issues are critical for all ocean areas, so the chapter also considers the linkages of governance arrangements in ABNJ with those for areas within national jurisdiction.

Holistic perspectives relating to global level patterns in ocean governance arrangements are needed to inform our understanding of how best to implement governance of the oceans in the integrated and coordinated fashion envisaged by UNCLOS. This study seeks to determine the weaknesses and gaps in the full set of ocean governance arrangements. It also seeks to determine if the arrangements comprise an overall emerging ocean governance architecture that can provide a basis for discussion, and finally to identify interventions to meet ocean governance needs.

Findings

Overall, 100 arrangements were found that were considered to be relevant to ABNJ with regard to the four issues of concern (Table 3.1) (see Mahon et al. 2015 for a full list of agreements in the database). Of these, 18 are constituting agreements and 82 are operational (see Section 3.1.2.1.2 for an explanation of these terms). The majority of the arrangements address pollution (55) and fisheries (43), with far fewer for biodiversity (25) and climate change (8). Of the entire set of arrangements, 23 are global in scope, with the remainder being specific to individual oceans or marine regions.

The number of regional agreements varies widely among ocean regions. The region with the largest number is the North Atlantic with 25, including relevant agreements covering the entire Atlantic as well as adjacent seas (Mediterranean, Caribbean, Baltic, Black). In contrast, in the South Atlantic there are only eight agreements, including those relevant for the entire Atlantic. The polar regions also have relatively few agreements, with six for the Southern Ocean and three for the Arctic Ocean. However, the assessment identifies the set of governance arrangements for the Southern Ocean to be among the most comprehensive for any region.

Table 3.1 Numbers of arrangements by issues, types and regions (B = biodiversity, F = fisheries, P = pollution, C = climate change)

Region	Type of arrangement	Issues covered												Total
		F	P	B	C	FP	FB	PB	PC	BP	FPB	PBC	FPBC	
Overall	Constituting	0	10	1	1	1	2	0	0	0	2	1	0	18
	Operational	27	34	5	1	0	6	2	1	1	0	0	5	82
	Total	27	44	6	2	1	8	2	1	1	2	1	5	100
Global	Constituting	0	2	1	1		2	0	0		1			7
	Operational	3	8	1	1		1	1	1		0			16
	Total	3	10	2	2		3	1	1		1			23
Atlantic	Operational	1		1										2
North Atlantic	Constituting	0	3	0			0	0		0			0	3
	Operational	4	10	1			2	1		1			1	20
	Total	4	13	1			2	1		1			1	23
South Atlantic	Constituting	0	1				0							1
	Operational	2	2				1							5
	Total	2	3				1							6
North Pacific	Constituting	0									1		0	1
	Operational	4									0		1	5
	Total	4									1		1	6
South Pacific	Constituting	0	1									1	0	2
	Operational	9	5									0	1	15
	Total	9	6									1	1	17
Indian Ocean	Constituting	0	3				0							3
	Operational	2	8				1							11
	Total	2	11				1							14
Arctic Ocean	Operational	1		1									1	3
Southern Ocean	Constituting	0	0	0		1	0						0	1
	Operational	1	1	1		0	1						1	5
	Total	1	1	1		1	1						1	6

Regional agreements are considered to be important means of translating global agreements to specific geographical areas, which is essential for an ecosystem approach (Crowder et al. 2006, Young et al. 2007, Rice et al. 2011). A closer look at the coverage of issues by regional agreements reveals some of the gaps (Table 3.1). For example, there are several regions with no agreement of any kind for biodiversity. Several of the biodiversity agreements are also specific to a species (polar bears) or taxon (seals, albatrosses and petrels, sea turtles) and do not provide broad coverage of habitats and communities. In the case of climate change, there are two global agreements, the UNFCCC and its Kyoto Protocol, and six combined issue regional agreements in which climate change is identified. In these, climate change is identified only as a factor that must be taken into consideration in dealing with the other issues, rather than something to be addressed directly. This is not unexpected for an issue that is essentially global in nature.

Chronology of agreements

Governance agreements with relevance for ABNJ first began to come into force in the late 1940s (Mahon et al 2015). However, it was not until the late 1970s that a sizable number of both constituting and operational agreements came into force, with constituting agreements peaking in the late 1980s and early 1990s. The peak for operational agreements occurred shortly thereafter. Since the early 2000s, few constituting agreements have come into force, while operational agreements have continued to come into force, albeit at a slower rate. Despite this tapering off, many gaps in coverage of ABNJ areas and issues remain; particularly for biodiversity and ecosystems.

Assessment of policy cycles

Based on the TWAP governance methodology (Mahon et al. 2011), scoring criteria were used to assign each arrangement a score for each of the stages of its policy cycle (Table 3.2). The full conceptual background to this process is provided by Mahon et al. (2013; 2015). In this assessment the advisory and decision-making stages of the policy cycle were each considered in two modes -- policy mode and management mode -- making a total of seven stages assessed: (1) Provision of policy advice, (2) Policy decision-making, (3) Provision of management advice, (4) Management decision-making, (5) Management implementation, (6) Management review, and (7) Data and information management (Table 3.2). Provision for carrying out each of these policy cycle stages is considered to be an important component of the institutional arrangements needed for good governance (Fanning et al. 2007, Mahon et al. 2013). The scores in each case ranged from 0 to 3 and are intended to reflect the institutional strength of the arrangement for transboundary governance at that particular policy cycle stage. An overall policy cycle completeness score is derived from the sum of scores of the individual stages and expressed as a percentage of the highest score attainable. It is important to note that a *high* completeness score means that the arrangements are specified on paper but does not mean that they are operating in practice.

Table 3.2 The criteria used to assign scores to the policy cycles stages for each arrangement.

Provision of policy advice - responsible body and score	0 = No transboundary science policy mechanism, for example COP self advises[8] 1 = Science-policy interface mechanism unclear - irregular, unsupported by formal documentation 2 = Science-policy interface not specified in the agreement, but identifiable as a regular process 3 = Science-policy interface clearly specified in the agreement[9]
Policy decision-making - responsible body and score	0 = No decision-making mechanism[10] 1 = Decisions are recommendations to countries 2 = Decisions are binding with the possibility for countries to opt out of complying 3 = Decisions are binding
Provision of management advice - responsible body and score	Same as for policy advice above
Management decision-making - responsible body and score	Same as for policy decision-making above
Management implementation - responsible body and score	0 = Countries alone 1 = Countries supported by secretariat 2 = Countries and regional/global level support[11] 3 = Implemented through a coordinated regional/global mechanism[12]
Management review- responsible body and score	0 = No review mechanism 1 = Countries review and self-report 2 = Agreed review of implementation at regime level 3 = Agreed compliance mechanism with repercussions
Data and information management - responsible body and score	0 = No DI mechanism 1 = Countries provide DI which is used as is 2 = DI centrally coordinated, reviewed and shared[13] 3 = DI centrally managed and shared[14]

8 Nothing in the documentation indicates a mechanism by which scientific or policy advice is formulated at the transboundary level prior to consideration by the decision-making body.
9 This can be internal or external.
10 This refers to decisions on matters that will have a direct impact on ecosystem pressures or state. It does not refer to mechanisms for making decisions on the organisation itself, such as process or organisational structure.
11 This means support from regional programmes or partner organisations arranged via the secretariat.
12 For example a coordinated enforcement system with vessels following a common protocol and flying a common flag identifying them as part of the mechanism, as in the case of the Forum Fisheries Agency surveillance flag.
13 For both 2 and 3 data are checked for quality and consistency, but for 3 there is a place where all the data can be found, whether as actual data or metadata.
14 Here the regime could also be the actual collector and compiler of the data, as in the International Pacific Halibut Commission.

Typically, intergovernmental agreements fall into two categories: (1) constituting agreements[15] and (2) implementing or operational agreements (Breitmeier et al. 2006). Constituting agreements are aimed at setting the broad context and issues for cooperation, with the expectation that these will be further refined and made actionable by operating agreements. The operating agreements are aimed at giving specific effect to the broader objectives of constituting agreements. They often appear as protocols or annexes to constituting agreements. In this study, protocols are treated as separate agreements as they often have different membership and timeframes to their constituting agreements, whereas annexes are part of the constituting agreement.

The analysis of policy cycle stage scores shows differences in strength among the policy cycle stages, and between constituting and operational agreements (Figure 3.1). Both types of agreements score higher for the advisory stages, where the majority score 3, than for the decision-making stages, where the majority score 1. This is because while the majority of arrangements do have clearly identified mechanisms for both policy and management advice, the decisions made are predominantly recommendations which contracting parties may or may not choose to implement. As might be expected, the extent to which decisions made are binding is considerably higher for operational agreements than for constituting agreements. As regards implementation, the peak for operational agreements is 0, which means that it is entirely up to the member countries (Figure 3.1). It is only slightly higher for constitution agreements with a peak at 1 indicating that there is some secretariat support for implementation. Overall, the picture for most policy cycle stages, and for overall completeness is that there is clearly considerable scope for strengthening most stages of the policy cycles for both types of agreement.

The analysis of policy cycle scores by issue shows some differences in strength among the issues (Figure 3.2). For both policy and management advice, the distribution of scores appears similar among issues, although advisory mechanism scores in fisheries and biodiversity arrangements were higher than for pollution. For decision-making, fisheries arrangements clearly scored highest, with decisions made for pollution being primarily in the form of recommendations for contracting parties. In contrast, fisheries arrangements scored lowest for implementation, which is predominantly at the level of contracting parties. Biodiversity and pollution arrangements (primarily within national waters) were considerably more likely to have regional level support.

Overall structure of arrangements

The analysis of the entire set of global and regional arrangements for ABNJ governance reveals an overall pattern that may provide a useful framework for identifying gaps and weak areas and for developing interventions to address them. The overall picture is one of two complementary sets of networks (Figure 3.3). The first set is the 'global-to-regional issue-based networks'. They are shown as vertical rectangles which reflect the major global arrangements for each of the four issues of fisheries, pollution, biodiversity and climate change. The second set is the crosscutting 'regional intersectoral clusters/networks'. They are illustrated in Figure 3.3 by horizontal rectangles representing five hypothetical 'regional intersectoral clusters/networks' (Regions A-E). The solid circles indicate that representation of 'global-to-regional issue-based networks' is incomplete in the regional clusters, reflecting gaps to be filled.

15 Also sometimes referred to as framework agreements.

Figure 3.1. The distribution of scores for each of the seven policy cycle stages, and overall policy cycle completeness for the two major types of arrangements (see Table 3.2 for the scoring criteria).

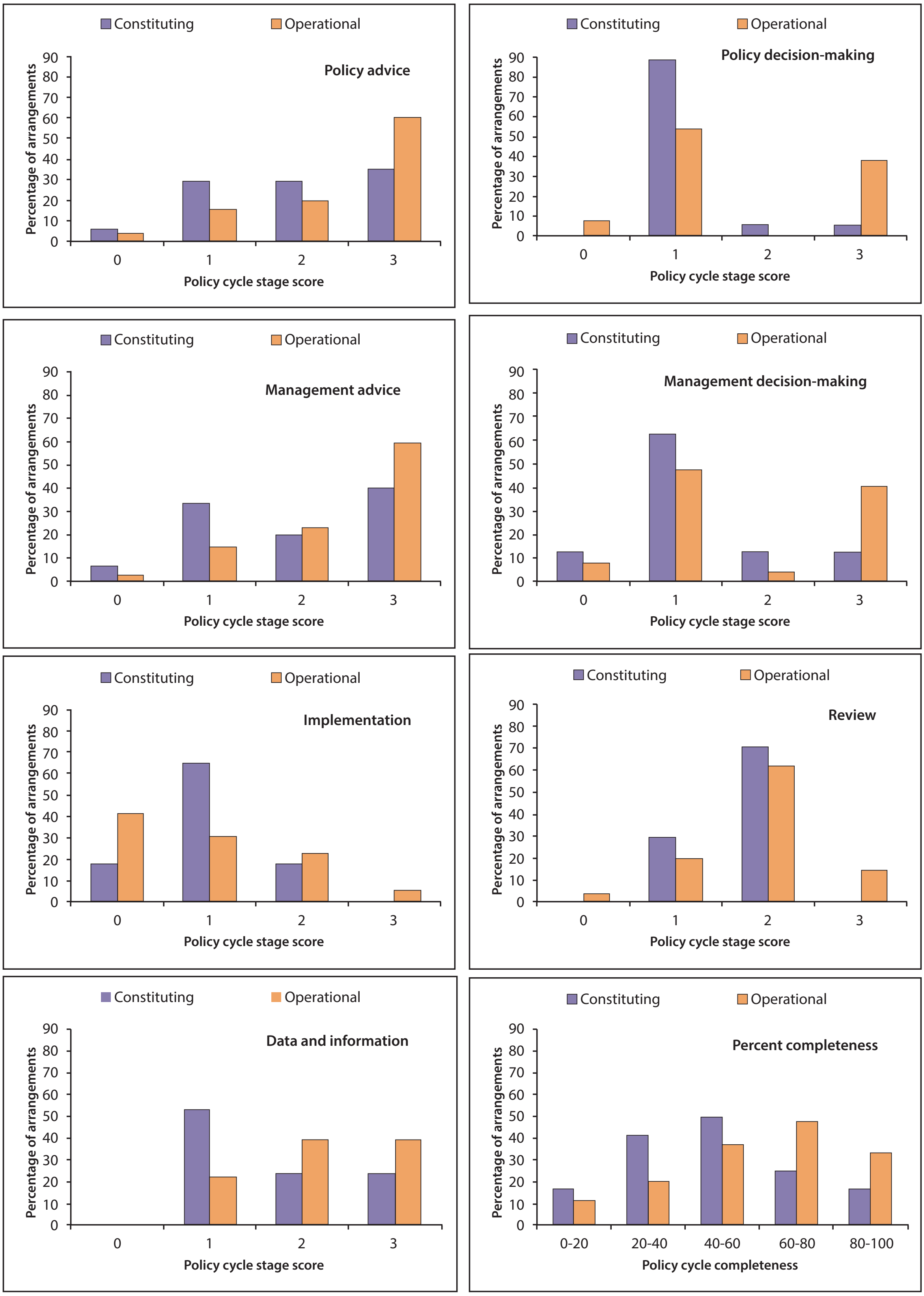


Figure 3.2. The distribution of scores by issues (fisheries, biodiversity and pollution) for each of the seven policy cycle stages, and overall policy cycle completeness. (see Table 3.2 for the scoring criteria).

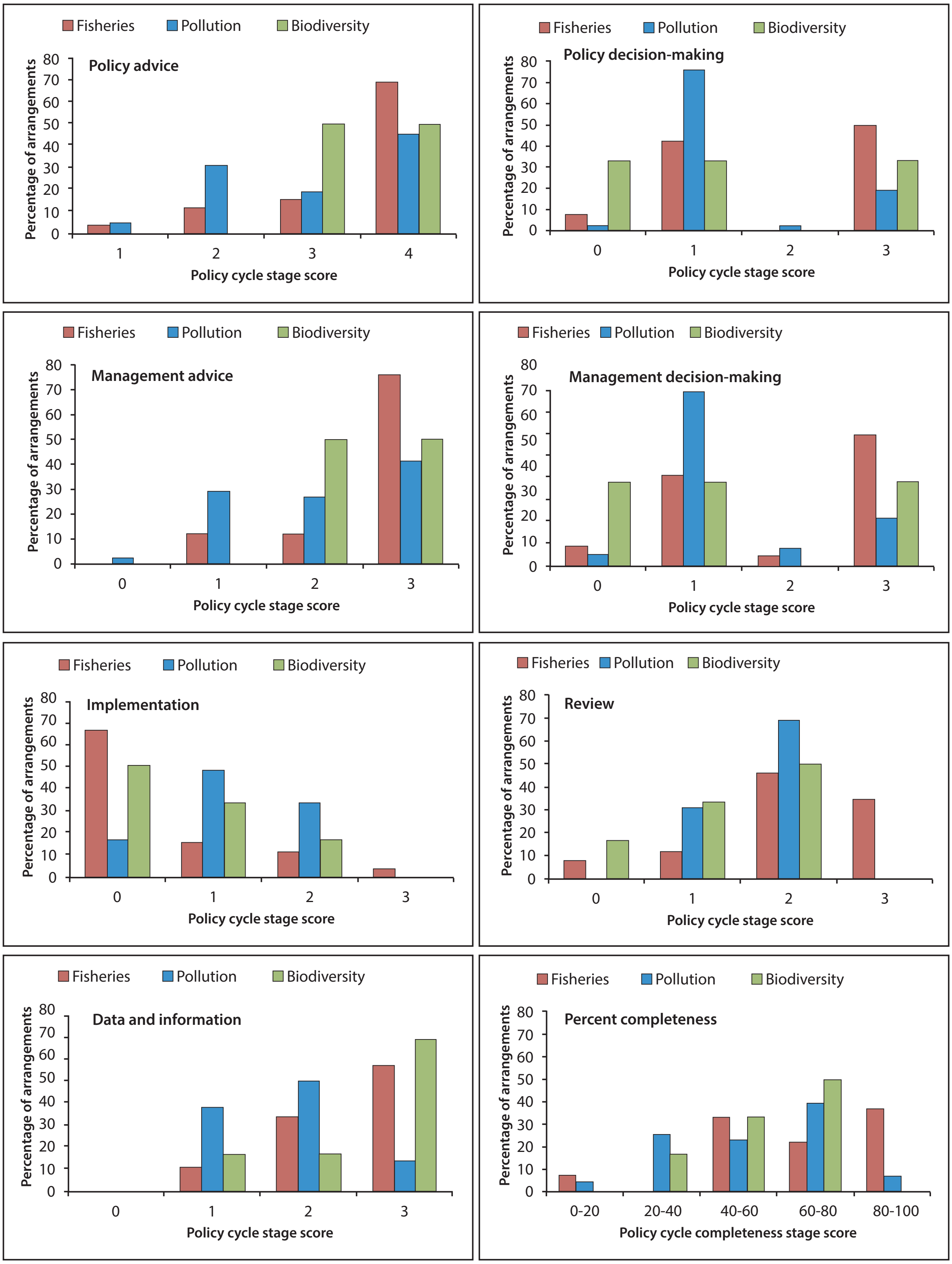
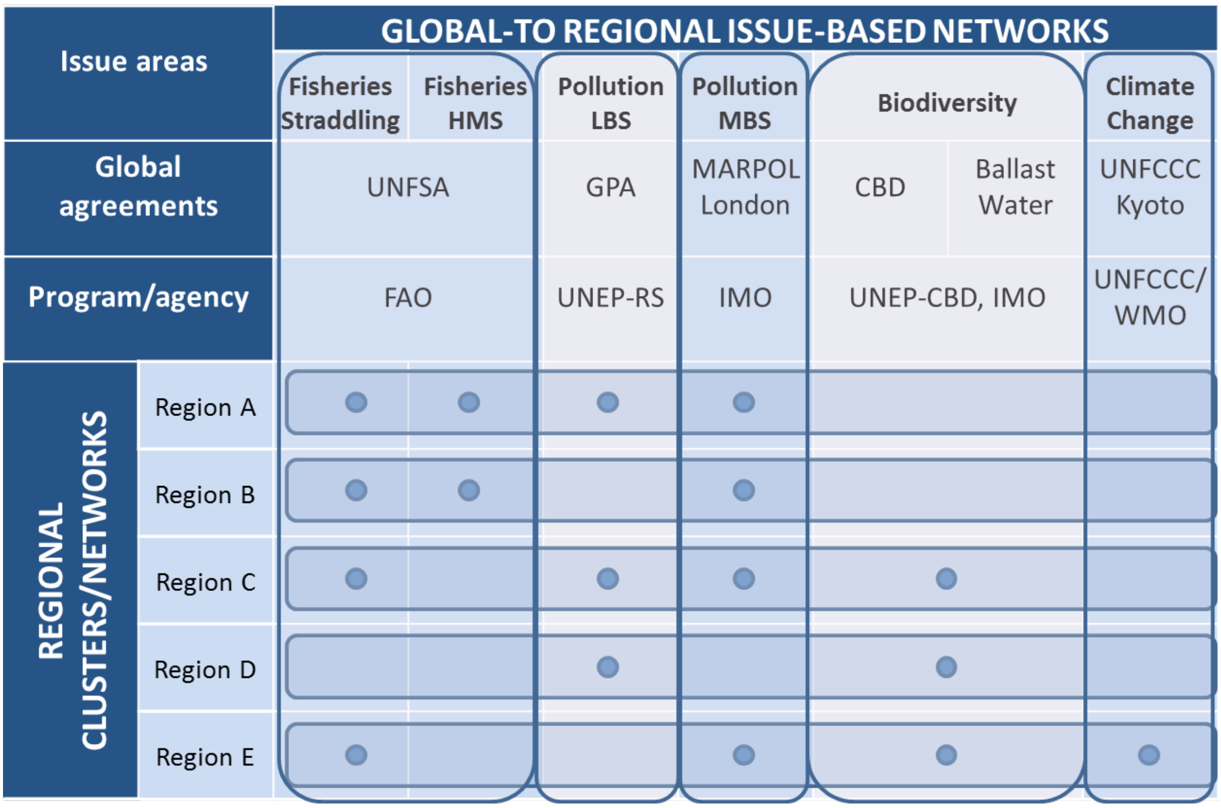


Figure 3.3 The global ocean governance structure comprising 'global-to-regional issue-based networks' of arrangements and complementary 'crosscutting regional intersectoral networks' of arrangements illustrated here for five hypothetical regions A-E. The solid circles indicate that the issue covered by the global-regional network is reflected in the arrangements comprising the regional cluster.



Global-to-regional issue-based networks

The global-to-regional issue-based networks comprise constituting and operational agreements at global and regional levels. They provide the potential for vertical interplay needed between regional and global arrangements. The majority of the arrangements that have been included in the database are either directly administered by, or associated with, the programmes of a relatively small number of UN agencies and programs which serve to anchor these networks as shown in Figure 3.3. It should be noted that the United Nations Convention on the Law of the Sea (UNCLOS) is a constituting agreement that provides an overarching framework for governance of the oceans, including ABNJ, and so is not shown in Figure 3.3. However, it should be noted that not all agreements with relevance to ABNJ are connected to UNCLOS, for example: CITES, CBD, GPA.

For fisheries, the UN Fish Stocks Agreement (UNFSA), along with the FAO Compliance Agreement and FAO Code of Conduct are the major global constituting agreements, with the FAO being the agency responsible for promoting implementation of its Code of Conduct and Compliance Agreement and the UN General Assembly (UNGA) being responsible for the UNFSA. Many of the Regional Fisheries Bodies (RFBs) and Regional Fisheries Management Organisations (RFMOs) in the database are established with reference to the Constitution of the FAO under Articles VI and XIV. Article XIV bodies are established by treaty, generally have a management mandate and are more independent than Article VI bodies (Freestone 2011). Other RFBs which are independently constituted by the contracting parties are also loosely associated with the FAO through an FAO-facilitated network of RFBs' secretariats. The RFB network first convened in 1999 as the 'Meeting of FAO and Non-FAO Regional Fishery Bodies or Arrangements' (FAO 1999) and met four times before changing its name in 2005 to the Regional Fishery Body Secretariats Network (RSN).

To some extent, the Committee of Fisheries (COFI), a subsidiary body of the FAO Council, can be seen as an overarching policy setting body for RFBs globally, although none of the agreements or the voluntary code explicitly identifies COFI as playing this role. COFI presently constitutes one of two[16] global intergovernmental fora where major international fisheries and aquaculture problems and issues are examined and recommendations addressed to governments, RFBs, non-governmental organisation (NGOs), fish-workers, FAO and the international community, periodically on a world-wide basis. COFI had met 29 times up to 2013. COFI has also been used as a forum in which global agreements and non-binding instruments were negotiated (FAO 2013).

The RSN first met in 2007 (FAO 2007) and has met twice since. These meetings, held in parallel with COFI meetings are not formal FAO meetings, but provide the opportunity for exchange of experiences and best practices among RFBs. The 2007 meeting was attended by 18 marine RFBs as well as RFBs for inland waters and several other related organisations such as the Southeast Asian Fisheries Development Center (SEAFDEC) and The International Council for Exploration of the Seas (ICES). In parallel with this, FAO has been promoting performance reviews of RFBs with a view to developing guidelines for best practices (Ceo et al. 2012). It is evident from the above that there is in place a mechanism that could be used for networking regional fisheries bodies and linking them with the major global arrangements, but with a focus on fisheries. This mechanism could also link these regional and global arrangements with fisheries related NGOs and research entities, but to achieve this, the meetings would have to be opened up to these organisations. An assessment of the performance of this mechanism is beyond the scope of this study.

The International Maritime Organisation (IMO) is home to another cluster of arrangements pertaining largely to pollution. It provides the secretariat for six global level operational agreements relating to marine based pollution and one relating to biodiversity - the Ballast Water Management Convention (BWMC).[17] Given that these relate to global shipping, there is less imperative for them to be reflected in regional level arrangements. The IMO itself promotes implementation of these agreements at the regional level through five IMO Regional Presence initiatives.[18] Perhaps more significantly, the promotion and implementation of IMO arrangements is often facilitated at the regional level through Regional Seas Programme protocols relating to: ship generated waste, oil spills, disposal of hazardous waste at sea, dumping at sea, and contamination from exploration. It should be noted that there are global level pollution arrangements that are not part of the IMO cluster. The Vienna Convention/Montréal Protocol, and the Stockholm Convention function independently.[19]

The Regional Seas Programme of UNEP, which began in 1974, is the most extensive initiative promoting regional implementation of global arrangements. There are 18 Regional Seas areas of which 17 are indirectly or directly connected to ABNJ and are included in the database. Of these 17,5 are directly administered by UNEP, 7 were constituted under UNEP but are managed by other organisations and 4 are entirely independent. However, all with secretariats take part in UNEP organised regional seas activities, such as the series of 15 global level meetings of Regional Seas Conventions and Action Plans (RSCAP) which began in 1998. The mandate of all but four of the Regional Seas Agreements is limited to waters within national jurisdiction.

One of the most prominent activities across Regional Seas areas is implementation of the 1995 Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) (UNEP/GPA 2006). This is approached through regional protocols (11) addressing land-based sources of pollution and activities (LBSA). However, this is not the only global level agreement for which regional level implementation is pursued under the Regional Seas Programme and its conventions. As indicated above, several IMO based global agreements are reflected in Regional Seas protocols. Regional level implementation of the marine aspects of the major global biodiversity

16 The UNGA also serves in this role both through its review conferences of UNFSA implementation and its annual sustainable fisheries resolution. FAO COFI is largely fisheries ministries, whereas the UNGA represents all nations and all interests.

17 It is due to the biodiversity focus of this arrangement that it is not included under MARPOL as an annex (Jose Matheickal, pers comm. February 2014).

18 One Regional Maritime Adviser for the Caribbean, based in Trinidad and Tobago, and four Regional Coordinators based in: Côte d'Ivoire for West and Central Africa (Francophone), Ghana for West and Central Africa (Anglophone), Kenya for Eastern and Southern Africa and the Philippines for East Asia.

19 The arrangements for the newly created Minamata Convention on Mercury remain to be determined.

arrangements - Convention on Biological Diversity (CBD), Ramsar Convention, Convention on International Trade in Endangered Species (CITES), and Convention on Migratory Species (CMS) - is also often pursued via Regional Seas protocols (Mahon et al. 2015).

In most cases, the protocols relating to biodiversity are more recent than those for pollution. Thus, there has been gradual expansion and update of many of the Regional Seas agreements to include biodiversity. However, few Regional Seas conventions or programmes address biodiversity in ABNJ (Pacific Island Region, Southern Ocean, Northeast Atlantic, Mediterranean). Protocols and annexes relating to biodiversity are mainly focused on species and habitats in areas of national jurisdiction, usually through the establishment of protected areas. While these protected areas may at times protect straddling or highly migratory species such as sea turtles and sea birds, the respective protocols are not considered to be substantially related to ABNJ biodiversity conservation.

While the networks described above help to make global level fisheries and pollution arrangements applicable at the regional level, there is no comparable network or institutional arrangement for place-based biodiversity conservation in ABNJ. As indicated above, several important biodiversity arrangements may be facilitated at the regional level under the Regional Seas Secretariats but these are almost entirely within areas under national jurisdiction. The 2008 effort under the CBD to address this gap is focused on cataloguing and describing Ecologically or Biologically Significant Areas (EBSAs) and is aimed at providing scientific information and advice for place-based biodiversity conservation in both AWNJ and ABNJ (Druel 2012). However, there is still a lack of a complete global level policy process for ABNJ that can make decisions about which areas should be protected, and the regional institutional arrangements needed for implementation (Druel et al. 2013).

Climate change, the fourth issue to be addressed, is in some ways qualitatively different from the other three. Its effects will be experienced in all regions and ecosystems of the planet. Thus far, discussions about mitigation have taken place in global level arenas and do not appear to have a regional implementation component with an ocean focus. Adaptation on the other hand will need to be implemented at regional, national and local levels. Only three regional agreements could be found that made reference to addressing climate change adaptation or vulnerability in ABNJ - the Antarctic Treaty System, the Arctic Council, and the Pacific Islands Forum - of which the latter two are constituting agreements. It is not clear from the agreements examined how climate change will be dealt with at the regional level. It is likely that it will be dealt with largely as a crosscutting issue in sectoral agreements.

These ‘global-to-regional issue-based networks’ play an important role in facilitating lateral linkages among regional organisations and connecting them with the global level arrangements. However, they are largely sector or issue specific, leaving the question as to how integration across issues and sectors is structured for ocean governance. It can be argued that there is a need for integration at both global and regional levels. The need to integrate across marine related issue areas within the UN system was highlighted in 1992 at UNCED. In 1993, the UN agencies dealing with ocean and coastal issues formed the Sub-committee on Oceans and Coastal Areas of the UN Administrative Committee on Coordination (ACC SOCA) to coordinate activities relating to Chapter 17 of Agenda 21. In 2003, it was decided to establish a separate Oceans and Coastal Areas Network (subsequently renamed UN-Oceans) to provide effective, transparent and regular inter-agency coordination on ocean and coastal issues within the United Nations system. UNESCO-IOC hosted the first meeting of UN-Oceans in 2005. Altogether, there are 15 bodies with membership in UN-Oceans (Departments of the UN Secretariat, UN Programmes and Funds, UN Specialized Agencies, related organisations and conventions).

Thus far, UN-Oceans has not had any dedicated staff. The Coordinator and Deputy Coordinator and with them the Secretariat rotated among member bodies every two years. An evaluation of UN-Oceans concluded that due to its ad hoc structure and lack of dedicated human and financial resources, it was ineffective, and unlikely to be able to achieve its objectives (Zahran and Inomata 2012). The review recommended that UN-Oceans be provided with a Secretariat and that it be institutionalised with clear procedures for program development and decision-making. The review also recommended that countries should have ocean focal points with which UN-Oceans would interact directly.

New Terms of Reference (ToR) for UN-Oceans were approved by the UNGA in 2013 (UNGA resolution 68/70) and further reviewed in 2014. These ToRs name the UN Division for Ocean Affairs and Law of the Sea (UN-DOALOS) as the permanent focal point for UN-Oceans. What is not clear is whether the mechanism will be provided with the resources needed to be effective. The increased prominence of oceans at Rio+20 suggested that coordination of UN activities in relation to oceans would be likely to receive increased attention from the UN in the coming years (UN Secretary General 2012).

There is a substantial literature on inter-relations (or as it is referred to in the governance literature, interplay) among international institutions upon which a strengthened UN-Oceans could draw (Stokke 2001, Young 2002, Oberthur and Gehring 2006, Oberthur 2009, Stokke et al. 2011). Oberthur (2009) presents a typology of interplay among international institutions and discusses approaches to managing interplay. One of the key areas for enhancement is systematic promotion of inter-institutional learning. This can be pursued by explicitly recognising the importance of institutional process and memory both within and between arrangements, such that process promotes learning and knowledge and experience are retained in a form that is shareable. Attention to clear and transparent policy cycles and in particular science-policy interfaces is critical for building 'learning institutions'. However, questions about limited mandates, rigid hierarchies and varying priorities leave the future of constructive interplay unsure, unless there is a strong call for enabling mechanisms for cooperation from the UNGA or via a new international agreement.

Regional clusters for EBM

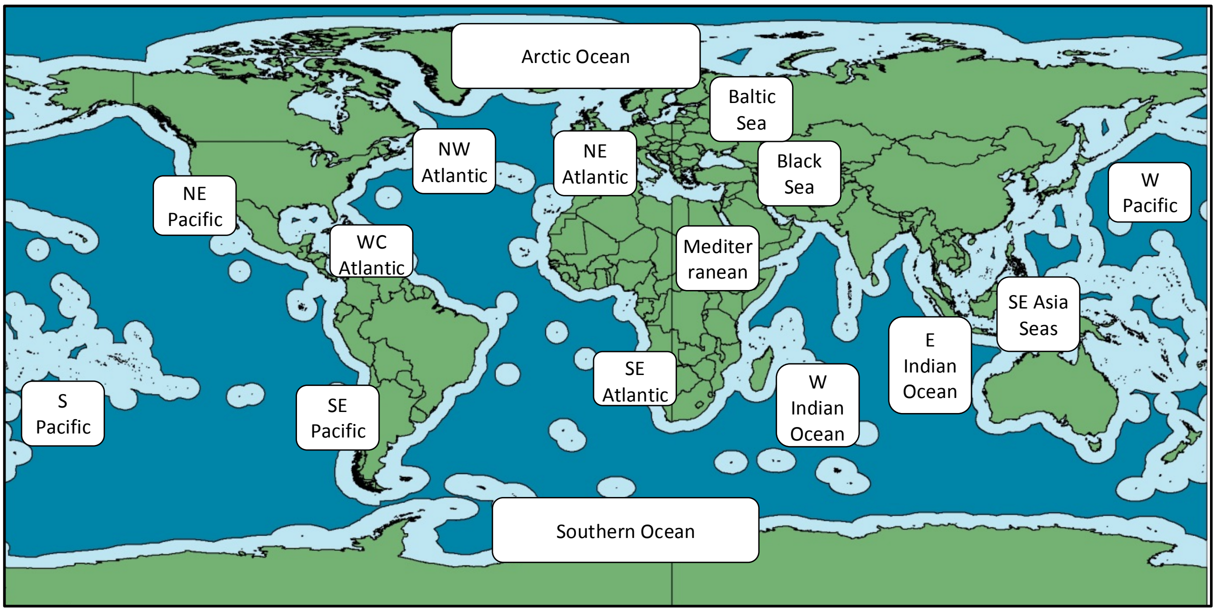
At the regional level, there appear to be 16 regions in the world where arrangements pertaining to ABNJ issues (and often to ocean issues in general) overlap and interact (Figure 3.4). The governance literature recognises the occurrence of such clusters of arrangements and refers to them as 'regime complexes' when they exhibit certain characteristics – three or more arrangements interacting based on a common purpose and set of principles but not hierarchically interrelated (Orsini et al. 2013). These clusters of arrangements provide potential for improving regional or 'place-based'[20] implementation of global arrangements. They also provide potential arenas for horizontal interplay needed for integration across issues, and for the integration of regional issue-specific arrangements with the wider spectrum of regional economic cooperation activities.

In this section, these clusters are examined to determine if they do indeed form entities for which the whole is, or could be, greater than the sum of the parts. If so, these could provide an entry point for assessment of governance architecture at the regional level. The existence of these regional clusters also raises the question as to whether global ocean governance can be enhanced by strengthening them and promoting integration among them. This would be best done in parallel with strengthening the global-to-regional issue-based networks discussed in the previous section, which together with the regional clusters can be seen as forming a single global ocean governance architecture.

A full examination of the connectivity among arrangements within the regional clusters would require considerable information on their interplay which may comprise several aspects, ranging from data sharing to full collaboration in decision-making and implementation. Information at this level of detail is not available for the regional clusters identified directly from the documentation for the regional clusters identified and would require more intensive enquiry. Therefore, this study can only undertake a preliminary evaluation of the interrelations among arrangements within regional clusters based on formal interactions documented for the organisations. Undoubtedly, many interactions are not explicit in the material reviewed for the arrangements. For example, organisational representatives may attend meetings of other organisations in the cluster even when there is no formal interaction between the arrangements.

20 The term 'place-based' is used broadly here in the sense of Young et al. (2007) to encompass scales from regional down to much smaller specific areas which may be identified as in need of management.

Figure 3.4. The 16 regional clusters identified.



Each of the 16 regional clusters shown in Figure 3.4 is fully described by Mahon et al. (2015) with:

- A diagram showing the types of arrangements, the issues they cover and the documented interactions among them;
- A table showing the spatial overlaps of the main arrangements in the cluster (based on GIS shape-files for the arrangements);
- An overview of the regional cluster that covers (i) its spatial extent, (ii) the extent to which there appears to be overarching integration, (iii-vi) what is in place for each of the four issues (fisheries, pollution, biodiversity, climate change), and (vii) its relevance to ABNJ.

The description for the Western Central Atlantic cluster is included below as an example. Details of the other 15 clusters can be found in Mahon et al. (2015).

The clusters vary widely with regard to all of the above characteristics, including spatial coherence. Frequently, regional arrangements addressing the issues of concern were developed without reference to each other and other regional arrangements operating in the same area. Some arrangements, notably those involving RFMOs for highly migratory species (HMS), appear in several clusters because of their large spatial scale. For example, ICCAT is included in each of the five Atlantic Ocean clusters. Only a few of the clusters were found to have clearly identifiable overarching mechanisms for policy development and coordination (for example: Pacific Islands Region, Arctic, Antarctic, Mediterranean, Southeast Pacific).

The Western Central Atlantic: The arrangements comprising the Western Central Atlantic cluster are depicted in Figure 3.5. The spatial overlaps among the key arrangements are shown in Table 3.3, and the regional cluster is summarised in Table 3.4.

Figure 3.5. The arrangements comprising the Western Central Atlantic regional cluster (shaded arrangements address areas within national jurisdiction only)

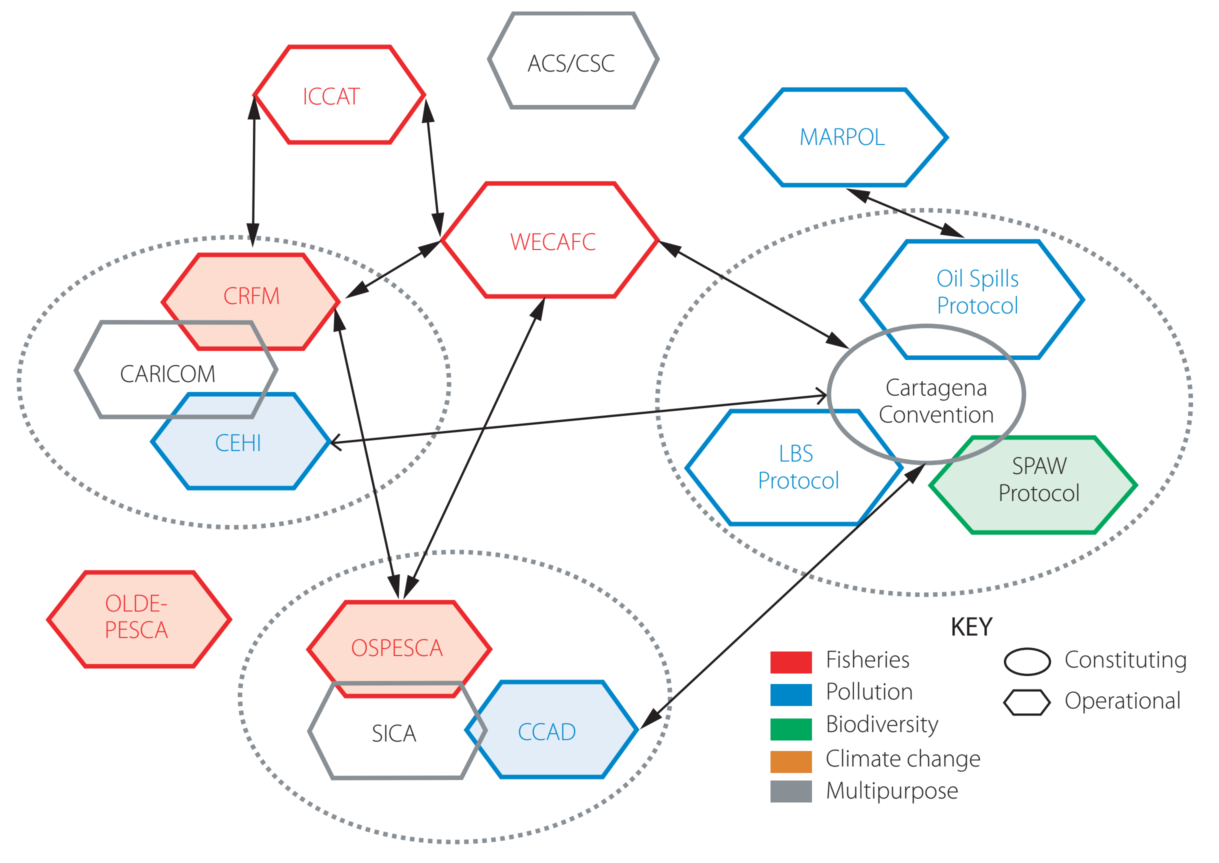


Table 3.3. Areas (million km²) covered by the key arrangements in the Western Central Atlantic regional cluster and the percentage overlap of the arrangements

	CRFM	ICCAT	OLDEPESCA	OSPESCA	WECAFC	Cartagena
Area	2.0	97.4	6.9	2.1	18.2	6.6
CRFM		2	9	3	11	30
ICCAT	100		42	37	100	100
OLDEPESCA	32	3		59	16	43
OSPESCA	3	1	18		4	12
WECAFC	100	19	42	37		100
Cartagena	99	7	42	37	36	

Table 3.4 Characteristics of the Western Central Atlantic regional cluster

Spatial extent	The arrangements comprising this regional cluster are largely focused on the actual area of the Western Central Atlantic or parts of it, with the exception being ICCAT which has Atlantic Ocean-wide mandate. Most focus primarily on AWNJ.
Integration	While there are several linkages among arrangements, there is no body with an overarching mandate for coordination.
Fisheries	There are several bodies with responsibility for fisheries in this region. The FAO RFB (WECAFC) covers the entire region, while others such as CRFM and OSPESCA are part of subregional integration organisations. OSPESCA and OLDEPESCA also have mandates outside the region, in the Pacific.
Pollution	The Cartagena Convention's Oil Spills and LBS Protocols are the main arrangements for pollution
Biodiversity	The Cartagena Convention's Specially Protected Areas and Wildlife Protocol addresses biodiversity only within EEZs in the region and is not included in the database.
Climate Change	There are no climate change arrangements within the region that specifically address ABNJ.
Relevance to ABNJ	As with the other semi-enclosed seas, the relevance of the Western Central Atlantic Region is largely with regard to possible impacts of regional level pollution on ABNJ. However, in this region linkages with fisheries for HMS are perhaps more important than for most of the semi-enclosed seas.

Discussion

This study has focused on the governance arrangements and architecture for ocean ABNJ. It has taken a structural approach looking at the many arrangements that relate to governance of ABNJ and the way that they appear to be interrelated, globally and regionally. It has looked at the individual arrangements from the perspective of whether they have been established in such a way as to be able to carry out the full policy process considered necessary for 'good governance'. The study has also looked for any patterns among organisations at global and regional levels that may relate to governance functioning and that may also make it easier for stakeholders to understand and interact with global ocean governance. Attention was paid to science-policy interfaces, and the extent to which there appeared to be separate sets of governance arrangements for areas under and areas beyond national jurisdiction.

Good governance and effective governance

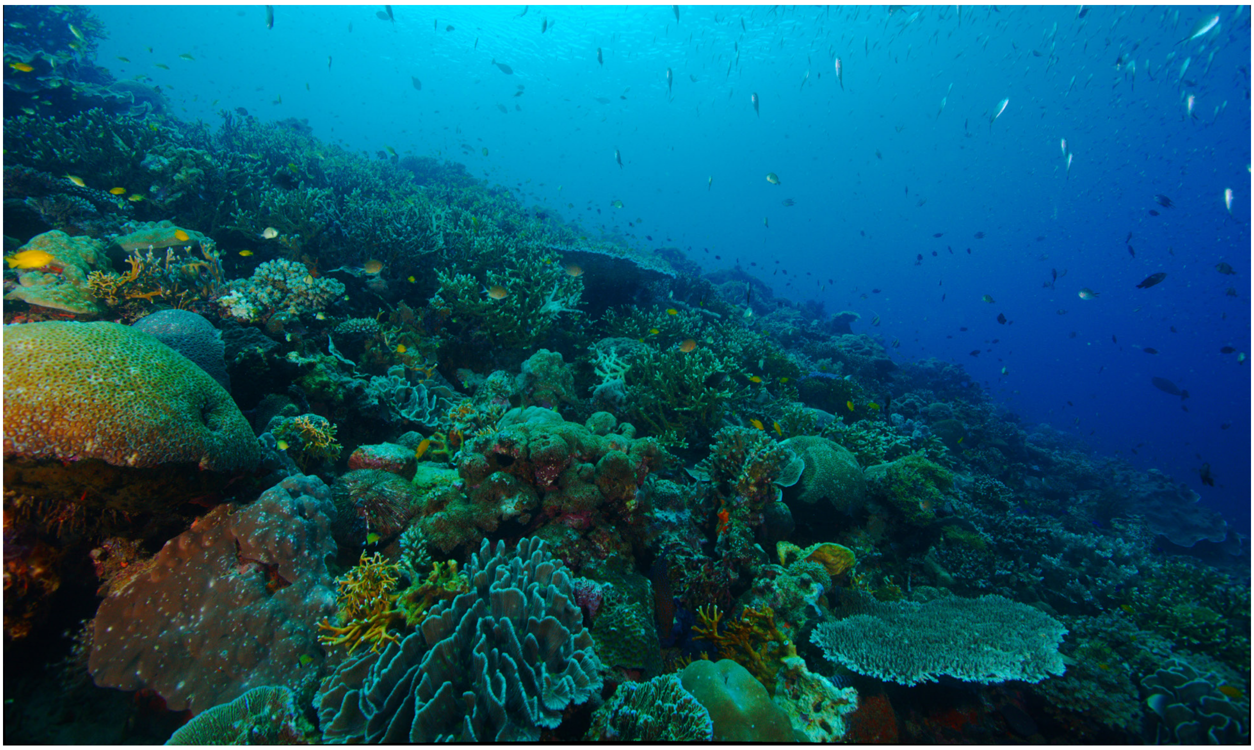
The assessment of the individual arrangements indicated areas of weakness in the policy cycle stages for ocean governance arrangements. A key challenge in this study was to deal with governance arrangements and architecture without venturing into the assessment of governance effectiveness. This limitation was necessary because assessing governance effectiveness would involve evaluation of outcomes and impacts that require a substantial amount of physical, ecological, social and economic information over appropriate periods of time. Much of what was assessed in the policy cycle scoring process can be considered as reflecting whether 'good governance' practices are in place (Young 2013, UNDP 2014). For example, having clearly specified processes and mechanisms across the seven policy cycle stages is seen as likely to improve characteristics of 'good governance' such as transparency, accountability, and ease with which stakeholders can engage with the process. Ultimately, these characteristics might be expected to produce better governance results, and are often cited as being desirable characteristics of governance processes in their own right (Lemos and Agrawal, 2006, Lockwood et al. 2010). However, the state of governance research is such that it is not possible to be definitive about the relationship between these 'good governance' characteristics and governance effectiveness.

The global architecture for ocean governance

This study takes a holistic perspective of global architecture for ocean governance as comprising 'issue-based global-regional networks' and cross cutting 'regional intersectoral clusters/networks'. This structure may be seen as emerging, but far from complete and with much dysfunctionality. It is thought that the holistic perspective provided here can move the global-regional ocean governance community towards a better understanding of what has been achieved over the past several decades, where the major gaps are, and what the critical next steps may be to address these gaps and strengthen the entire system. This holistic perspective is thought to be of value in helping those working within parts of the system to see the full picture and especially those working outside the system to engage with what has been described as a very complex, disordered and fragmented set of arrangements for the ocean (Freestone 2010; Rothwell and Stephens, 2010, Töpfer, et al. 2014).

The ideas relating to networks, nesting of arrangements, the importance of scale and interplay among arrangements underpinning this perspective are prominent in conceptual discourses on governance (Young 2002, Kooiman et al. 2005, Sorensen and Torfing 2007, Young 2013) and many have been derived from analyses of global and regional regimes and regime clusters (Miles et al. 2002; Biermann et al. 2009b; Biermann and Pattberg, 2012). Polycentric approaches such as regional clusters juxtaposed with global clusters facilitate achieving benefits at multiple scales as well as experimentation and learning from experience with diverse policies (Ostrom 2010). There is also an ongoing discourse about how lessons learned from research on governing 'the commons' at smaller scales might inform approaches at regional and global levels (Dietz et al. 2003). However, much of this thinking has failed to gain traction in the world of practitioners and institution builders for global environmental governance. It is thought that this study can make a contribution towards bringing those working at the conceptual level together with those responsible for making regimes work in practice.

Regional clusters are given special attention in the next section, because the global-to-regional, issue-based networks have been the primary focus of global ocean governance thus far and have received the most attention regarding strengthening. Despite this, there are many weaknesses in these global-to-regional, issue-based networks that should be addressed, in particular the need for integration among them. In this regard, the upgrading of UN-Oceans or development of an effective alternative should be a priority.



Characteristics and potential role of regional clusters

The 16 regional clusters for ocean governance reflect a diversity of regional level approaches to pursuing (or not) intersectoral integration and ecosystem-based management for the ocean. While the governance literature has recognised the existence of regime complexes (Orsini et al. 2013), the regional clusters in this study appear to be different, being primarily spatially defined and with a broad focus (or potential focus) on marine EBM. Within the clusters identified, interaction appears highest among fisheries management arrangements. In many instances Regional Seas conventions and action plans are also active in integrating pollution and biodiversity aspects, although few include ABNJ. In most clusters, the FAO Ecosystem Approach to Fisheries (EAF) and the UNFSA mandate to protect marine biodiversity are obvious starting points for building capacity for EBM and would require linkages with Regional Seas and other non-fisheries arrangements in the cluster. One can envisage the strengthening of clusters to the level where the full range of ocean governance interests, including biodiversity and pollution in ABNJ, is engaged and integrated.

Few of the clusters were found to have clearly identifiable overarching mechanisms for integrated policy development and coordination. The Pacific Islands Forum (PIF) and its Council of Regional Organisations of the Pacific (CROP) is the most prominent example of such a mechanism. Two other mechanisms developed with the express purpose of coordination are the Antarctic Treaty System and the Arctic Council. In the Mediterranean, coordination for sustainable development is approached through the establishment of the Mediterranean Commission on Sustainable Development (MCSD) in 1996, in association with the Barcelona Convention. The Secretariat of the Barcelona Convention supports the activities of the MCSD. In the southeast Pacific, the interaction between the FAO and CPPS, which also serves as the Secretariat for the Lima Convention, has the potential to promote EBM. In Southeast Asia, PEMSEA, a home-grown coordination body emerged as a bottom-up response to a perceived lack of regional policy/coordination capability. In other regions, an ocean specific mechanism for overarching policy development and coordination is either absent or is partially taken up by the Secretariat of the Regional Seas Conventions (or its counterpart). However, this may mean that linkages between the major issues of Regional Seas Conventions, such as pollution and environment/biodiversity, with other sectors, notably fisheries, shipping and tourism, remain weak or absent.

The extent to which the clusters form discrete spatial entities is also highly variable. The regional agreements comprising them vary considerably in location and size of area covered. The spatial relations among agreements within regional clusters cannot be easily shown on static maps, so this is not attempted here. They can be explored interactively in the OneSharedOcean.org website developed for TWAP. The regional arrangements were usually developed without reference to other regional arrangements operating in the same area and were designed to cover the specific issue of concern. Some arrangements, notably the RFMOs for HMS cover large ocean areas and appear in several clusters. ICCAT, for example, is included in each of the five Atlantic Ocean clusters. Ultimately, if regional clusters are to become a focus of ocean governance reform and strengthening, it will be necessary to better define their spatial scope.

In most clusters, provisions for technical advice appear to be largely by mechanisms that are internal to the individual arrangements that comprise them. A few of the regional clusters also appear to have crosscutting arrangements for the provision of technical advice involving separate bodies, namely PICES in the North Pacific, ICES in the North Atlantic, the SCAR in the Antarctic and the IASC in the Arctic. Each of these technical advisory arrangements has a different history and relationship with the other arrangements in their cluster. They may provide some degree of integration across issues, but solely at the technical level. These crosscutting providers of technical advice may be a useful component of improved integration, particularly if they are mandated to take a more proactive role in identifying interactions among issues that should be considered in policy making.

The extent to which the arrangements within regional clusters are integrated with the broader regional political economies undertaken by bodies such as ASEAN, SADC, SAARC, MERCOSUR and CARICOM is also of interest. Söderbaum and Granit (2014) argue that this is important if transboundary water issues are to achieve the desired prominence at the regional level and be mainstreamed into regional programmes. This is likely to become increasingly important if the trend of the past few decades towards regionalism continues (Kluvánková-Oravaská and Chobotová 2012). The information collected in this study is insufficient for a comprehensive assessment of the extent to which these linkages occur or the opportunities for developing them. However, some preliminary observations are possible. Only the coordinating mechanisms for the Pacific Island Region and the Mediterranean Sea appear to have strong linkages with regional multipurpose political organisations. Some connectivity is evident in the Western Central Atlantic where agencies associated with the two major regional integration organisations, the Caribbean Community and Common Market (CARICOM) and the Central American Economic Integration System (SICA) are part of the cluster despite the absence of an overall coordinating mechanism (Mahon et al. 2013). In the Bay of Bengal area in the Western Indian Ocean, there appears to be some connectivity between fisheries and the Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC). In southern Africa, there is a Fisheries Protocol that provides some connectivity between fisheries arrangements and South African Development Region (SADC). In the Pacific, the Asia-Pacific Economic Cooperation body (APEC) has an Oceans and Fisheries Working Group (OFWG) that links the work of fisheries bodies with this multipurpose organisation. However, for the most part, these mechanisms are focussed on AWNJ. As indicated above, these are preliminary observations and will require further investigation. The findings from this study indicate that despite their current deficiencies, regional clusters could have a potentially important role in implementing EBM in their respective regions, including ABNJ if their mandates are extended, and should be the focus of initiatives to build and strengthen them. This view is supported by Rochette et al. (2014) and consistent with strategy 6 of the UNEP Regional Seas Strategic Directions 2013-2016 (UNEP 2014). The regional clusters would complement the desired 'global-to-regional, issue-based networks'. To pursue this, further work needs to be done on assessing their role and developing approaches and programs to strengthen them.

There are several facets to strengthening the structure and functionality of regional clusters as governance units. Broadly, these are the extent to which:

- the arrangements that comprise them are geographically coherent (spatial overlap and fit);
- the individual arrangements within the cluster reflect good governance structure (as per the assessments in this study) and practice;
- there are functional linkages (interplay) among the arrangements comprising the cluster;
- clusters are vertically linked to global processes; and
- they share a common purpose and set of principles and can deal with one another as equals.

These all need to become the focus of increased attention that seeks to build regional clusters within which there are shared values and principles, such as conservation of biodiversity, accountability, transparency, efficiency thought to be essential for 'good governance'.

Science-policy interfaces

The UNEP Foresight Process on Emerging Environmental Issues for the 21st century, concluded that the crosscutting issue "Broken Bridges: Reconnecting Science and Policy" is the fourth most pressing one regarding efforts to achieve sustainable development (UNEP 2012). The panel noted that critical scientific knowledge is not being communicated effectively to audiences ranging from decision-makers to the general public. Many of the arrangements assessed state 'best use of scientific information available' as a foundational principle. To give effect to this principle, it is essential that there be clearly identifiable mechanisms for the transformation of available science into policy and management advice that can be used by decision-makers. These mechanisms are referred to here as science-policy interfaces.

The importance of the science-policy interface is a main reason for the policy cycle based approach in this assessment and more explicitly the inclusion of the policy cycle stages relating to development and provision of policy and management advice. While these fields provide insight into the science-policy mechanisms in place in arrangements, there are other important factors that determine their functionality. These include the extent to which quality information is available, and the extent to which there is a demand from the decision-makers for scientific information. Both of these factors are also reflected in the policy cycle, as the data and information and decision-making stages. Ultimately, however, it is the linkages among the policy cycle stages just mentioned that will determine whether the science-policy interface is functional and effective. These linkages could not be evaluated within the scope of this assessment and should be a focus of further work (Mahon et al. 2015)

It is also important to look beyond the mechanisms within individual arrangements to determine if there are identifiable overarching science-policy interfaces within the global and regional networks. These are thought to be essential for the network integration needed for EBM. The science-policy interfaces at each of the three levels are examined in greater detail by Mahon et al. (2015). The findings suggest that some of the issues requiring further investigation could include the extent to which:

- the advisory mechanism is independent of the decision-making and implementation mechanisms;
- policy advice tends to come from the same body that is providing technical/management advice; and
- science-policy interface processes are adaptable with regard to being able to change the questions that are being put to advice providers.

Assessment of current status

The evaluation of the strengths of the policy processes for arrangements for ABNJ and the overall global structure constitute an assessment of what is currently in place. This is a partial baseline assessment of ocean governance architecture. However, there are other aspects of governance architecture that could be pursued to develop a more comprehensive baseline. These include:

- Analysis of the spatial fit of arrangements and regional clusters to the spatial issues, for example the extent to which the multiple spatial aspects of biodiversity are covered at the global and regional levels in ABNJ;
- The extent to which there is spatial coherence among arrangements within a regional cluster;
- The extent of engagement of countries in arrangements, regional clusters and global networks as indicated by signing of the arrangements and by their engagement in processes;
- The extent to which there is progress within arrangements in moving towards EBM such as the adoption of EBM as a principle and/or establishment of EBM Working Groups;
- The extent to which there is a mechanism specified for integrating policy and management across issues within regional clusters and at the global level; and
- The linkages among arrangements, or clusters of arrangements.

A spatial analysis of the fit of arrangements and clusters to the issues requires additional information on the distribution of ecosystems, resources, and sources of negative impacts. For fisheries, the distribution of fishery resources is well known, at least for ABNJ fisheries since these are largely commercial. Mapping these against the arrangements developed for their governance should be a relatively straightforward task. Spatial coverage of fisheries for HMS is essentially complete, provided by five well-established RFMOs (ICCAT, IATTC, IOTC, WCPFC, CCSBT) (Molenaar 2005, Freestone 2011). In contrast coverage for demersal fishery resources is much less complete, with the majority of the South Atlantic and North Pacific having no coverage, as well as smaller but significant areas in other oceans (Molenaar 2005, Freestone 2012). Furthermore, RFMOs with responsibility for demersal resources in ABNJ are relatively recent.

The situation for ecosystems and biodiversity in ABNJ is much more complex and less advanced (Druel et al. 2012, Ban et al. 2014). The development of classification systems for, and information on, the distribution of marine ecosystems is at a relatively early stage in development. It was only in 2007 that classification of coastal and shelf regions into marine eco-regions appeared (Spalding, et al. 2007). Equivalents for ABNJ have only recently been developed (UNESCO 2009, Harris and Whiteway 2009, Rice et al. 2011, Spalding et al. 2012, Watling et al. 2013). The alternative to a comprehensive, zoning, approach to ecosystems and biodiversity in ABNJ, has been to encourage competent international organizations to apply the information available on EBSAs to design management measures capable of avoiding significant adverse impacts, but this approach has not gained traction as there is as yet no mechanism to encourage cooperation on biodiversity in ABNJ. For this reason, many governments, scientists and NGOs are proposing a new agreement under UNCLOS that would provide for a global level coordinating mechanism, establish common objectives and principles including ecosystem-based management, systems of marine protected areas, and procedures for environmental impact assessment, as well as to provide funding to incentivize cooperation and enhance the capacity of developing countries (Hart 2008, Druel and Gjerde 2014).

A spatial perspective on coverage of biodiversity in ABNJ, and indeed the ocean overall would provide an unfavorably biased picture. While there are several global and regional arrangements with wide geographical coverage, they may be narrow in terms of the coverage of species or ecosystems, for example, the Agreement on the Conservation of Albatrosses and Petrels, which is global but applies only to these species, the two sea turtle MOUs for the Americas and Indian Ocean/Southeast Asia region or the polar bear agreement. The Ballast Water Convention is also global but provides coverage for a very specific issue; introduction of alien invasive species by ballast water discharge.

Gaps in pollution coverage of LBS and MBS at the regional level are related to the extent to which Regional Seas conventions and their pollution related protocols are in place to address pollution within areas under national jurisdiction that can, in most cases, ultimately be transported into ABNJ. Here there are numerous significant gaps in coverage, many of them in areas of high coastal population and extensive marine activity (Mahon et al. 2015).

A comprehensive baseline for ocean governance architecture will also require considerably more detail on the structural aspects of the global framework for ocean governance described in this report. For example, the extent and nature of vertical and lateral interplay among arrangements is an important aspect of architecture that could not be adequately explored in this assessment. While the identification of networks and regional clusters is based on inferred linkages, a baseline that would provide a basis for monitoring change should include information on actual linkages. This requires a substantial investigation using approaches such as social network analysis.

One ocean, one governance architecture?

The perspective on the overall, emerging, global architecture for ocean governance developed in this study provides the opportunity to take a holistic view of the entire set of arrangements and their interrelations. In some areas, there may be overlap between arrangements that pertain to ABNJ and those that pertain to AWNJ. Some regional regime clusters include a combination of arrangements with mandates for areas within EEZs, mandates for ABNJ and mandates for straddling issues. Consequently, it may be most appropriate to perceive ocean governance arrangements globally as a single set of integrated arrangements structured as described in this study: 'global-to-regional issue-based networks' complemented by 'regional intersectoral clusters'. This structure could reflect what is desirable and therefore needed to address governance in both ABNJ and AWNJ in an integrated and holistic fashion. The key point regarding structure is that it is more advanced for AWNT, and weak for ABNJ, particularly with regard to biodiversity and ecosystems.

Conclusions and recommendations

The key conclusions of the study are:

- Normative characteristics representing 'good governance' can be assessed in ocean governance arrangements as a basis for targeting interventions and monitored improvements, but 'good governance' may be context specific;
- There are significant gaps in coverage of the issues for ABNJ particularly for biodiversity, but also to a lesser extent for pollution and fisheries for straddling and demersal stocks;
- The entire set of governance arrangements for ABNJ and AWNJ may be best approached as a single global-ocean governance structure; and
- The perspective of the single global-ocean governance structure as comprising 'global-regional issue-based networks' and 'regional intersectoral clusters' provides a framework that may help to improve understanding of the very complex, disordered and fragmented set of arrangements for the ocean.

From this perspective, the emphasis should then be on strengthening the existing set of global/regional arrangements to address deficiencies and fill gaps. This includes:

- Strengthening regional clusters (both mandate and capacity) to address issues in adjacent ABNJ;
- Strengthening the global level constituting and operational arrangements for biodiversity;
- Paying attention to structures that are needed to improve adaptive capacity;
- Exploring ways of strengthening lateral linkages among regional clusters; and
- Subscribing to a general emerging set of principles, in particular conservation in addition to sustainable use, as well as the ecosystem and precautionary approaches, that cuts across AWNJ and ABNJ.

Based on the analysis conducted for this study, recommendations can be made in three areas:

(1) Individual arrangements;
(2) Regional intersectoral clusters; and
(3) Global-to-regional issue-based clusters.

At the level of individual arrangements, there is the need to support monitoring of the extent to which 'good governance' practices are observed and to assess how these practices relate to governance effectiveness. Monitoring of 'good governance' should be context specific, based on a common set of criteria. The refinement of 'good governance' criteria at the arrangement level will be an iterative process.

Strengthening regional clusters of agreements, particularly so that they can undertake EBM in offshore waters, including ABNJ, is seen as a critical component of strengthening ABNJ governance. This will include promotion of integration mechanisms, expansion of mandates to include biodiversity conservation in ABNJ, improvement of interplay among arrangements within clusters, as well as building new linkages with regional multipurpose organisations to increase political understanding of and support for ocean governance. Clearly this will also strengthen governance in AWNJ.

Vertical interplay between regional and global processes and the capacity to integrate at the global policy level is also weak and requires attention. UN-Oceans is currently the primary UN programme specialized to achieving such integration, and efforts to strengthen UN-Oceans appear to have stalled. However, the proposal for an UNCLOS Implementing Agreement, if it sets forth the conditions necessary for effective interplay (for example: non-hierarchical organizations operating in sync based on a common purpose and set of principles) could improve vertical as well as regional horizontal interplay for the key issue of biodiversity (Druel and Gjerde 2014).

3.1.3 Notes on Methods

The approach taken to the assessment was to assemble all governance agreements that were found to have relevance to the four issues of concern in the ABNJ: fisheries, biodiversity, pollution, and climate change. These agreements were compiled into a database to facilitate assessment of the extent to which the issues are covered either globally or regionally. The assessment also examined each arrangement from the perspective of policy processes to determine whether processes considered to be adequate for good governance are in place as described above. The arrangements were also examined from a spatial perspective to determine geographical overlaps and gaps as well as the extent to which ABNJ were covered by governance arrangements.

Developing the database of governance arrangements for ABNJ

An arrangement is any multilateral agreement, together with organisational structures and processes in place to give effect to it[21]. The determination of direct relevance is based on whether the agreement is intended to address an ABNJ or straddling issue. On this basis, all relevant global agreements were included as well as many regional ones, such as regional fisheries conventions and Regional Seas Programme conventions that were considered to be relevant to ABNJ. The process of identifying agreements continued until no new ones were found. Relevant agreements were sought in the literature and on the Internet where several databases of international agreements can be found[22]. The criteria for selection of regional agreements to be included differed depending on the issue area.

With regard to fisheries, all agreements for Regional Fishery Management Organisations (RFMOs) and Regional Fisheries Bodies (RFBs) with responsibility extending into ABNJ or for highly migratory or straddling stocks were included. It should be noted that this includes a wide diversity of types of fisheries bodies with mandates ranging from purely advisory to those with the capacity to make binding decisions on fisheries management (Molenaar 2005, Freestone 2011).

21 In the governance literature the term 'regime' is also often used to refer to arrangements as defined here.

22 Mainly: ECOLEX http://www.ecolex.org/start.php; National University of Singapore http://cil.nus.edu.sg/2009/cil-documents-database/; University of Oslo, Faculty of Law, treaty database http://www.jus.uio.no/english/services/library/treaties/; International Environmental Agreements (IEA). Database Project, http://iea.uoregon.edu/page.php?file=home.htm&query=static

With regard to pollution, the approach taken recognised that all land-based sources of pollution (LBS) impacting ABNJ pass through coastal waters. Therefore, regional agreements addressing LBS were considered to be directly relevant to ABNJ. Most marine-based sources of pollution (MBS) also have the potential to be transported by currents from EEZs into ABNJ. The exception might be dumping of non-polluting non-soluble solids. However, dumping agreements also cover many kinds of wastes that can be transported by currents and were therefore included. From the outset, this approach leads to a preponderance of pollution-oriented agreements which are primarily aimed at addressing coastal pollution problems.

For biodiversity, the inclusion of agreements oriented towards national waters was considered. These are primarily protocols arising from Regional Seas conventions. It was thought that while the inclusion of pollution agreements under Regional Seas conventions was important for the reasons given above, the case for inclusion of biodiversity agreements was less clear. For the majority of Regional Seas-based biodiversity agreements, the only connection with ABNJ would be when protected areas or other measures were established that provided protection for straddling or highly migratory species (HMS) such as sea turtles, seabirds, and marine mammals. It was decided that including these agreements would provide a biased picture regarding biodiversity conservation in ABNJ.

The inclusion of shipping arrangements was also considered. For example, IMO routing measures under the Safety of Life at Sea (SOLAS) Convention has been used to minimise impacts of shipping on biodiversity. However, it was agreed that this convention could not be perceived as having a stated mandate for biodiversity conservation or ecosystem-based management (EBM), and that it should not be included in the database.

For each of the agreements included in the database, a variety of information was obtained. The primary sources for the information included in the database were the actual conventions and agreements, rules of procedure for the organisations and secretariats for the agreements, and organisational websites. When all the desired information could not be found in these sources, other documentation and websites were explored. The database is in the form of an Excel spreadsheet with the key information in the cells. Comment boxes are used to record details, such as excerpts from agreements that are considered necessary context for what was included in the table cells. The first part of each database record includes basic background information on the agreement. The second part of each record includes information aimed at evaluating the policy processes that are intended to give effect to the agreement (see Mahon et al. 2015 for a full list of variables in the database).

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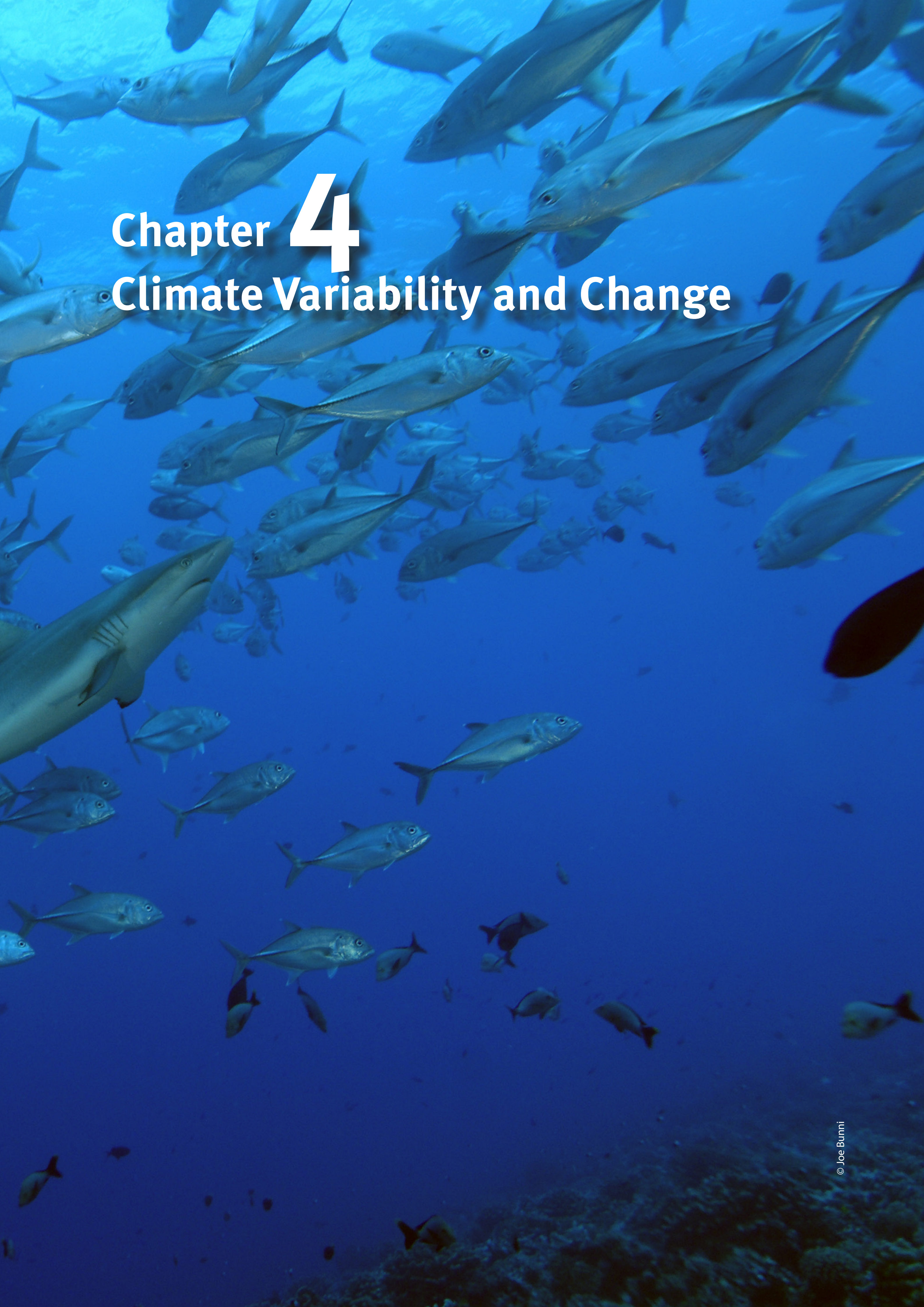
Chapter 4
Climate Variability and Change



Chapter 4.1 The Ocean as Part of the Climate System

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Climate Variability and Change

4.1 The Ocean as Part of the Climate System

4.1.1 Summary and Key Messages

This Chapter introduces the specific physical and chemical aspects of climate change for the ocean, and in doing so, provides the immediate context for the following chapters within this Section on Climate Variability and Change, and its impacts on the open ocean. A broad overview of the importance of the ocean as a major component of the climate system is given. As well, the Chapter conveys the main climate change aspects in relation with the ocean, as background information for the climate change effects on the marine environment and ocean related human activities which are presented in various chapters throughout the Open Ocean Technical Assessment Report.

The ocean is a major component of the physical climate system; in fact it is the main component in view of its heat capacity and the fluxes of heat, water and chemical components, including carbon dioxide (CO_2). Major aspects of climate change are associated with the ocean acting as a vehicle for heat, momentum, water and chemical transport. It is also the main component of the global cycles for water, CO_2 and other chemical compounds, and as a medium for storage, transformation, transport and exchange of radiatively and chemically active gases and particles. Sea level change, an important indicator of climate change monitored globally since 1993 by satellite altimetry with up to millimetric precision, is a consequence of a combination of internal ocean and external effects. The physical and chemical properties are briefly presented in this Chapter, providing perspective to the indicators developed and explained elsewhere in this Report.

The progress in scientific understanding of the role of the ocean as part of the climate system has been reviewed by the Intergovernmental Panel on Climate Change (IPCC) throughout its assessment cycles. The Fifth Assessment Report (AR5), which provides the most up to date review of scientific information on climate change and the ocean and an overview of impacts already observed or expected from a range of climate change scenarios in socio-economic sectors. This Open Ocean report focuses on some of the climate change aspects which are particularly relevant either to human settlements near the ocean or to biological balance of the ocean. This Chapter is as an introduction to those aspects, making use, based to a large extent on AR5 material and complemented by a few more recent articles.

In view of its large heat capacity compared to the atmosphere (of the order of 1000 times), the ocean controls to a large extent the time-scales and variability of the climate system. Changes in the ocean may result in climate feedbacks that either increase or reduce the rate of climate change. Climate variability and change on time-scales from seasons to millennia are therefore closely linked to the ocean and its interactions with the atmosphere and cryosphere. The large inertia of the ocean means that they naturally integrate over short-term variability and often provide a clearer signal of longer-term change than other components of the climate system. Observations of ocean change therefore provide a means to track the evolution of climate change, and a relevant benchmark for climate models.

The ocean is coupled to the atmosphere primarily through the fluxes of heat and freshwater (evaporation minus precipitation). These are strongly tied to the sea surface temperatures (SST) and are dependent on atmospheric conditions and waves. Vertical mixing takes place through turbulent processes driven primarily by the surface wind stress and convective buoyancy, and is strongly dependent on density stratification, with the mixed layer base acting as a partial shield for the downward propagation of physical properties. The transfers at the mixed layer base by entrainment and turbulent processes are essential to determine the structure of the ocean interior and the overall oceanic budgets. However larger scale convective mixing which occurs in localized regions at high latitudes in winter, mostly in the North Atlantic and Southern Ocean, drives the Meridional Overturning Circulation (MOC): the main mechanism for transporting near surface properties to deep ocean layers.

A comprehensive ocean observing system has been built with major upgrades in the last thirty years and an increasing role of automated deep ocean measurement devices and satellite observations. However the sustainability of the ocean observing system and its ability to apprehend climate related changes in the deep ocean remain critical issues. This Chapter also introduces the climate change scenarios for the 21st century, based on advanced socio-economic simulations associated with international greenhouse gas emission policies, to be used in following chapters of the Open Ocean Report. Two reference scenarios, under the acronym "Representative Concentration Pathways" (RCP) are mostly used in this report: RCP 4.5, an intermediate stabilisation scenario, and RCP 8.5, a high emission scenario, likely to happen in the absence of concerted emission policies. (See Glossary Box 2 for explanation)

Key messages

- Ocean warming has dominated the energy stored in the climate system in the last 40-50 years, accounting for approximately 93 per cent of the energy accumulated between 1971 and 2010, according to IPCC AR5;
- Changes in sea-surface salinity are observed in response to changes in precipitation, evaporation and runoff, as well as ocean basin circulation, with an increase in contrasts between saltier and fresher water regions;
- Arctic sea ice cover displays a progressive decrease and thinning, which has been well documented since satellite observation has been available, with a decrease of the seasonal minimum area of 11 per cent per decade since 1979, according to IPCC AR5;
- Changes in surface fluxes and wind waves have been observed, however the length of the observation period and the accuracy of estimates do not easily allow the distinguishing of long term changes from decadal type oscillations. The clearest signal corresponds to the Southern Ocean with a significant increase in surface wave height and wind stress in the last 50 years;
- Changes in the large scale deep ocean circulation have been mostly monitored in the last twenty years, with particular attention to the Atlantic Meridional Overturning Circulation, for which recent observations indicate a slowing down since 2004;
- The ocean represents a net sink for the atmospheric dioxide and it is estimated that about 30 per cent of its anthropogenic emissions are absorbed by the ocean, one of the consequences being an acidification of near surface layers of the order of 0.1 pH units in the last century; and
- Global sea level rise is one of the most certain impacts of climate change: since 1993, as observed from tide gauges and satellite altimetry, it is of the order of 3mm/year, to be compared with an average of 1.7 mm/year over the 20th century. Important regional effects are observed with sea level variations from negative values over the Eastern Pacific to about four times the mean global value in the Indonesia-Philippines area.

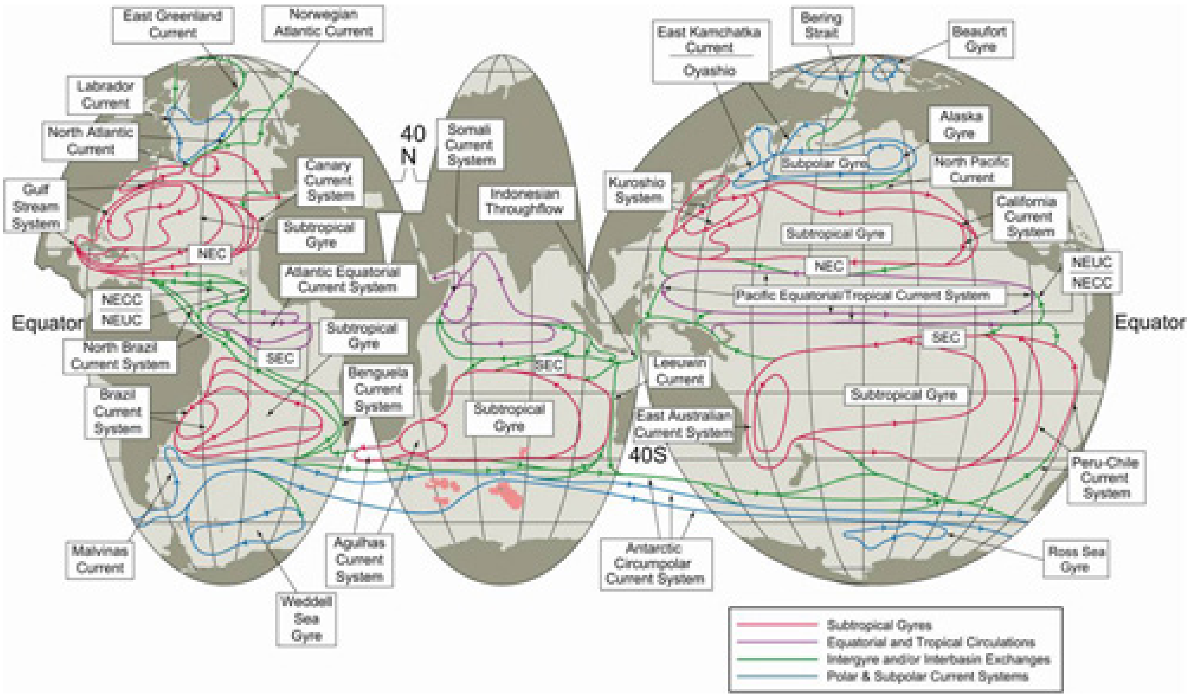
4.1.2 Main Discussion

Ocean circulation and global transfer mechanisms

The horizontal near-surface large-scale circulation (Figure 4-1), mainly driven by winds in presence of the Earth's rotation, is organized in ocean gyres with a large part of the transport carried out by western boundary currents. The circulation in the Northern Hemisphere consists of anti-clockwise subpolar gyres, clockwise subtropical gyres and mainly zonal equatorial current systems. In the Southern Hemisphere, the ocean circulation is dominated by basin-scale anti-clockwise subtropical gyres and a strong Antarctic circumpolar eastward current.

The deep ocean circulation, better understood since the identification of the Merdional Overturning Circulation (MOC), is schematically described in Marshall and Speer (2012), and is shown in Figure 4-2. The MOC is the main vehicle by which climate related quantities are distributed worldwide within the ocean. Its main feature is the "conveyor belt" structure across the ocean basins, with geographically distributed upwelling and fairly localised sinking in the Weddell and Ross seas around Antarctica and the Labrador and Greenland-Iceland Sea in the Northern Atlantic. Superimposed

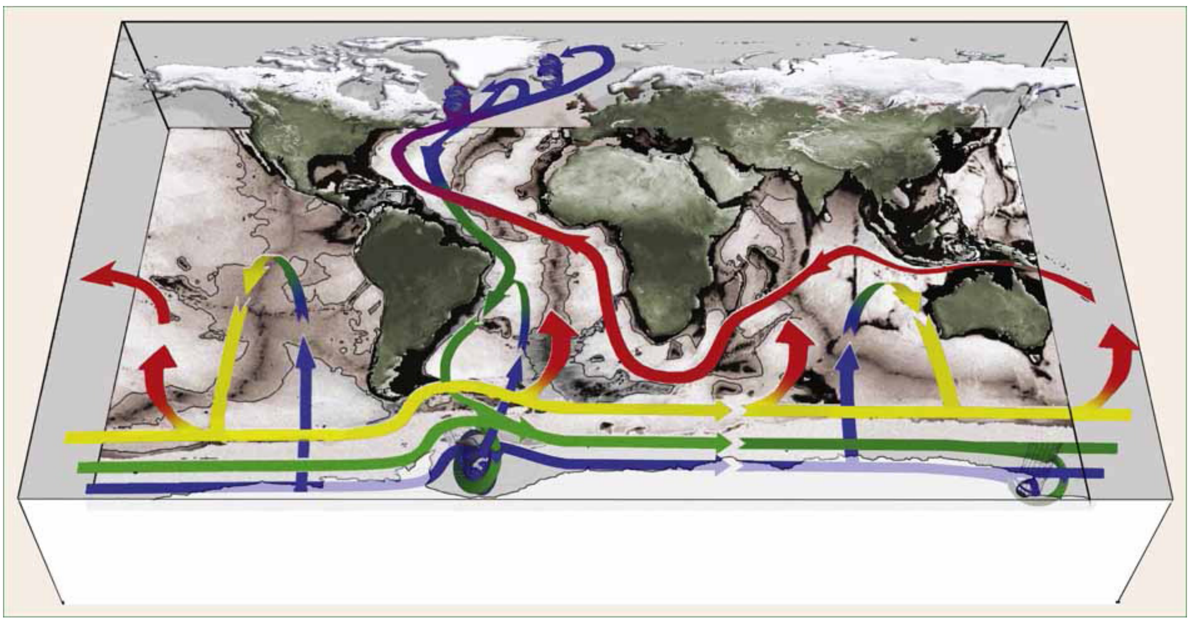
Figure 4.1. Surface circulation schematic.



Source: Talley et al. (2011) modified from Schmitz (1996)"

on the mean oceanic circulation, a number of modes of variability have been identified and are important drivers of climate variations. The most well known is the El Niño Southern Oscillation (ENSO) with successive occurrence of anomalous warming of the Eastern Pacific Ocean (El Niño) and anomalous cooling (La Niña) over periods of several months to a year with a periodicity of two to seven years. There is significant inter-decadal variability in this oscillation as well as in similar ones occurring in the other oceans. Other large-scale modes exist in the other oceans and interact with the atmosphere at time scales relevant to seasonal to inter-annual climate forecasts.

Figure 4.2. Schematic view of the Meridional Overturning Circulation (MOC)

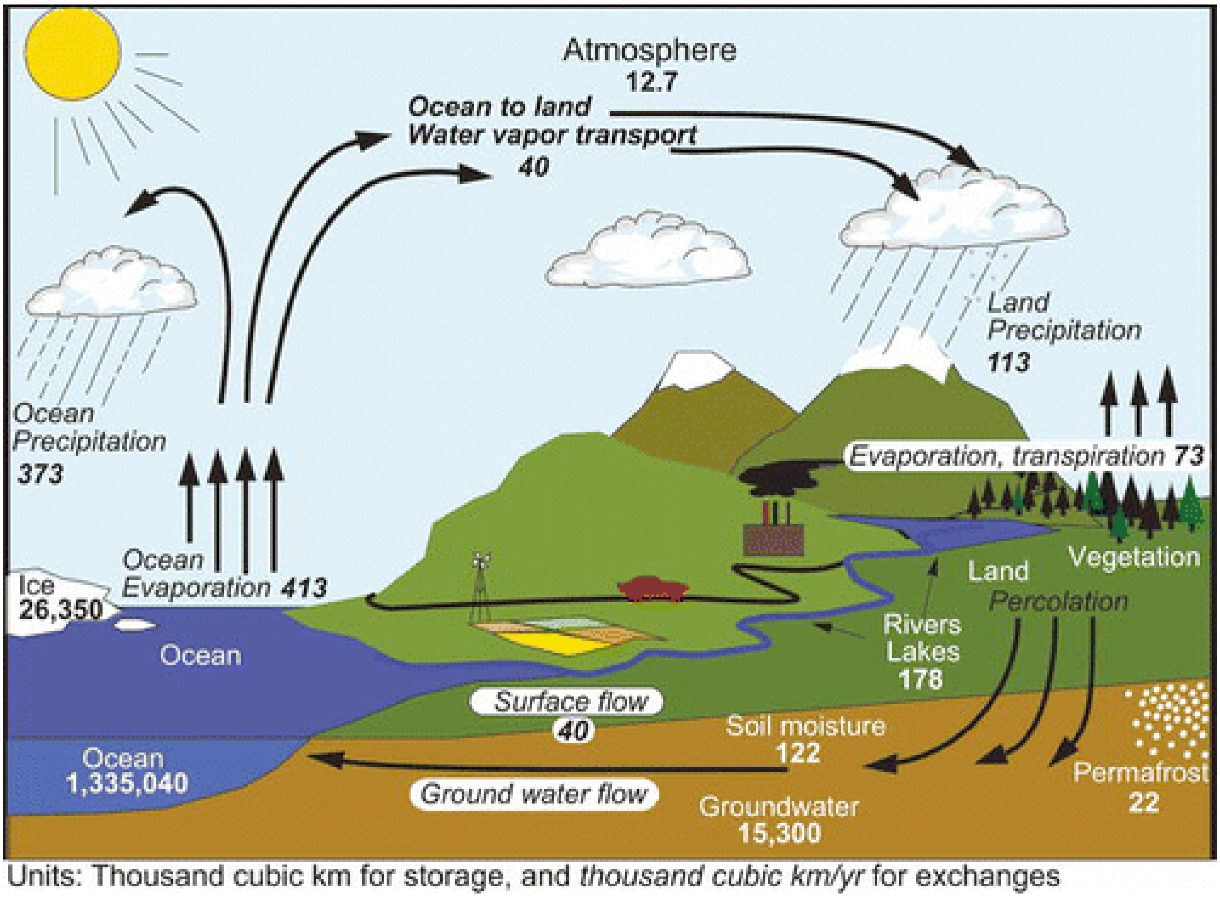


Source: Box 1 in Marshall and Speer (2012)

In addition to large-scale modes, internal ocean dynamics favour the production of meso-scale eddies, which have a significant role in horizontal transports.

One of the main features of the climate system is the storage and transport of heat and freshwater by the ocean. Global mean budgets, that are global estimates of sources and sinks, provide a first order picture of the role of the ocean in the climate system. Figure 4-3 (from Trenberth et al. 2007) provides an overview of the components of the global hydrological cycle, highlighting the role of the ocean as the main reservoir and medium for exchange of water. The two main reservoirs of freshwater: the cryosphere (mainly ice caps and continental glaciers) and groundwater, represent respectively, approximately 2 and 1 per cent of the ocean storage. Surface water storage in soils, lakes and rivers is about two orders of magnitude smaller. The storage of water in the atmosphere is another order of magnitude smaller. Estimates of yearly fluxes presented here, and coming from various recent sources, provide overall magnitudes for the exchanges of water between the ocean and the atmosphere (of the order of 400 000 km^3/yr). About one tenth of it is transported by the atmosphere to continents and returns to the oceans by land surface flow. Those fluxes display inter-annual fluctuations and are sensitive to climate change, although uncertainties in their global evaluation are still relatively large compared to climate trends over the last three to four decades. Updated estimates from re-analyses covering the 2002-2008 period can be found in Trenberth et al. (2011) and also give an idea of the remaining uncertainties. Imbalances in the above fluxes produce observable changes in the main reservoirs, some of those being presented below.

Figure 4.3. The hydrological cycle. Estimates of the main water reservoirs (plain fonts, in 103 km^3), and the flow of moisture through the system (slanted font, in 103 km^3/yr)

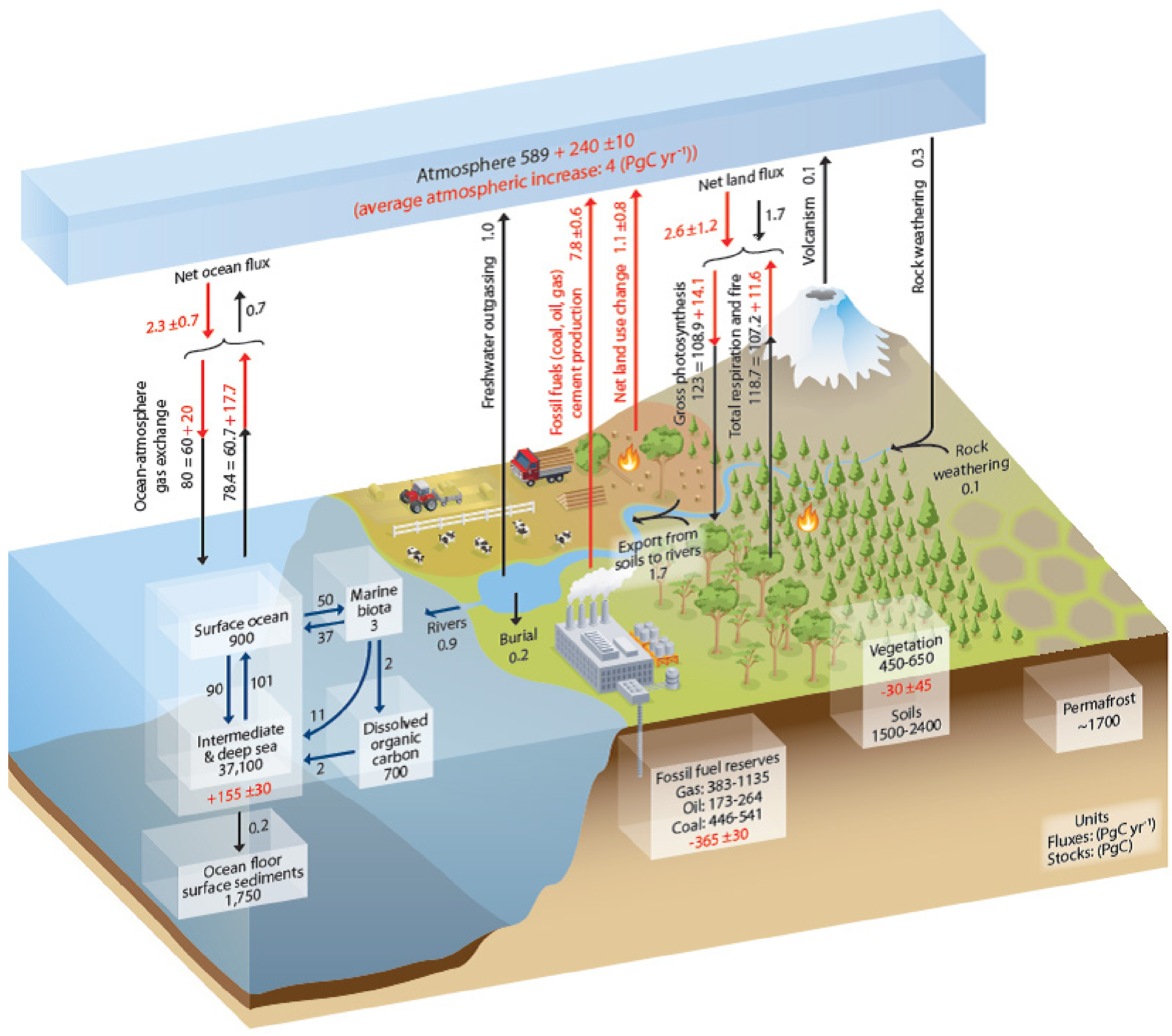


Source: Trenberth et al. (2007)

Similar diagrams are available for the global heat budget, with the ocean exchanging sensible and latent heat with the atmosphere to approximately balance the radiative budget at the ocean surface. The radiative budget itself is a sum of incoming shortwave solar radiative flux, longwave thermal radiative flux downward from the atmosphere and upward from the ocean surface. Global estimates of sensible heat fluxes are of the order of 17-20 W/m^2 and 80 W/m^2 for the latent heat flux. Those figures are respectively of the order of 10 and 90 W/m^2 (if only considering the global oceanic surface). Year to year variations of those fluxes are estimated from global re-analyses in Trenberth et al. (2011). Heat budgets at the top of the atmosphere or at the ocean surface are not exactly balanced and it is this relatively small imbalance, inferior to 1 W/m^2 at the ocean surface, which is the signature of climate change.

Similarly the ocean acts as a reservoir and vehicle for carbon and other chemical compounds and particles. Carbon is transferred primarily between the atmosphere and the ocean through the exchange of CO_2, as displayed in Figure 4.4. The main figures of relevance for this report relate to the CO_2 fluxes at the ocean-atmosphere interface and the

Figure 4.4. Simplified schematic of the global carbon cycle. Numbers represent reservoir mass in PgC (1PgC=1015 gC) and annual carbon exchange fluxes (in PgC/yr). Black numbers and arrows indicate reservoir mass and exchange fluxes estimated for the time prior to the industrial Era, about 1750. Red arrows and numbers indicate annual "anthropogenic" fluxes averaged over the 2000-2009 time period. These fluxes are a perturbation of the carbon cycle during industrial Era post 1750. Red numbers in the reservoirs denote cumulative changes of anthropic carbon over the Industrial Period 1750-2011. Uncertainties are reported as 90 per cent confidence intervals.



Source: IPCC AR 5 WGI Report, Figure 6.1 various levels of ocean storage. The figures are in PgC that is in gigatons of carbon. The net CO_2 flux at the ocean surface is only about 2 per cent of downward and upward fluxes of the order of 80 Pg of carbon/year. This large variability is dependent on differences in partial pressure and physical conditions at the air-sea interface. The ocean stores approximately 50 times the present atmospheric content of carbon (about 37 000 Pg for the intermediate and deep layers), mostly as dissolved inorganic carbon, and a small fraction as dissolved organic carbon. The marine biota, mostly phytoplankton and other microorganisms, store about 3 Pg (3 gigatons) of carbon with a relatively fast turn over (a few weeks) and exchange with the ocean reservoirs in the various ocean layers. The final deposition of carbon on the ocean floor is estimated to be one order of magnitude smaller, that is about 0.2 Pg/year, which means a very large residence time (order of 100 000 years) of inorganic carbon within the ocean reservoir. The above figures have evolved since the beginning of the industrial era and this will be discussed further below.

In addition to its role in the carbon cycle, the ocean is a major element of all global bio-geochemical cycles of importance for climate variability and change, namely methane, nitrogen and nitrous oxide cycles, and exchanges with the atmosphere a large range of chemical components.

The above description provides an overview of the global role of the ocean, which needs to be completed by a mapping of atmosphere-ocean fluxes and a description of transports by the oceanic circulation, as available for example in Stocker (2013). However major uncertainties remain in atmosphere-ocean flux datasets.

The ocean observing system

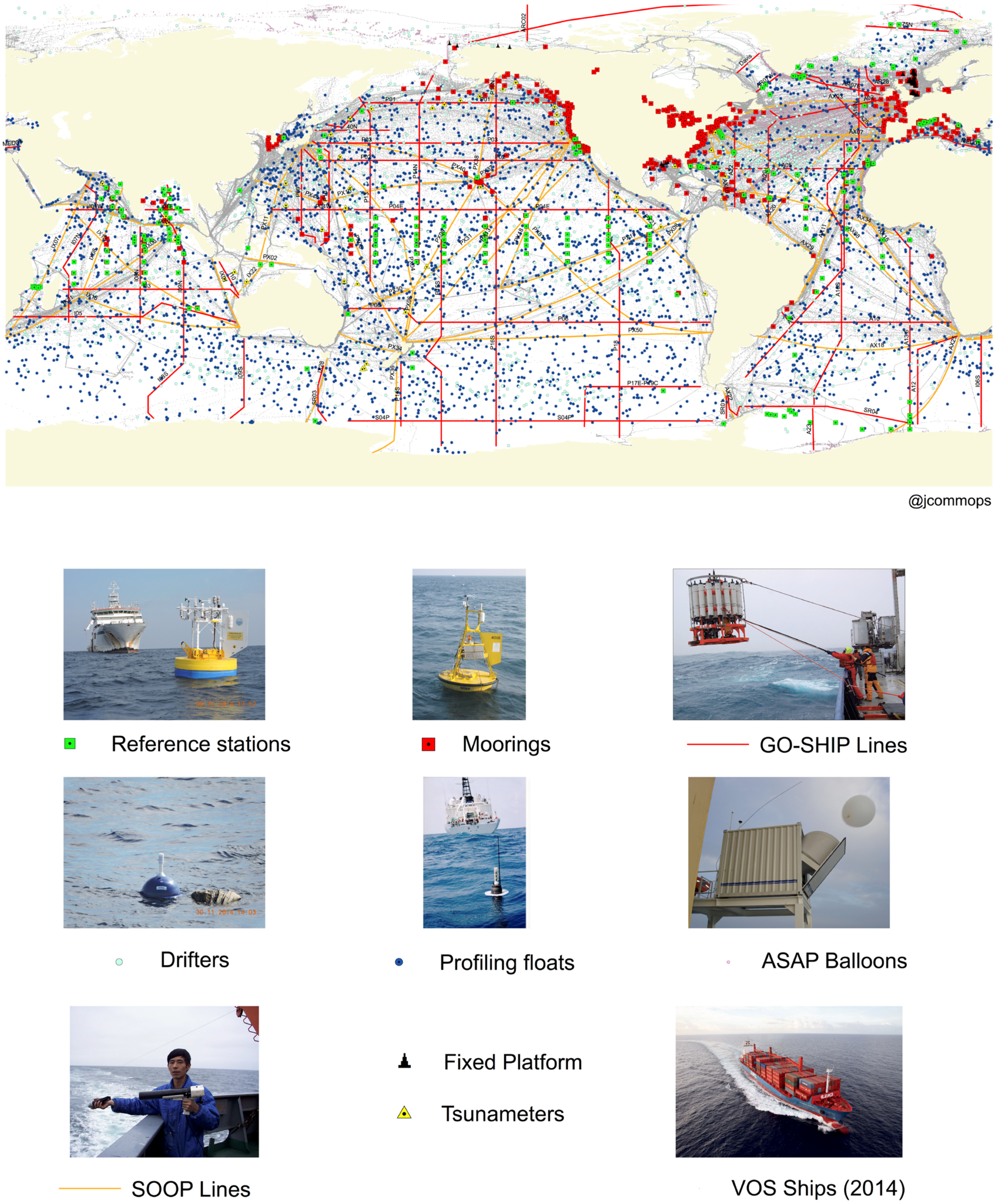
Climate information from the ocean is dependent on the in situ observation network and on the capacities for satellite remote sensing.

An overview of in situ systems and networks is available in Gould et al. (2013). Direct surface scientific ocean observations are relatively recent and date from the second half of 19^{th} century. However it is only since the 1970s that the ocean interior has been monitored in a systematic way with profiling conductivity-temperature-depth probes, current meter moorings, floats and drifters with expendable bathythermographs (XBT). Satellite navigation and transmission systems allowed significant progress in localisation and transmission of observations. Therefore assessments on climate change features for the ocean are reliable for approximately the last forty years.

The present ocean observing network (Figure 4-5) forms part of the coordinated by the Global Ocean Observing System (GOOS). Historically, it was developed as a driver for the Tropical Ocean Global Atmosphere program (TOGA), 1985-1994, and the World Ocean Circulation Experiment (WOCE), 1990-2002, and reinforced under the impulse of two major scientific conferences, OceanObs99 held in France (1999), followed by OceanObs09 held in Venice (2009) (see for example UNESCO, 2012). As illustrated in Figure 4-5 for a specific period (Sept 2015), the main features of the present ocean observing network include:

- A network of about 100 reference open ocean stations providing surface and deep ocean time series of physical and, for some of them, biogeophysical parameters;
- An array of tropical moorings providing continuous surface and subsurface reference information in the tropical Atlantic, Pacific and Indian Oceans;
- Surface measurements from volunteer ships;
- A global network of about 1200 surface drifters;
- A global network of sea level observing stations (from the Global Sea Level Observing System [GLOSS]);
- Regular XBT subsurface temperature sections up to 1000 meter depth from voluntary ships;
- An array of about 3000 "Argo" floats covering the open oceans with temperature and salinity measurements up to 2000 m. depth with approximately a 300 km spatial resolution; and
- Oceanographic cross-sections by specialized ships at specific locations.

Figure 4.5. Status of the Global Ocean Observing System (GOOS) in September 2015 (according to JCOMM-GOOS), with observing platforms that provide sustained ocean data from the sea surface to the abyssal ocean at varying temporal and spatial resolutions.



Source: JCOMMOPS, 2015

The development of satellite tracking allowed the development of automatic systems and was essential for the availability of a truly global in situ observing system. In addition, satellite observations, progressively developed since the 1970s, provided a huge quantitative change in the availability of global data. An overview of ocean remote sensing from space is available in Fu and Morrow (2013). SST has been available since the 1970s from infra-red and microwave remote-sensing with progressive improvements in precision and resolution. Surface winds can be derived from roughness measurements by scatterometer, demonstrated by Seasat in 1978 and currently available since the 1990s. Ocean colour radiometry, at the basis of phytoplankton remote-sensing, has been demonstrated in 1978 on board CZCS (Coastal Zone Color Scanner) and has been available since the 1990s. The global mean dynamic topography (taking into account the sea surface equilibrium height corresponding to the ocean general circulation) is derived with the help of geodetic and altimetry satellite missions. Geoid models have been greatly improved by the recent geodetic missions, GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) and GRACE (Gravity Recovery and Climate Experiment). This provides a basis for processing satellite altimetry data, which are available from TOPEX/Poseidon starting in 1992 and from several subsequent missions including ERS (Earth Remote-sensing Satellite), Envisat and Jason satellites, with up to millimetric precision. Another new development in ocean observation from space is the advent of sea surface salinity by microwave radiometry available since 2010 from ESA's Soil Moisture and Ocean Salinity Mission (SMOS) and since 2011 from NASA's Aquarius satellite.

Observed climate changes related to the ocean: temperature and salinity

For the purpose of this Report it is appropriate to restrict the assessment to 1971-2010, where data coverage is significantly improved as compared to earlier periods. A large part of IPCC assessed information relates to ocean temperature and heat content changes on one side, salinity and freshwater content on the other side.

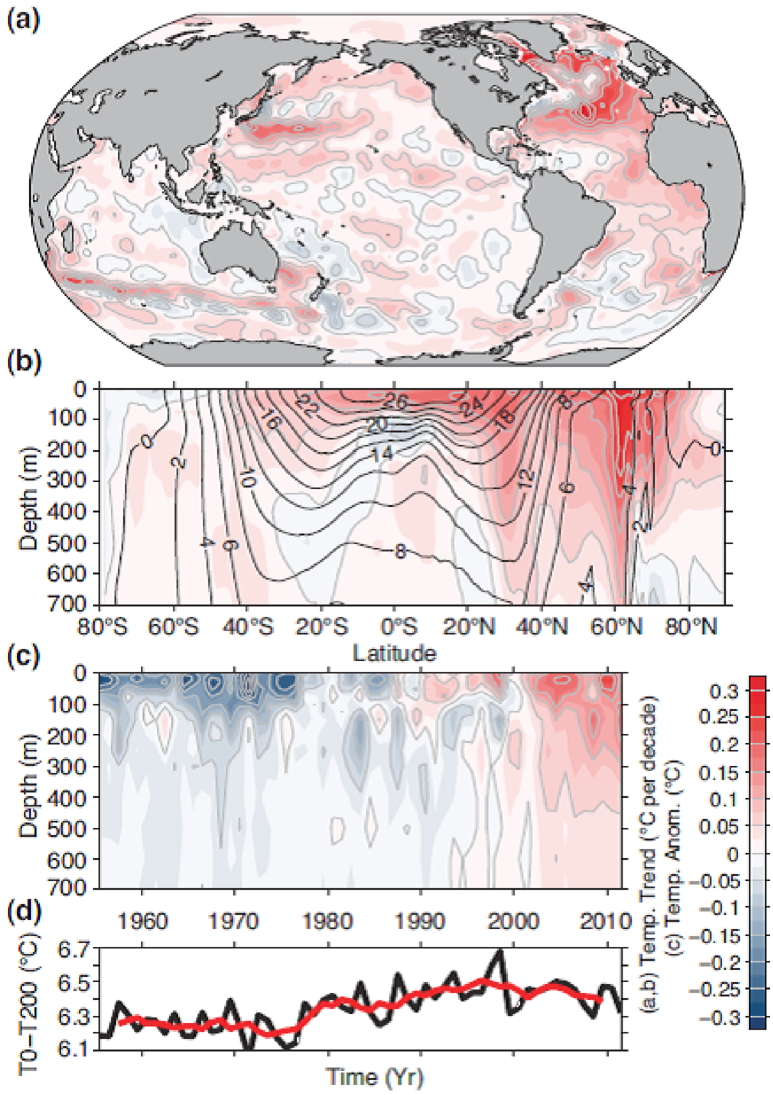
Ocean warming is the most obvious feature in line with lower atmospheric warming and the net influx of additional energy in the climate system. In fact ocean warming dominates the increase in energy stored in the climate system, accounting for approximately 93 per cent of the energy accumulated between 1971 and 2010, according to the assessment of observations in AR5 Chapter 3 (Rhein et al. 2013) from which this and the following conclusions have been drawn. Independent observations of SST, subsurface temperature and sea level rise (which include a substantial component due to thermal expansion) show a high level of agreement for this warming trend.

According to AR5, "it is *virtually certain* that the upper ocean (above 700 m) has warmed from 1971 to 2010" and "it is *likely* that the ocean warmed between 700 and 2000 m from 1957 to 2009, based on 5-year averages". Measurements below 2000 m are sparser and assessed only during the period 1992 to 2005. During this period "it is *likely* that the ocean warmed from 3000m to the bottom" while "no significant trends in global average temperature were observed between 2000 and 3000 m depth". Estimates of trends in heat content have been made during the same periods. "It is *virtually certain* that upper ocean (0 to 700 m) heat content increased during the relatively well-sampled 40 year period from 1971 to 2010" and "warming of the ocean between 700 and 2000 m *likely* contributed about 30 per cent of the total increase in global ocean heat content (0 to 2000 m) between 1957 and 2009".

More detailed information is available from Figure 4.6 where it shows that the global warming in the 1970-2010 period occurs at all levels in the upper 700m layer, with a progressive spread of the warming from the upper layers to deeper layers (c), with an increasing vertical gradient in the first 200m (d) and a clear indication that warming is largest in the North Atlantic and the western temperate Pacific Ocean.

One of the important features related to the ocean warming is an estimate of the energy intake of the main components of the global climate system, as illustrated in Figure 4.7: the additional energy stored in the climate system, expressed in ZJ (10^{21}Joules) units, is mostly absorbed in the ocean, about two third of it in the upper 700 m, with a slight slowing down of this heating in the last decade. In the 700-2000 m layer, the heating is *likely* to be steady for the last 20 years. Below 2000 m, data are sparse but it seems that the 2000-3000 m layer does not warm up significantly whereas some heating is observed in the deeper layers below 3000 m reached by the overturning circulation. This Figure also illustrates the uptake of heat for melting ice caps and glaciers, as well as the ground over

Figure 4.6. a) Depth averaged temperature trend for 1971-2010 (longitude vs. latitude, colours and grey contours in degrees Celsius per decade). b) Zonally averaged temperature trends (latitude vs. depth, colours and grey contours in degrees Celsius per decade) for 1971-2010 with zonally averaged mean temperature over-plotted (black contours in degrees Celsius). c) Globally averaged temperature anomaly (time vs. depth, colours and grey contours in degrees Celsius) relative to the 1971-2010 mean. d) Globally averaged temperature difference between the ocean surface and 200 m depth (black: annual values, red: 5-year running mean). All panels are constructed from an update of the annual analysis of Levitus et al. (2009).

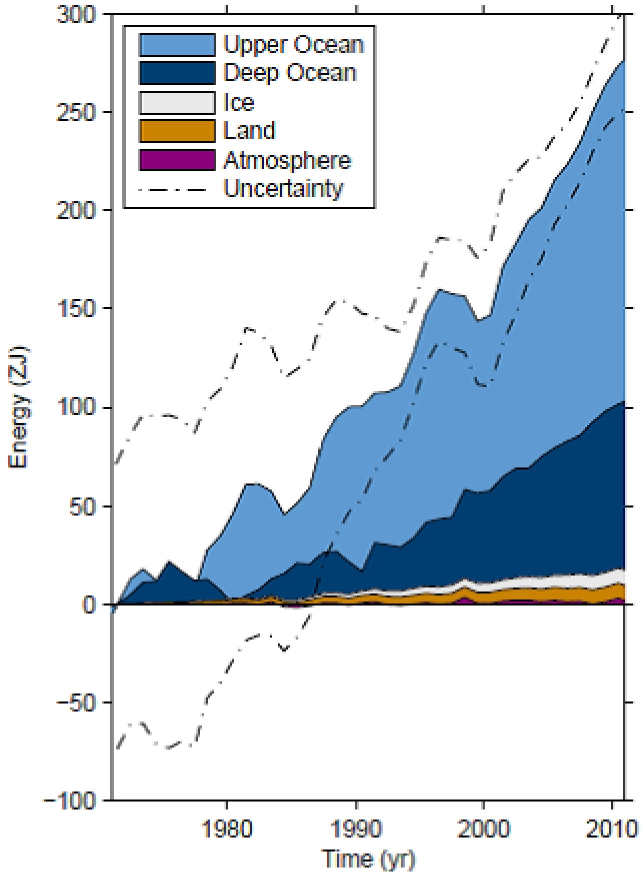


Source: Figure.3.1 from AR5 WGI

land surfaces (about 3 per cent of the total for each) and the extra heat stored in the atmosphere (of the order of 1 per cent of the total).

Recently, increased attention has been given to the relationship between ocean and atmospheric heat uptake, in order to provide a sound basis for the explanation of year to year variations of the global atmospheric temperature. Temperature records since the beginning of the 21st century, in fact since the 1998 El Niño year, seem to indicate a slowdown of climate warming compared to the three last decades of the 20th century, although this is very much dependent on the filtering method. This feature is often referred to as a "climate warming hiatus". It is explained either by changes in the net input of energy of the overall "climate system", or by increases of the global heat uptake of the ocean. The first set of explanations include contributions from a prolonged solar minimum (Hansen

Figure 4.7. Energy accumulation within the Earth's climate system estimates are in ZJ (1 ZJ=1021 J), and are given relative to 1971 and from 1971 to 2010, unless otherwise indicated. Ocean warming (heat content change) dominates, with the upper ocean (light blue, above 700 m) contributing more than the deep ocean (dark blue, below 700 m; including below 2000 m estimates starting from 1992). Ice melt (light grey; for glaciers and ice caps, Greenland and Antarctic ice sheet estimates starting from 1992 and Arctic sea ice estimates from 1979-2008; continental warming (orange); and atmospheric warming (purple; estimate starting from 1979) make smaller contributions. Uncertainty in the ocean estimate also dominates the total uncertainty (dot-dashed lines about the error from all five components at 90% confidence intervals).

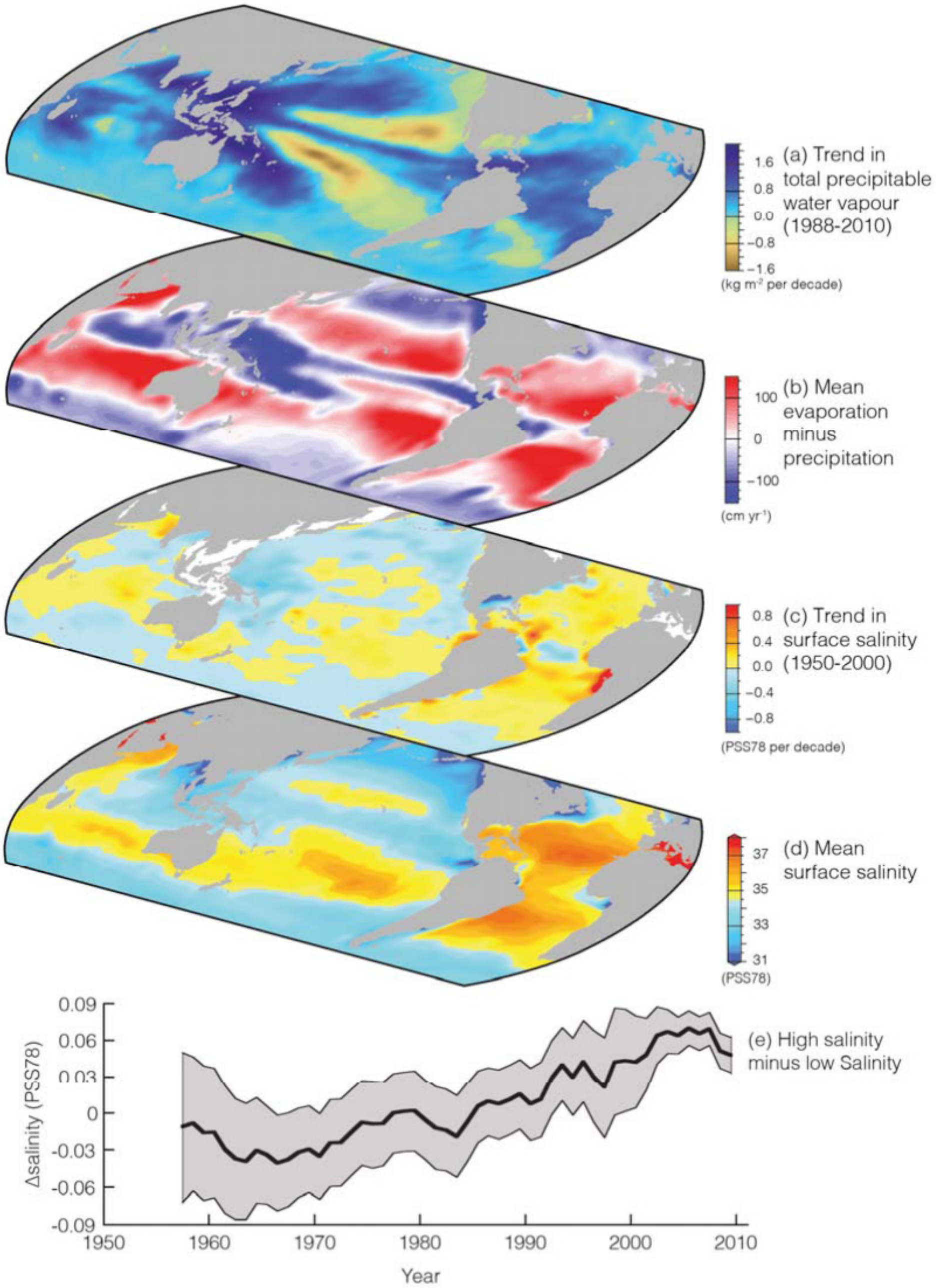


Source: Figure 1 Box 3.1 from AR5 WG I

et al. 2011), increased anthropogenic aerosols (Kaufman et al. 2011), stratospheric water vapour (Solomon 2010) and aerosols (Solomon 2011). However several recent articles, such as Guemas et al. (2013) indicate that ocean basin scale multi-year temperature variations may very well explain this “hiatus”. England et al. (2014) show that a pronounced strengthening in Pacific trade winds, as observed over the past two decades, is sufficient to account for the cooling of the tropical Pacific and for a substantial slowdown in surface warming through increased subsurface ocean heat uptake. Those studies do not take into account 2014 figures which, with a new global temperature record, may indicate the end of this slower warming period.

Changes in sea surface salinity (Figure 4-8) are expected in response to changes in precipitation, evaporation and runoff, as well as ocean circulation. In general, but not in every region, salty regions are expected to become saltier and fresh regions fresher. AR5 indeed indicates that “it is *very likely* that regional trends have enhanced the mean geographical contrasts in sea surface salinity since the 1950s: saline surface waters in the evaporation-dominated mid-latitudes have become more saline, while relatively fresh surface waters in rainfall-dominated tropical and polar regions have become fresher. The mean contrast between high and low salinity regions increased by 0.13 [0.08–0.17] from 1950 to 2008 (expressed in Practical Salinity Scale 1978, PSS78). It is *very likely* that the inter-basin contrast in freshwater content has increased: the Atlantic has become saltier and the Pacific and Southern oceans have freshened". A new study (Skliris et al. 2014) based on expanded data sets (1950-2010) and new re-analyses provide higher confidence in the assessment of trends in ocean salinity, with a confirmation that "the Atlantic-Pacific salinity contrast increases and the upper thermocline salinity maximum increases while the salinity minimum of intermediate waters decreases".

Figure 4.8. Changes in sea surface salinity are related to the atmospheric patterns of Evaporation minus Precipitation (E-P) and trends in total precipitable water: (a) Linear trend (1988 to 2010) in total precipitable water (water vapor integrated from Earth's surface up through the entire atmosphere) (kg m–2 per decade) from satellite observations. (b) The 1979–2005 climatological mean net evaporation minus precipitation (cm yr–1) from meteorological reanalysis data. (c) Trend (1950 to 2000) in surface salinity (PSS78 per 50years). (d) The climatological-mean surface salinity (PSS78) (blues <35; yellows-reds >35). (e) Global difference between salinity averaged over regions where the sea surface salinity is greater than the global mean sea surface salinity ("High Salinity") and salinity averaged over regions values below the global mean ("Low Salinity").



Source: TFE.1, Figure 1 from IPCC WGI report, Technical Summary

Changes at the ocean surface: sea ice cover, surface fluxes, wind waves

Sea ice cover is an important component of the climate system, and directly related to ocean thermodynamics. It influences Earth surface albedo and fluxes at the air-sea interface. Changes of sea ice cover are sensitive indicators of climatic conditions, with a number of consequences for human activities. Regional sea ice observations, first done in the Arctic, span more than a century and indicate significant interannual changes. An overall view has been available since the advent of satellite imagery and more specifically with microwave imaging systems since 1979. Arctic sea ice cover varies approximately between $15x10^6$ km^2 in winter and $6x10^6$ km^2 in summer, with a minimum occurring in September. According to AR5, the average extent of sea ice has decreased by about 3.8 per cent per decade since 1979 whereas the minimum September value has decreased by 11 per cent per decade, reaching a record minimum of 3.44×10^6 km^2 in 2012 (minima observed in the two following years, 2013 and 2014, were of the order of $5x$ 10^6 km^2, still about 20 per cent below the 1980-2010 average). This left ice-free areas through the Canadian Arctic Archipelago and North of Siberia. Ice thickness, first measured by submarine observations and since 1993 by satellite altimetry, has decreased in the average by almost a factor of two (from over 3.5 metres to below 2 metres) in the last 40 years, with a strong reduction of multi-year ice compared to seasonal ice. Estimates of Arctic ice volumes have been available from laser altimetry on the Icesat satellite (2003-2008) and radar altimetry on the Cryosat 2 satellite (since 2010), and confirm a significant decrease within the 10 year period where data are available.

Antarctic sea ice is largely seasonal, with average extent varying from a minimum of about $3x10^6$ km^2 in February to a maximum of about $18x10^6$ km^2 in September. It is, on average, thinner and more mobile than arctic ice, with an average thickness of the order of one meter at the time of maximum extent. Pluri-annual trends are less pronounced than in the arctic and overall slightly positive, of the order of 1.5 per cent per decade. There are regional differences in trends, with a fairly large increase in the Ross Sea and decreases seen elsewhere. Overall the climate change signal is too weak to make robust conclusions for the Antarctic Ocean as a whole.

Exchanges at the atmosphere-ocean interface are the main driving factors of the ocean circulation. They consist of sensible and latent heat fluxes, freshwater fluxes as evaporation and precipitation, momentum flux through wind stress, and fluxes of CO_2 and other chemical components. Surface waves are also an important feature of the ocean surface, involved in the physical processes at atmosphere-ocean interface.

Sensible and latent heat fluxes are highly variable, in time and space. Direct measurements are available locally and estimates have been carried out from a combination of model re-analyses, satellite and in situ observations. Averaged maps are available and displayed for example in Stocker (2013) and greatly contribute to the understanding of the mechanisms driving ocean circulation. Heat budget estimates taking into account the observed variation of the global ocean heat content in the period 1971-2010 indicate an increase of the mean heat flux from the atmosphere to the ocean of 0.55 W/m^2 over the period. However, as assessed in AR5, a direct detection of changes in air-sea fluxes remains beyond the ability of currently available surface flux data sets.

Limitations in the measurements or in local estimates of the evaporation and precipitation fields over the ocean from remote-sensing or re-analyses prevent making robust conclusions on climate change effects. However long-term reconstructions of precipitation over the ocean for the 20th century seem to indicate a slight upward tendency of global precipitation, compatible with a trend of 0.06 mm per decade derived from a 25 year satellite data record in the tropical belt from the Global Precipitation Climatology Project (Gu et al. 2007). Skliris et al. (2014), using extended re-analyses, confirmed an increase in the net evaporation in the subtropics and a net precipitation over subpolar latitudes, with an acceleration of those features in the last 30 years.

Wind stress maps are equally available, from a combination of re-analyses, satellite-based data and in situ observations. The weight of re-analyses in those estimates does not allow a *high* confidence level in estimated climatological variations. The clearest change corresponds to the Southern Ocean with a significant increase of the averaged wind stress from approximately 0.15 $N.M^{-2}$ in 1950 to more than 0.2 $N.M^{-2}$ in the last decade (Swart and Fyfe 2012). Wind stress in the tropical Pacific has also increased in the last twenty years but no clear trend was observed in the earlier 30 year period, and in this case natural decadal oscillations may be the dominant feature. Changes in wind stress over the North Atlantic have also been observed during the later part of 20th century with some indication of northward shift of the region of maximum stress (Wu et al. 2012).

Surface wind waves are generated by wind forcing and are partitioned into the wind-sea (wind-forced waves directly related to the surface wind but propagating slower than the wind), and the swell (lower frequency and fast propagating waves fed by inverse energy cascading effects and radiating from high wind areas). Significant wave height (SWH) is a measure of the wave field resulting from a combination of both processes, and is approximately equal to the highest one-third of wave heights. SWH has been observed throughout the 20th century by voluntary observing ships mostly in the North Atlantic and North Pacific. Systematic buoy observations have been available since the late 1970s and satellite altimetry data since the mid 1980s. SWH observations are complemented by model wave hindcasts, one of them being available since 1871. Satellite altimetry shows positive trends for extreme SWH in the Southern Ocean, North Atlantic and North Pacific but the period covered is limited to about 30 years. The main conclusion retained by IPCC AR5 (with *medium* confidence) is that “mean SWH has increased since the 1950s over much of the North Atlantic north of 45^0 N, with typical winter season trends of up to 20 cm per decade”.

Changes in ocean circulation

As the systematic observation of deep ocean circulation is limited to the last two decades, ocean circulation studies in relation to climate mostly concern the ocean basin gyres, the MOC, and water exchanges between ocean basins. Observed changes in the Pacific Ocean circulation over the last two decades include the intensification of the North Pacific subpolar gyre, the South Pacific subtropical gyre and subtropical cells; an expansion of the North Pacific tropical gyre; and a southward shift of the Antarctic Circumpolar Current (ACC). These dynamical changes induced sea level changes as described below (refer for example to Zhang and Church 2012), however they are *likely* predominantly due to the internal variability of the climate system at time scales from a few years to several decades. The Atlantic Meridional Overturning Circulation (AMOC) has also been the object of a number of studies, the most recent one by Smeed et al. (2014) demonstrating evidence of a weakening of the AMOC between 2004 and 2012. The observational record is still short for ascertaining a long-term trend instead of a decadal type oscillation, but this feature is the object of much attention in 21st century simulated scenarios, for its potential impact on European climate. Observations and model studies of the Antarctic Meridional Overturning Circulation suggest that changes in wind stress may drive a slowing down of the overturning cell in the Antarctic Ocean, and a reduction in the northward transport of bottom water associated with its warming.

Changes related to the carbon cycle

The Surface Ocean CO_2 Atlas (SOCAT), an international effort supported by UNESCO-IOC/SCOR IOCCP (International Ocean Carbon Coordination Project), SOLAS (Surface Ocean Lower Atmosphere Study) and IMBER (Integrated Marine Biogeochemistry and Ecosystem Research), brings together in a common format, all publicly available surface water CO_2 data from the global ocean (for example: Bakker et al. 2014). A recent review of CO_2 global budgets is available in Le Quéré et al. (2014). According to AR5, anthropogenic CO_2 emissions to the atmosphere from 1750 to 2011 (the sum of fossil fuel combustion, cement production and land use change) are estimated as 555 PgC, out of which 155 PgC are estimated to have been stored in the ocean, and 160 PgC in the biosphere over the land area not affected by land use change. The net flux of CO_2 at the ocean surface is a relatively small difference between large upward or downward fluxes displaying large regional variations depending on both atmospheric and oceanic conditions. Overall the ocean represents a CO_2 sink, and presently absorbs approximately 30 per cent of the anthropogenic emissions, as displayed in Figure 4-4. The actual net fluxes evolve with time and increase in function of the atmospheric CO_2 content, but this increase is modulated by oceanic climate variability and is slowed down by the increase of CO_2 in the ocean surface layer. The most recent figures for the period 2000-2009 (corresponding to Figure 4-4) indicate an uptake of 2.3 PgC/year by the ocean for a total anthropogenic emission of 7.8 PgC/year and an average accumulation of 4.0 PgC/year in the atmosphere. This uptake is modulated by inter-annual variability with year to year variations of the order of 0.2 PgC/year and the estimated decadal trend of CO_2 uptake by the ocean is estimated at 0.13 PgC/year per decade. Khatiwala et al. (2009), indicate that ocean uptake of anthropogenic CO_2 has increased sharply since the 1950s, with a small decline in the rate of increase in the last few decades. They also found that the Southern Ocean has a major role in this process, and presently representing 40 per cent of the CO_2 uptake.

Three types of processes drive the evolution of CO_2 once it reaches the oceanic surface layer:

- its dissolution in sea water as carbonic acid;
- the cycling of carbon through marine ecosystem processes; and
- the transport of carbon between the surface and deeper layers by turbulent processes and large-scale vertical mixing.

The uptake of CO_2 by the ocean changes the chemical balance of seawater. A chemical equilibrium is reached between CO_2, carbonate and bicarbonate ions in the presence of partly ionized water. The pH of the water therefore decreases with total dissolved inorganic carbon. The mean pH of surface waters ranges from 7.8 to 8.4 in the open ocean, remaining slightly basic. A number of observations confirm the decrease of ocean surface pH since the pre-industrial Era, of the order of 0.1, which represents an increase of acid ions of the order of 30 per cent, and may already have a significant impact on biological balance (for example: Beman et al. 2011). An update on pH observations is available in Takahashi et al. (2014). Time-series for pH (taken at fixed stations) indicate regional differences in the acidification process: the ocean is slightly more acidic in the tropics than in temperate regions but with a larger buffer capacity in the tropics, which means smaller long-term changes. Observations at selected stations, available for about 30 years, indicate the largest pH reduction in the northern North Atlantic and the smallest in the subtropical South Pacific.

Another important consequence of increased CO_2 absorption by the ocean and the subsequent ocean warming is the decrease of dissolved oxygen concentration in the open ocean thermocline over the last 50 years (for example: Keeling et al. 2011), which is discussed in Chapter 4.3 This decrease is consistent with the expectation that warmer waters can hold less dissolved oxygen and that warming induced stratification leads to a decrease in the transport of dissolved oxygen from surface to subsurface waters. In addition to the carbon cycle, the ocean has a primary role in the global cycle of the other elements, nitrogen, phosphorus, iron, silicon, which are all altered in some ways by human activity, and are essential to the maintenance of oceanic biological activity, which itself feedbacks in the global cycles. These aspects are covered in Section 5 of this Open Ocean Technical Assessment Report.

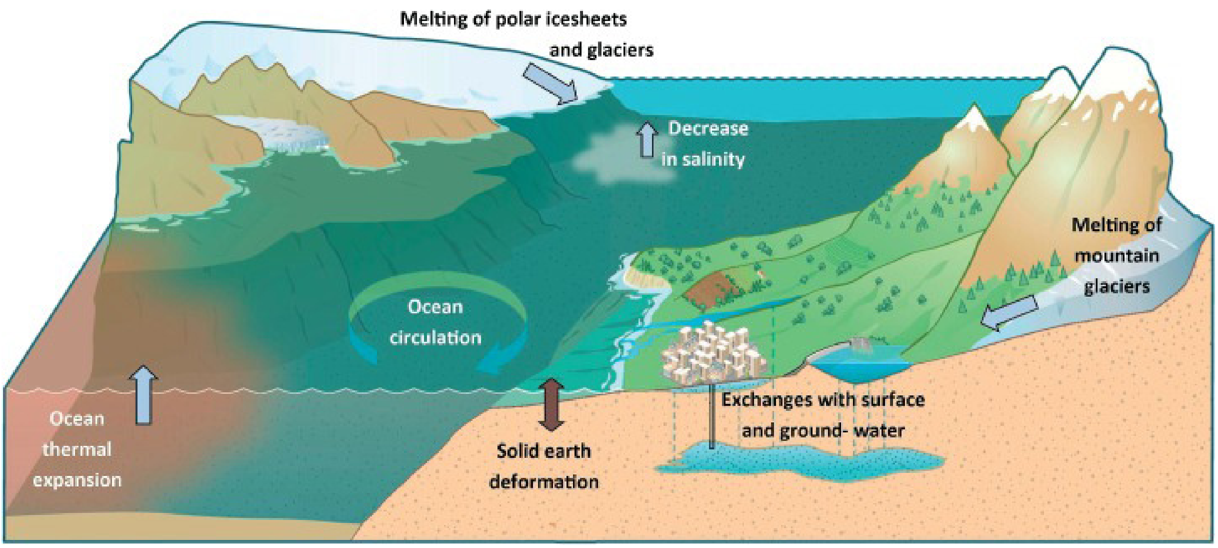
Sea-level change

There is strong observational evidence that sea levels are rising globally and this is one of the most direct consequences of climate change. Observed sea level rise over the 20th century is of the order of 1.7mm/year and has increased to about 3mm/year in the last 20 years. A good understanding of the physics of sea level change can be obtained from Church et al. (2013), with coastal impacts highlighted in Cazenave and Le Cozannet (2014). A review of sea level observations since the end of 19th century including recent satellite data is available in Church and White (2011). A complete review and assessment of climate change is available in IPCC AR 5 and an extensive overview of impacts including from extreme events can be found in Lowe et al (2010). Sea level varies at all time and space scales, short time scales corresponding to wind waves, tides and surges linked to weather conditions. For practical purposes, it is convenient to apply filters in order to separate short time scales from larger ones and separately deal on one side with Mean Sea Level (MSL) with short time scales removed, and on the other side extreme sea level with short time scales included.

Variations considered here first relate to MSL and include time scales from the order of a month onwards, which are the only ones globally reported as part of the Permanent Service for Mean Sea Level (PSMSL). Global sea-level rise associated with regional effects and the resulting impact on the coastal zone is one of the main challenges from climate change in the 21st century. Sea level is the ocean parameter which has been observed for the longest period (from around 1700 onwards) and its changes directly affect human activities. However it is only progressively, with the organisation of worldwide observation networks and the advent of satellite remote sensing in the last two decades, that a global view has emerged. Sea level temporal variations integrate multiple ocean, meteorology and geodesy related signals and are geographically dependent. Absolute sea level is defined with respect to the centre of the Earth, whereas relative sea level (measured by tide gauges and matters for impact assessments) is related to the level of the continental crust or local Earth's surface. Relative sea level changes can thus be caused by absolute changes of the sea level modified by absolute movements of the continental crust.

A schematic view of the main processes involved in relative sea level changes is given in Figure 4.9 from Cazenave and Le Crozannet (2014). Recent estimates for the period 1961-2003 from Slangen et al. (2014) displayed in Figure 4.10 provide a quantitative overview of those processes.

Figure 4.9. Sketch showing the main factors causing sea level changes.



Source: Figure 2 from Cazenave and Le Cozannet (2014)

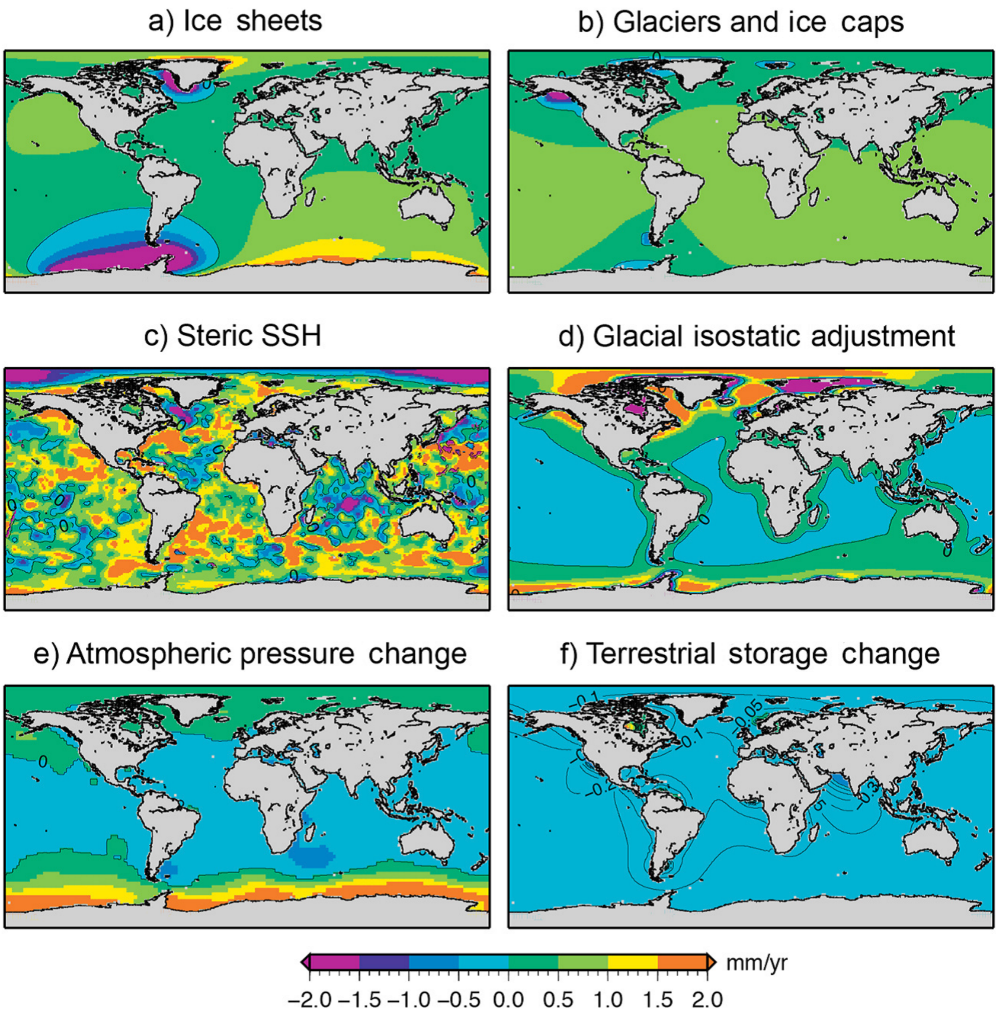
Global absolute mean sea level changes occur mostly at decadal and longer time scales, and result from two major factors (mostly related to recent climate change) that alter the volume of water in the global ocean:

i) density changes (or steric changes, Figure 4-10 c) due to thermal expansion and changes in salinity. Thermal expansion is the main cause of global mean sea level change whereas changes in salinity tend to compensate each other at the global level and are mostly felt regionally. The global mean effect of thermal expansion in the last twenty years is approximately 1.1mm/year according to AR5.

ii) the exchange of water between oceans and other reservoirs. Aside from the ocean, the two main reservoirs of water on Earth are the cryosphere (ice sheets, glaciers and icecaps) and land water reservoirs. The water content of the atmosphere is much smaller and its changes are negligible in this context. Figure 4-10a) displays the sea level rise resulting from Greenland and Antarctica ice sheets melting with a global effect of the order of 0.6mm/year in the last 20 years. Figure 4-10b) displays the result of icecaps and continental glaciers melting with a global effect of the order of 0.85 mm/year in the last 20 years (inclusive of Greenland glaciers). Land water reservoirs include snow storage for which year to year variations are negligible. Lakes, including human built reservoirs, tend to increase with time, and ground water storage tends to be depleted by human activity. The combined effect of the above has not been uniform in the last century, with a negative contribution to sea level rise in the 1960s and a positive contribution in the last 20 years of about 0.38 mm/year.

Measured relative sea level is in addition influenced by atmospheric pressure, ocean circulation changes linked to changing wind patterns and land height changes. Figure 4.10e) displays the regional pattern due to atmospheric pressure change with a sea level rising effect in polar regions and lowering effect in the tropics but a negligible global effect. Regional land height changes can be due to tectonic effects, subsidence (natural or from anthropogenic origin) or sedimentation. However the main effect at global scale results from the glacial isostatic adjustment, the continuing rise of land masses that were depressed by the weight of ice sheets during the last glacial period, as displayed on Figure 4.10f), with a resulting global lowering of sea level estimated at 0.3mm/year.

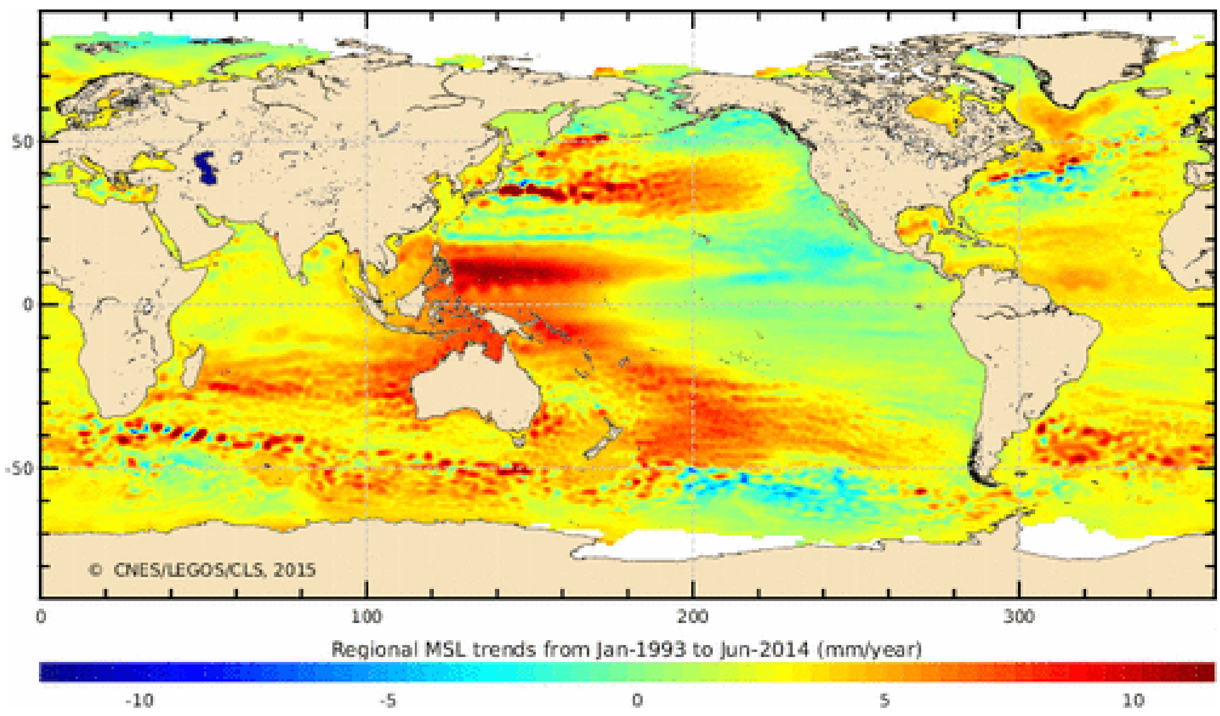
Figure 4.10. Regional sea-level trends (mm yr–1) over the period 1961–2003 for the following contributions; (a) ice sheets, (b) glaciers and ice caps, (c) steric change, (d) glacial isostatic adjustment, (e) atmospheric pressure loading, and (f) terrestrial water storage change from groundwater extraction and reservoir impoundment. The black line is zero-contour, except in (f) where every 0.05 contour is shown for clarity. All data are on a 1×1 degree grid.



Source: Figure 2 from Slangen et al. (2014)

Regional scale sea level changes result from the combination of global processes illustrated above and purely regional processes from meteorological or tectonic origin. They can also result from anthropogenic land movements related for example to ground water extraction that are a key component of subsidence in coastal cities. Regional sea level changes have been observed with high precision since 1993, with the availability of satellite altimetry in addition to the gauge network. A mapping of MSL change over the last 20 years identified areas of fast rising sea level in the Western Pacific, North Western Atlantic and South Indian Ocean, with more than three times the global average observed East of the Philippines (Figure 4.11). In contrast, areas of decreasing sea level were observed in the North Eastern Pacific and a limited region of the Southern Ocean. According to AR5 conclusions based on several recent studies, such as Levitus et al. (2009), regional sea level changes display multi-year or decadal patterns which are explained to a large extent by temperature changes throughout the ocean depth and to a lesser extent by salinity changes. In some regions a clear link has been established with changes in surface wind stress, for example the strong east-west signal in the tropical Pacific Ocean corresponds to an increase in the strength of the trade winds in the central and eastern part of this ocean (Merrifield and Maltrud, 2011). The length of the accurate observation of regional sea level does not allow a clear distinction between low frequency oscillation modes at the ocean basin scale and the signature of anthropogenic climate change, but it seems that a large part of observed signals relate to internal modes of ocean variability (Zhang and Church (2012); Stammer et al. (2013); Haigh et al. (2014)).

Figure 4.11. Combined map of regional patterns of observed sea level from satellite altimetry for the period January 1993 to June 2014



Source: CLS/Cnes/Legos

What has been covered up to now concerns Mean Sea Level. However, most impacts on the coast and inshore marine environments result from extreme events affecting sea level, such as storm surges, tidal effects and wind waves, which are superimposed on mean regional sea level. Global analyses of the changes in extreme sea level are limited and most reports are based on analysis of regional data (Lowe et al. 2010). Most records indicate an increase in extreme sea levels which seem to be explained by changes in mean regional sea level (for example: Hunter, 2011). However maps of trends in the height of 50 year events, available for about 100 locations worldwide, indicate either neutral of upward values of up to a few centimetres per decade. This information can be corroborated with studies of the frequency and intensity of storms. Observations on trends in tropical cyclones are not conclusive, although some studies indicate a decrease in overall numbers associated with an increased frequency of the strongest ones. For extra tropical cyclones, a poleward shift is observed in both hemispheres in the last 50 years, with limited evidence of lower frequency and increased intensity of high intensity events.

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Introduction to scenarios for 21st century used in the following chapters

Subsequent chapters describe estimates of changes in the main oceanic parameters, as obtained from model simulations covering the 21st century and beyond. The reference set of simulations is the CMIP5 (fifth phase of the Climate Model Intercomparison Project) set of climate model runs as described in Taylor et al. (2012). Models used for this are either coupled Atmosphere-Ocean Global Circulation Models (AOGCMs) describing dynamical and physical processes in the climate system with an interactive representation of the atmosphere, ocean, land and sea-ice, or "Earth System Models" (ESMs) including some of the main biogeochemistry processes, particularly those related to the fluxes of carbon between the atmosphere, the ocean and the land biosphere reservoirs. These models are generally initialised with quasi-equilibrium conditions corresponding to the pre-industrial era and are validated on 20th century simulations. Integrations on future conditions make use of specified time-varying concentrations of various atmospheric constituents and land-use properties based on a range of emission scenarios.

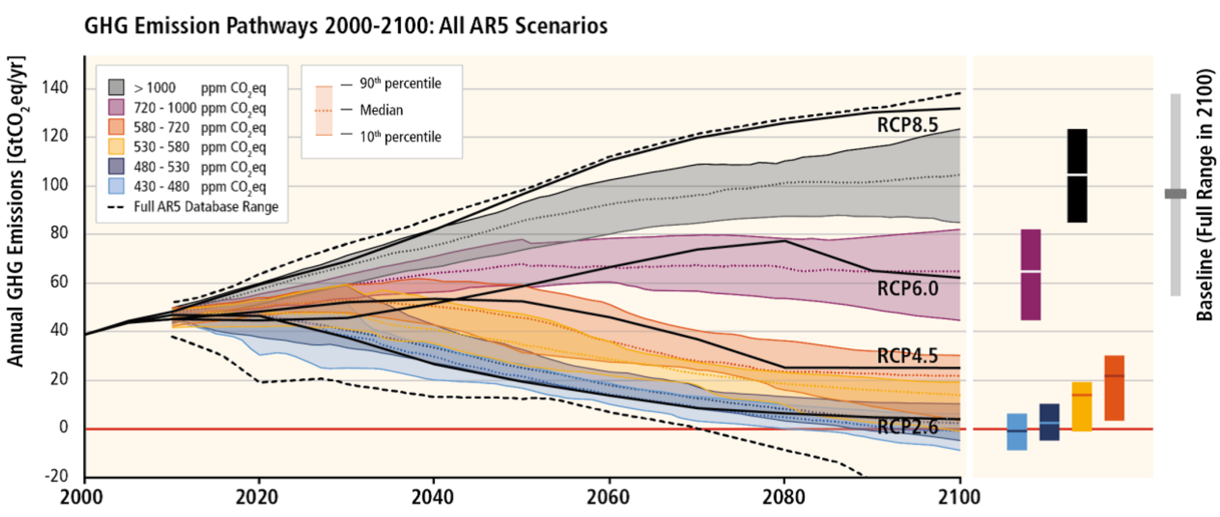
Future anthropogenic emissions of greenhouse gases, aerosol particles and other "forcing agents" for climate, such as land-use changes, are dependent on socio-economic factors, including demography, patterns of economic development and potential global geopolitical agreements designed to control emissions. SRES (Special Report Emission Scenarios) used as reference scenarios by climate models in AR4 were developed using a sequential approach, with socio-economic factors feeding into emission scenarios. These scenarios are being used in simple climate models to derive the key parameters which are necessary to run an advanced climate model. They did not explicitly take into account the implementation of global emission reduction strategies, such as those being negotiated under the United Nations Framework Convention on Climate Change (UNFCCC).

New scenarios used in AR5 to drive climate model simulations are based on estimates of the evolution of radiative forcing to be used as reference for AOGCM or ESM simulations. Those scenarios represent projections of greenhouse gas and aerosol concentrations obtained from "Integrated Assessment Models", which include economic, demographic, and energy consumption conditions in relatively simple climate models. The concentration projections can then be used as forcing parameters in complex interactive AOGCMs.

The scenarios are qualified as “Representative Concentration Pathways” (RCPs) and represent evolution patterns of Greenhouse Gases and aerosols defined over the coming three centuries (Refer to Glossary Box 2) They are labelled according to radiative forcing estimated at year 2100, target year of many model simulations. Radiative forcing quantifies the change in energy fluxes at the Earth’s surface resulting from changes in the atmosphere composition and processes such as cloud and aerosol effects which modify radiative fluxes, and is expressed in W/m² averaged over the globe. This radiative forcing is compared to a pre-industrial baseline set in 1750. Information displayed in the following sections of this report is based on two of the scenarios described in AR5: RCP 4.5, an intermediate emission stabilisation scenario; and RCP 8.5, a high emission scenario with no mitigation policy during the 21st century. RCP 4.5 corresponds to a pathway with radiative forcing progressively increasing from the present level of the order of 2 W/ m² to an asymptotic value of to 4.5 W/m² at stabilization after 2100. RCP 8.5 corresponds to a pathway with radiative forcing reaching 8.5 W/ m² at the end of the 21st century and with an asymptotic value of 12.5 W/m² reached around 2250.

Equivalent CO_2 emission profiles corresponding to the four scenarios used in AR5 (displayed in Figure 4-12) allow a comparison of the various scenarios. RCP 2.6 corresponds to a stringent mitigation scenario which aims to keep global warming *likely* below the 2 degree target above pre-industrial levels, objective put forward under the present international negotiations. RCP 4.5 assumes a mitigation strategy, which would reach a maximum global emission of about 55 Gt CO_2 equ/yr before 2050, with a decrease of the order of 50 per cent by the end of the century. In this case, the total CO_2 equivalent concentration would be in the range 530-580 ppm by the end of the century and the expected warming in the *likely* range 2.1-3.1 degrees compared to the pre-industrial era. By comparison, the present CO_2 equivalent concentration is approximately 430 ppm. In RCP 8.5 where no significant mitigation policy is applied, CO_2 equivalent concentration rises above 1000 ppm by 2100 and continues rising after that date, with emissions reaching an asymptotic value of 130 Gt CO_2 by 2100. RCP 8.5 corresponds to a *likely* warming larger than 4 degrees compared to the pre-industrial era (*likely* range 3.8-5.2), and increasing thereafter.

Figure 4.12. Pathways of global GHG emissions ($GtCO_2eq/yr$) in baseline and mitigation scenarios for different long-term concentration levels.



Source: Figure SPM 11 IPCC AR5

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Chapter 4.2 Models projections of ocean warming under “business as usual” and “moderate mitigation” scenarios

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4.2 Models projections of ocean warming under "business as usual" and "moderate mitigation" scenarios

4.2.1 Summary and Key Messages

As introduced in Chapter 4.1, the ocean is a key part of the climate system, through its role in the cycles for energy/heat, water, and carbon. Human-induced changes in climate affect the physics of the ocean, which influences marine ecosystems. The Conceptual Framework (Chapter 2) upon which the Open Ocean Component is built, assumes that a policy should target the improvement of human wellbeing. As there is a circular relation between human actions framed by the policies, and the impact of changes of marine services on human society, a scenario accounting for climate mitigation is required to project the current state of the ocean to the future. The IPCC considers 4 possible scenarios in its 5th Assessment (Chapter 4.1 and Glossary Box 2), starting with no change to the current situation and 3 scenarios showing increasingly stringent global mitigation policies.

This Chapter identifies some key indicators of the state of the ocean climate and their projected changes under the IPCC scenarios. Other Chapters in this Report have used these indicators as inputs to models for marine ecosystem response or cumulative human impact. Two of the four IPCC scenarios frame the possible evolution of the ocean: the one corresponding to the progression of radiative forcing without implementing a significant greenhouse gas reduction policy (RCP 8.5) and a best-case scenario with a feasible reduction policy (RCP 4.5). For sake of clarity, scenario RCP 8.5 is referred as "Business As Usual" (BAU), and RCP 4.5 is referred as "Moderate Mitigation" (MM).

A fundamental quantity in determining the role of the ocean in climate and in marine ecosystems is Sea Surface Temperature (SST). It affects the large-scale circulation of the atmosphere, and therefore patterns of rainfall and drought. Since many marine ecosystems are pelagic (near-surface), it is an important input to ecosystem models and estimates of their future state. The combination of a warming and acidifying ocean (see Chapter 4.5) directly threatens species as diverse as coral reefs (see Chapter 5.4) and pteropods (see Chapter 5.5). Climate models project a growth in the tropical warm pool (the area of permanently high temperature, typically above 28°C), the major driver of large-scale tropical atmospheric circulation and surface rainfall and evaporation patterns. Both scenarios show an increase of temperature, especially in Northern Hemisphere high latitudes. They also both indicate that a large fraction of the ocean will experience yearly recurring temperature increases of 2°C or more above the temperature observed in the period 1970-2000.

In Polar Regions, the so far pristine waters house fragile ecosystems. Sea ice creates an important habitat, and is a barrier to human activities: Arctic seas are impassable in winter. In the perspective of the Conceptual Framework driving this assessment (Chapter 2), the future of the Arctic region is found to be more pressing than the Antarctic. The Arctic region actually lacks the comprehensive legal framework that is protecting the Antarctic (Lennon, 2008). This leaves the region vulnerable to human pressures applied by the nearby populations living on its perimeter. The seasonal recession of sea ice is a spatial indicator of seasonal warming. This Chapter shows that in addition to seasonal variation, the total extent of Arctic sea ice has been regressing over the past 30 years. Climate model projections also show that the loss of sea ice in the Arctic is *likely* to be much more significant than in the Antarctic, with impact on navigation, opening access to natural resources and potentially increasing human pressures there. The combination of a lack of governing policies to protect the environment, with intense human pressure and dependence on the ecosystem services drives a concern for the future health of the Arctic ecosystems, and hence a focus of this Chapter.

Global warming has already led to a decrease of the area of Arctic sea ice observed at the end of Northern Hemisphere summers, which in turn may have implications on the global energy balance. With less ice cap surface, less energy is scattered back to space, resulting in more energy absorbed by the Earth's climate system, which in feedback, increases global warming.

This Chapter shows how models outputs are used to get a projection of the ocean variable states to 2030 and 2050. As projections of ocean warming are extensively used in other chapters, details of processing are described here.

In particular, some indicators based on projections of Sea Surface Temperature were computed specifically for this assessment, and they are reviewed in this Chapter. This Chapter also reviews projections and observations of the Polar Sea Ice area change; most of the conclusion being extracted from IPCC Assessment Report 5. Both ocean surface temperature and polar sea ice projection are addressed for BAU and MM scenarios.

Key messages

- The surface ocean is expected to warm, in an ocean-average sense, whether there is mitigation or emissions remain the same;
- Much of the surface open ocean will warm on the order of 1°C, though some will warm 2°C or more (especially in the Northern Hemisphere), under a "Business As Usual" emission scenario, by 2050. Even with mitigation efforts there will be significant surface warming;
- The area of regions with very warm water (>28°C) will increase substantially by 2050 under "Business As Usual" scenario, with *likely* effects on at least regional weather;
- Monthly departures from climatology will be enough to provide substantial thermal stress on many coral by 2050 under "Business As Usual" scenario;
- Arctic summer sea ice extent is expected to continue to diminish, particularly under "Business As Usual" scenario. By 2050 there may be no sea ice at the end of summer.

4.2.2 Main Findings, Discussion and Conclusions

As established in the IPCC's Fifth Assessment Report (IPCC AR5, 2014), Earth global warming affects the ocean thermodynamics and chemistry. Ocean warming dominates the global energy change inventory. Warming of the ocean accounts for about 93 per cent of the increase in the Earth's energy inventory between 1971 and 2010 (*high confidence*), with warming of the upper (0 to 700 metres) ocean accounting for about 64 per cent of the total. The scientific community used climate model simulations for a time-projection of the possible future state of the ocean. As explained in Chapter 4.1, CMIP5 model projections are using four different scenarios, named Representative Concentration Pathways (RCPs), depicting possible future global radiative forcing pathways, because of the adoption of hypothetical mitigation policies (See Glossary Box 2). The groups of researchers run their models for each scenario, resulting in an ensemble of projections. With each model having specific qualities, the ensemble mean of the model projections are considered. The spread of the model ensemble was also considered for an estimate of the disagreement between the models, showing the lowest and highest ranges for a given variable. When all models show similar pattern or trends, the confidence in the projection was enforced.

Different hypotheses of carbon emission regulations determine the four CMIP5 scenarios, corresponding to the various capacities of human society to implement regulations to reduce emissions and in turn lower the final radiative forcing applied to the global climate system. Scenario RCP 8.5 corresponds to the case where no specific policy is applied, often known as the "Business As Usual" scenario, and by such constitutes a base case for future assessment, in the sense that no mitigation policy is applied. To frame the future evolution of the ocean ecosystem, the simplest approach considered that it would be in between RCP 8.5 and a scenario applying reduction policies. The RCP 2.6 seems difficult to reach in practice, therefore RCP 4.5 was the best-case scenario for the work. Because RCP 8.5 corresponds to a direct projection of the present situation, more attention was payed to this scenario. For sake of clarity, scenario RCP 8.5 is referred as "Business As Usual" (BAU), and RCP 4.5 is referred as "Moderate Mitigation" (MM).

This Chapter introduces the analysis of the impact of climate change on the environment, including the biodiversity and human activities. Simple computations show the potential change of the Sea Surface Temperature (SST), computed as the ensemble mean of climate model outputs. The processed data set is available to the reader from the onesharedocean.org platform[23]. The results show how a warming ocean can lead to the expansion of the Indo-Pacific Warm Pool. The same data set was also used for a time projection of the Ocean Health Index (Chapter 8.2).

23 See page http://onesharedocean.org/open_ocean/climate/physical_effects

A simple indicator assessing the potential thermal stress on living organisms was defined. The assessments of stress on coral reefs and pteropods are in Chapters 5.4 and 5.5, respectively. The data generated for this first level of analysis is available to the reader from the onesharedocean.org platform[1]. The impact of global warming on the Arctic sea ice and the potential future state of the Arctic was also described, using observation data and modelling analyses.

All processing codes used in this Chapter are available (under GNU general public license) from https://github.com/IOC-CODE.

Ensemble means of SST projections

One of the most important and direct effects expected from climate change is an increase, at global scale, of the atmosphere and ocean temperatures, which are a direct consequence of changes in energy balance. Indicators based on the SST projection show the spatial scale and magnitude of future changes, as well as the difference between scenarios. This Chapter considers first the future evolution of SST by analyzing model projections, its consequence on the Indo-Pacific Warm Pool (an ocean feature playing an important role in global circulation), the occurrence of annual periods of higher warming potentially harmful to coral (Degree Heating Month Alert Level 2), and consequences of global warming on sea ice in the Polar Regions.

Projections of SST were obtained by computing the ensemble mean of model outputs under scenarios MM and BAU (see Methods 4.2.3). The result of the operation is a time-series of ocean surface temperature, grouped by decades, from 2010 to 2059 (which is the last year of decade 2050): the number of model averages per grid cell is in the final product, as well as the minimum-maximum amplitude between model averages. Figure 4.13 shows the sea surface temperature at the beginning of the projection under BAU, as the average of year 2010.

Figure 4.13. Initial value of the sea surface temperature projection ensemble mean, as the average of year 2010, for BAU (RCP 8.5)

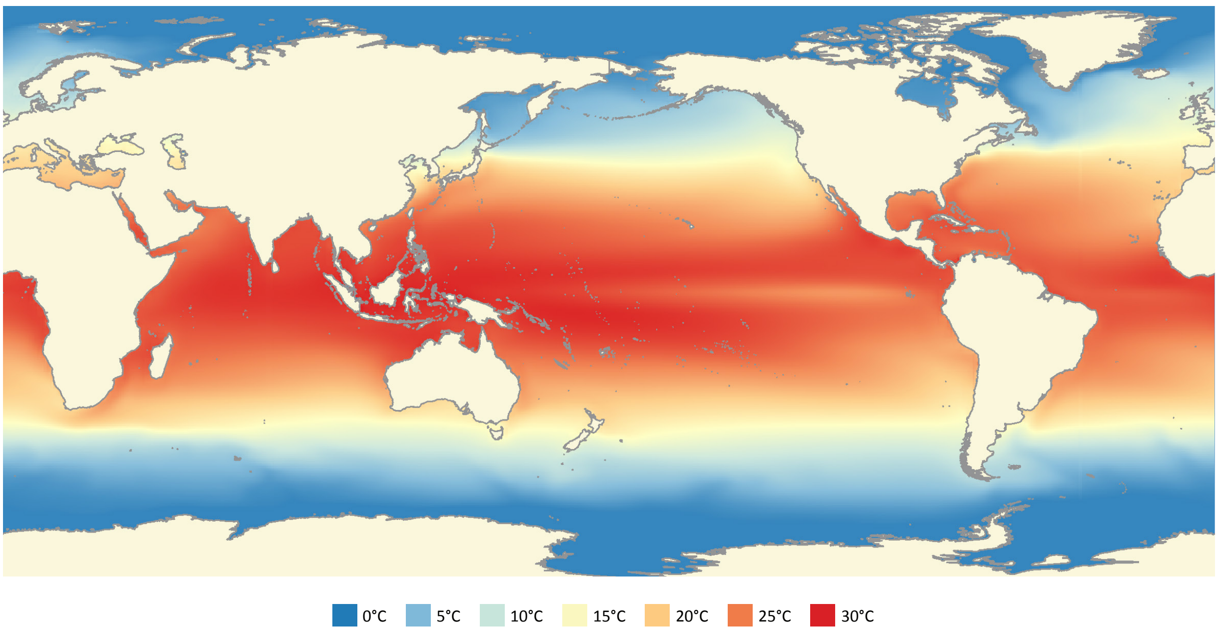
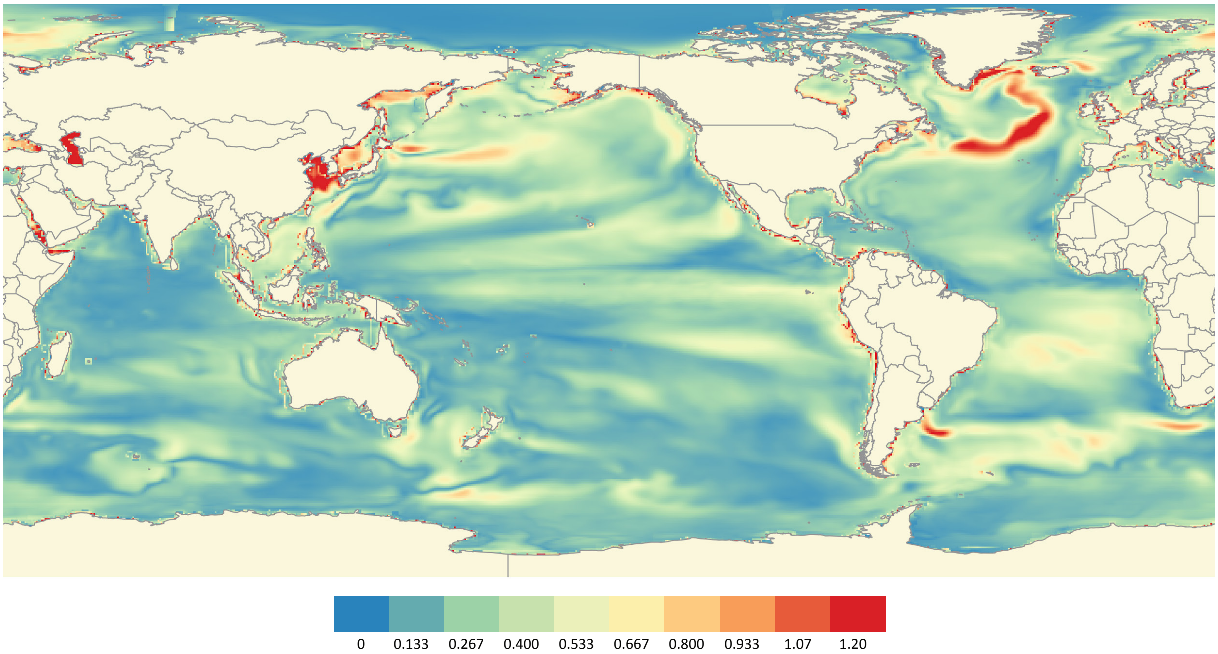


Figure 4.14 illustrates intrinsic ensemble mean variability, as the standard deviation for a given date. The colour bar was stretched to clearly show the existence of difference among the models, though this difference is in general rather low. The ensemble mean standard deviation remains below 0.5°C in most of the ocean, and a large fraction is even below 0.3°C. This spread among models is below the projected increase of temperature. Actually the expected

increase in temperature is expected to be not less than 0.75°C, and in general beyond 2°C for BAU around 2050 (see Figure 4 analysed in this section). The small spread has a spatial consistency and seems to correspond to differences in the modelling of the ocean local dynamic and thermodynamic features. These small differences among models justify the need to consider an ensemble mean, rather than a single model, which can smooth local discrepancies when carrying a global study.

However, some specific areas show higher spread of the model outputs, reaching up to 1.2°K, shown in red on Figure 2. Such differences between the models are generally found close to the shores and explained by the different representations of the coastline in the various models grids. Some features, generally ocean currents, such as in the North Atlantic, however, show higher magnitude of differences, which would deserve further analysis from the research team developing the models.

Figure 4.14. Standard deviation of the Sea Surface Temperature ensemble mean, 2050, July, BAU (RCP 8.5)



Computing the difference between the decadal temperature average for decade 2050 (2050-2059) and the climatology (period 1971 to 2000) shows that the entire ocean may experience a temperature increase, for both scenarios MM (**Figure 4.15**) and BAU (**Figure 4.16**). Some features, easily distinguished under MM (Figure 3) , show a local increased warming: in the northern Pacific, in the northern Atlantic close to the North America shores and, around European countries. This increased warming can be explained by local forcing (expressed in the scenarios) and by transportation through ocean circulation. Some features of the global circulation, such as the counter equatorial current also exhibit an increased warming. Both scenarios show that the Northern Hemisphere could have the highest temperature increase by 2050, with up to a 3°C increase compared to the climatology.

The Moderate Mitigation (MM) and Business-as-usual (BAU) scenarios are both projections of the future sea surface temperature (SST), with respect to the 1971-2000 climatology. The difference between the two scenarios, which can be linked to the uncertainty of the projections, is shown in **Figure 4.17** and indicates a SST difference below 0.5C over most of the ocean. Some rare locations (for example East of Japan) show a warming of about 1°C more for BAU than MM. Most of the Southern Seas, around the Antarctic show a very low difference (below 0.2°C). For some rare exceptions (for example in Central Atlantic), MM may result in a slightly higher increase than BAU.

Figure 4.15. Temperature difference between average temperature in decade 2050 and climatology (average temperature between 1971 and 2000), under MM (RCP 4.5).

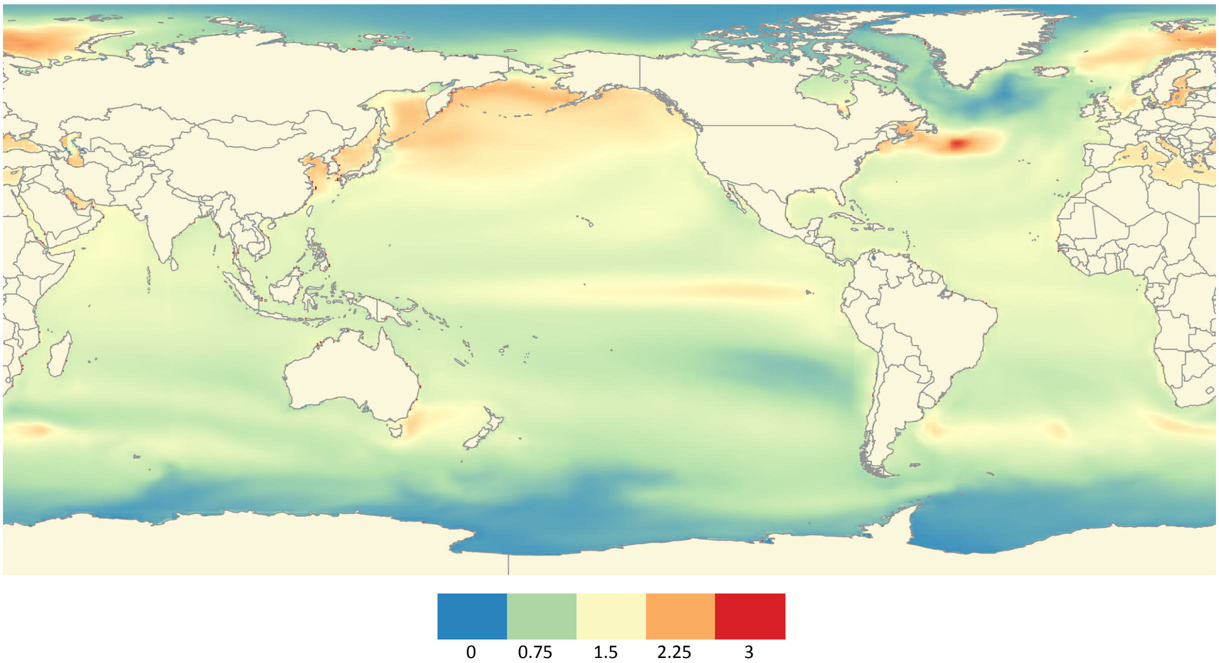


Figure 4.16. Temperature difference between average temperature in decade 2050 and climatology (average temperature between 1971 and 2000), under BAU (RCP 8.5).

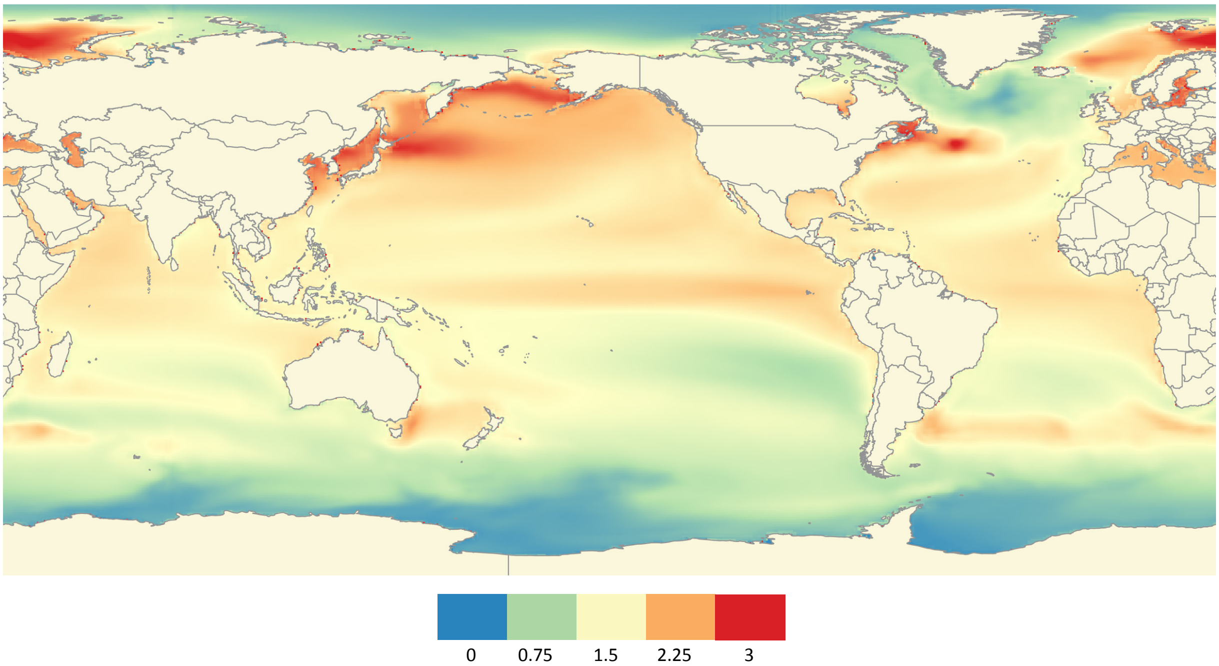
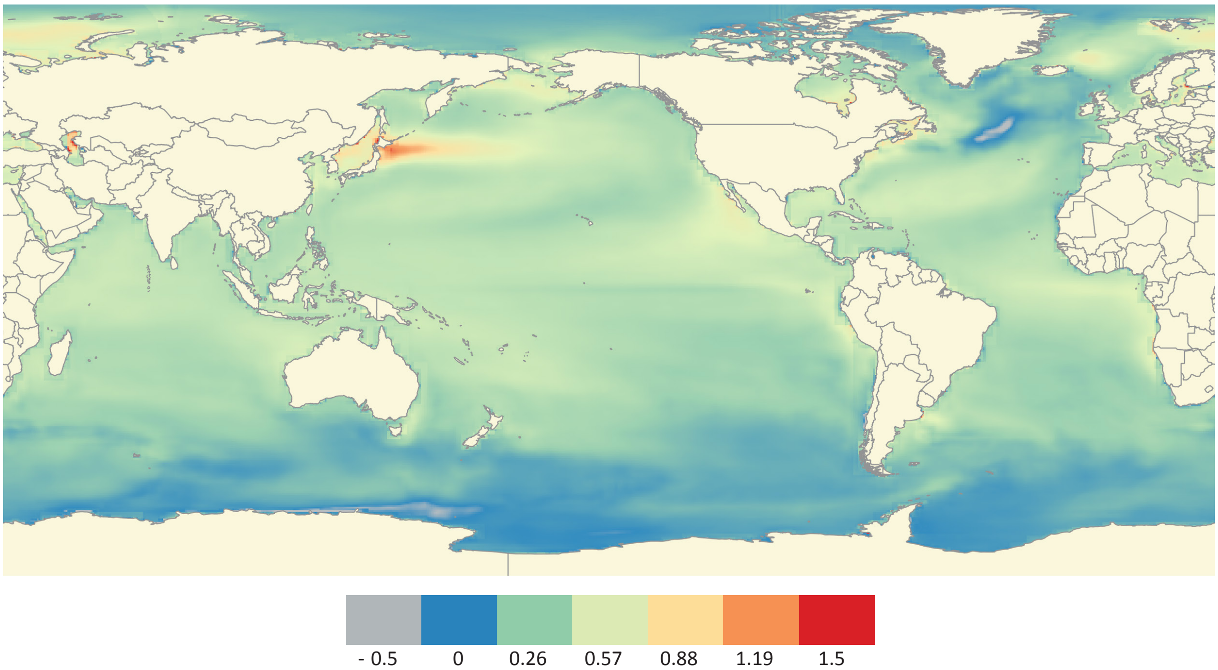


Figure 4.17. Comparison of SST increase under BAU (RCP 8.5) and MM (RCP 4.5) as a temperature difference, for decade 2050 compared to the climatology.



Warm Pools

The tropical Indo-Pacific Warm Pool (IPWP) possesses the warmest open ocean SST and the largest precipitation on the planet. The large scale heating over the tropical warm pools play a critical role in the global redistribution of heat, moisture, and momentum, resulting in a balancing of the global heat budget (for example Webster 1994; Lin and Johnson 1996). A considerable number of studies have shown the relations between the Western Pacific Warm Pool (WPWP) year to year variation in temperature and size and the El Niño Southern Oscillation (ENSO) and to global climate changes (for example Xiao-Hai et al. 1992; Wang and Mehta, 2008; Xie et al. 2014, Xiao-Han et al. 1992). The surface temperature time-projection projects the potential growth and warmth of the IPWP between MM and BAU. An important change in the size and temperature of the warm pool will result in atmospheric changes at regional and global scales, change in global circulation, and probably an impact on ecosystems. These consequences are not analysed in this Chapter, the presented material being an indicator of change available for further studies.

The IPWP is shallow, consistently warm water. Within scientific literature, several values of the iso-contour of temperatures delineating the IPWP and WPWP were found. This study uses 28°C, justified by Wyrtki (1989). However, the generated data contains a projection of the inner temperature, allowing comparison to more restrictive studies using 29°C as the definition of the Warm Pool. The colour ranges in the illustrations allow visualising areas corresponding to different definitions. Moreover, the whole globe was used to identify areas to which the same definition applies: further illustrations show that the current area identified as the IPWP is expected to expand across the Pacific, and that a similar area is found at the same latitude in the Atlantic.

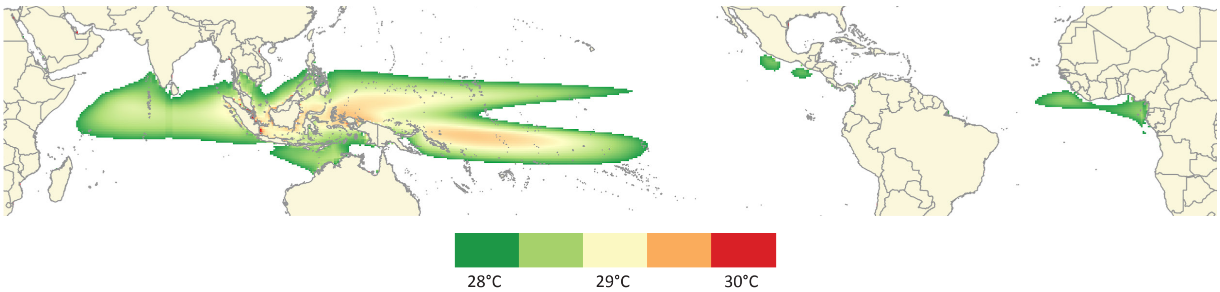
The IPWP is the portion of the ocean where the annual average temperature remains above 28°C. The time projection of the IPWP in terms of occupied surface and temperature was estimated on the CMIP5 ensemble mean of TOS.

Historical outputs of models, corresponding to models run before 2006, without any radiative forcing (and therefore irrespective of any RCP), were used to generate a climatology. For the period 1971 to 2000, a monthly average of the models SST was computed. The definition of the Warm Pool was applied to this climatological year. The resulting "climatological Warm Pool" is a reference state for assessing the Warm Pool warming.

The SST climatology based on models (1971 to 2000) shows an IPWP with temperatures mostly between 28°C and 28.5°C. There is a gradient of increasing temperatures when moving from the outside delineation toward its "core", with a peak of temperatures around 29.5°C in the Western Pacific part of the IPWP, near the Philippines and Papua New Guinea (**Figure 4.18**). Some parts of the Eastern Pacific, close to Mexico and the Eastern Atlantic, along Gulf of Guinea, also show waters with a temperature signature corresponding to our definition of a Warm Pool 28°C). The same figure shows that the outline corresponding to a temperature superior or equal to 28.5°C, sometimes found in the literature, is very close to the 28°C definition.

The current delineation of the Warm Pool is expected to increase in surface, under any scenario, as shown in the next figures. For this reason, a concept of a "Global" Warm Pool is introduced in this chapter, corresponding to any water matching the IPWP definition; this term was used rather than "Tropical Warm Pool" which is often used in the literature in lieu of IPWP. The rationale is not ecological, but rather corresponds to the fact that the permanently warm waters are expect to grow in area and eventually represent a continuous region around this equator. Further in this text, the distinction is made between the "Global" Warm Pool, corresponding to any water matching the definition, and the IPWP corresponding to the waters in the Indian Ocean and Western Pacific.

Figure 4.18. Spatial extension and temperature of the IPWP, according to a historical run of models (no radiative forcing), for the period 1971 to 2000.

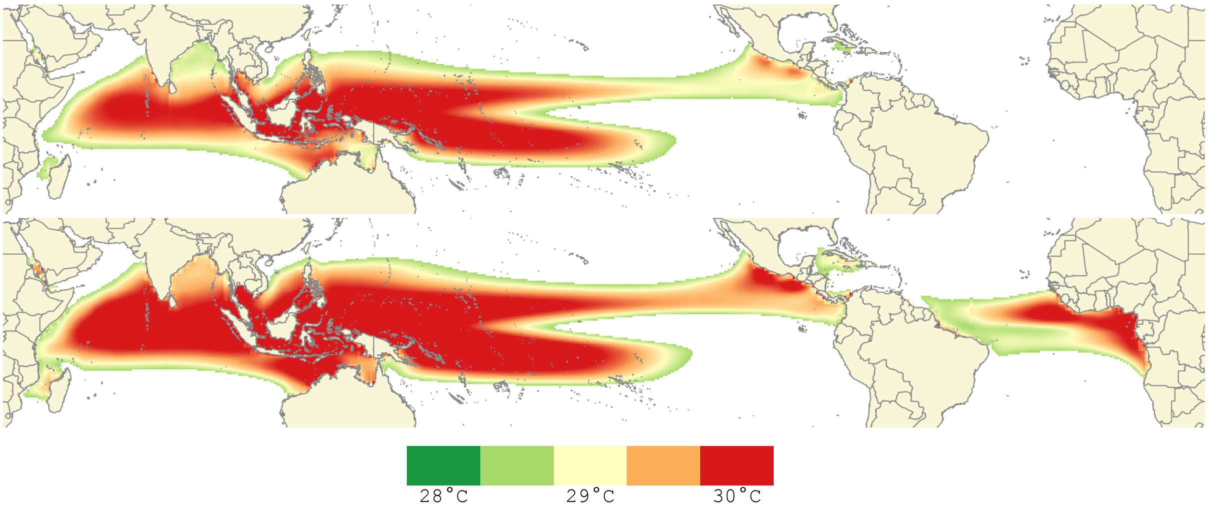


The projection of the Global Warm Pool to the end of decade 2050 (year 2059) is framed by scenarios MM and BAU. Both scenarios show a spatial extension of the IPWP to the Eastern African coast, in the Bay of Bengal and across the Pacific Ocean toward Central America. In addition, the overall temperature significantly increases, above 29.5°C for the largest part of the IPWP.

A similar pattern of expansion and warming is shared between MM and BAU, the first being more pronounced. BAU features the development of a large Warm Pool across the Atlantic Ocean, connecting the African Western Coast to Brazil.

The SST temperature increase forecast by the models under both scenarios allows the growth of the IPWP as well as the Global Warm Pool (**Figure 4.20**). To compare both scenarios, the areas were expressed as a fraction to the model estimate in 2010 (shown as dots for the IPWP in **Figure 4.20**, starting at one in 2010, only the regression lines for BAU has a bias below one). The climatology was not used as a reference to ensure extracting the progression, as it is a 30 year based estimate, while each point on **Figure 4.20** is an annual estimate.

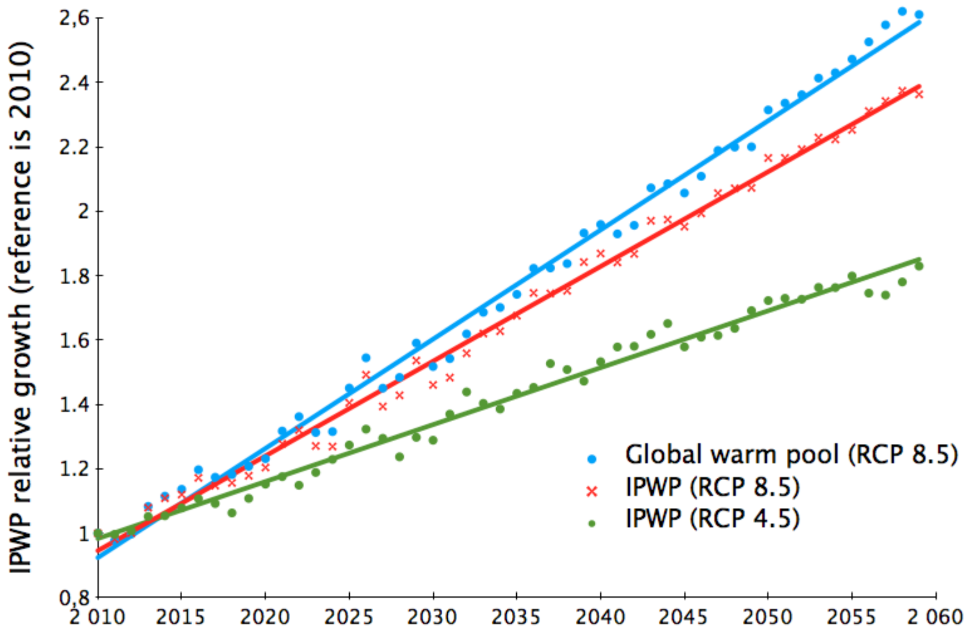
Figure 4.19. IPWP projection for year 2059, under MM (RCP 4., top) and BAU (RCP 8.5, bottom).



The time-series of the forecast IPWP shows an almost linear progression of the area of the IPWP (**Figure 4.20**) under both scenarios. The model outputs show a strong linear progression of the area with only inter-annual fluctuations. The Global Warm Pool (shown only for BAU) also grows linearly and follows a similar trend.

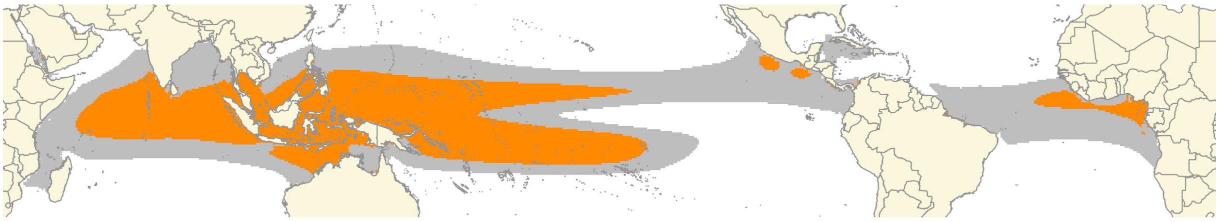
The relative surface increase is about 3 per cent per year for the Indo-Pacific area, under BAU. According to MM, the annual increase of the IPWP would be about 1.8 per cent a year. In spite of limited emissions in MM, the projected surface increases continuously and linearly, only slowing the process of the expansion by about two decades with respect to BAU.

Figure 4.20. IPWP relative area (area/area in 2010), for BAU (RCP 8.5) and MM (RCP 4.5). The continuous lines show linear fits.



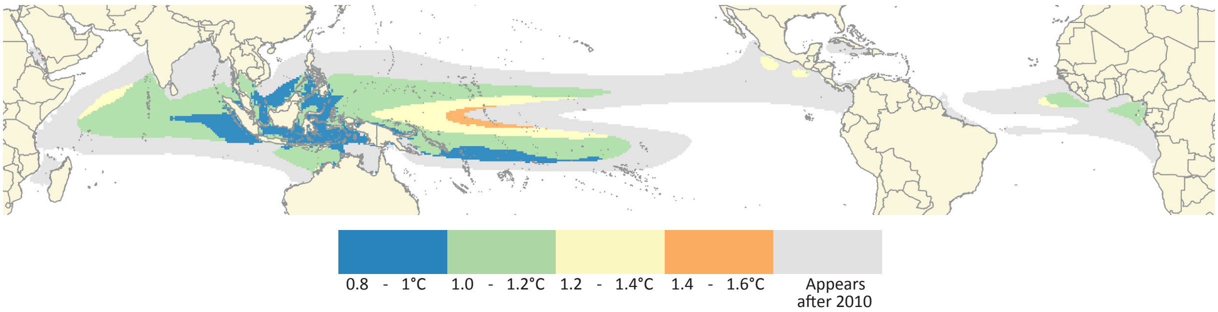
Areas possibly affected by the expansion of the Warm Pool at global scale, according to BAU, between 2010 and 2059 are shown in **Figure 4.21**. The Warm Pool expands to Northern Hemisphere latitudes, towards the Gulf of Bengal and to Taiwan in the Pacific. It also expands to the West to the Eastern coasts of Africa (from Somalia to Tanzania). Towards the South, it expands to the Gulf of Carpentaria. It also significantly expands into the Pacific connecting to Central America, along the northern path of the ENSO. The simulation also shows a significant expansion in the Atlantic, almost connecting the Gulf of Guinea to South America.

Figure 4.21. IPWP expansion between climatology (orange area) and 2059 (gray area), RCP 8.5.



In **Figure 4.22**, the IPWP temperature increases by at least 0.8°C in its core area between 2010 and 2050. The temperature increase is more important on the edges of the IPWP, reaching 1.6°C. The gray area corresponds to waters that become part of the IPWP once it expands. As the gray area does not match the warm pool definition at the initial date of 2010, no temperature increase can be defined consistently with the rest of the initial warm pool. The highest increase in temperature for the warm pool (as delineated in the 2010 initial period) is found across the coolest areas (**Figure 4.19**), whereas the warmest areas (closest to the central region of the Warm Pool, around Indonesia and Malaysia) gain less temperature.

Figure 4.22. Temperature increase of the initial warm pool area, for BAU (RCP 8.5).



Degree Heating Month and Thermal stress

In tropical regions, species are adapted to stable temperatures, in contrast with higher latitudes where seasonality is more pronounced. The increase in temperature is not expected to be constant and smooth, but rather to show peaks of temperature within the year, which may result in a stress for the tropical species accustomed to more stable conditions. Chapters 5.4 and 5.5 investigate in details the impact of ocean warming and acidification on the habitat and biological functions of corals and pteropods.

A risk indicator was used to represent the possible future impact on those species; combining temperature increase and acidification (see Chapter 4.4 for projections of acidification). The thermal stress indicator corresponds to the accumulation, in a four-month time-frame, of degrees Celsius above the local "normal" temperature, which is a good proxy of the stress on corals (Donner 2009). This indicator, named DHM for "Degree Heating Month", shows a significant level of alert if the accumulated excess of temperature goes beyond 2 °C in 4 months, known as an "Alert Level 2", and representing a potentially harmful situation for corals in hot water. The potential risk was expressed by the frequency of exposure (in a decade) to an Alert Level 2. Chapter 5.4 analyses the impact of heat stress and ocean acidification on coral reefs. The concept of a 2°C Alert as an indicator of risk makes sense for species living in warm equatorial waters were the seasonal amplitude is not expected to be as important as it is in temperate regions. Outside of warm waters coral reef areas, this indicator gives a sense of the repetition of warm peaks in a decade.

The projection of DHM Alert Level 2, under BAU, for decade 2050 shows that an annual Alert Level 2 affects most seas. A value of 10, shown in red in **Figure 4.23**, means that this alert occurred every year in the decade. Some regions may be free of any Alert Level 2, such as a fraction of the North Atlantic, the Southern Arctic Ocean, and some areas in the South Pacific (where a large fraction of the ocean also shows low frequency of occurrences).

For the same decade, and using MM, the occurrence of thermal stress Level 2 appears to be permanent (with ten annual occurrences in the decade). However, at a global scale, many regions would be spared which such a scenario. The decadal evolution, from 2020 to 2050 under MM is outlined in the Notes on Methods 4.2.3.

The two scenarios suggest a range of climate response where a large fraction of the ocean is exposed to an Alert Level 2 every year, suggesting that Alert Level 2 is *likely* to occur in those regions of the globe.

Figure 4.23. Frequency of DHM Level 2 Alert, for decade 2050 (2050-2059), under BAU (RCP 8.5).

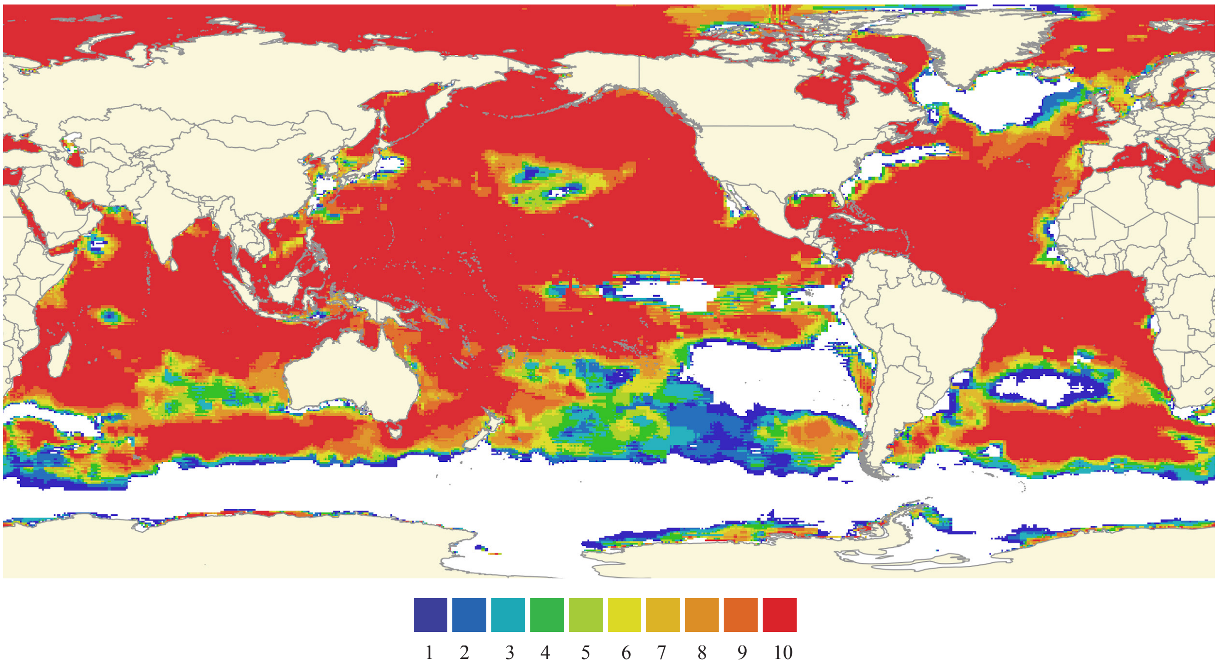
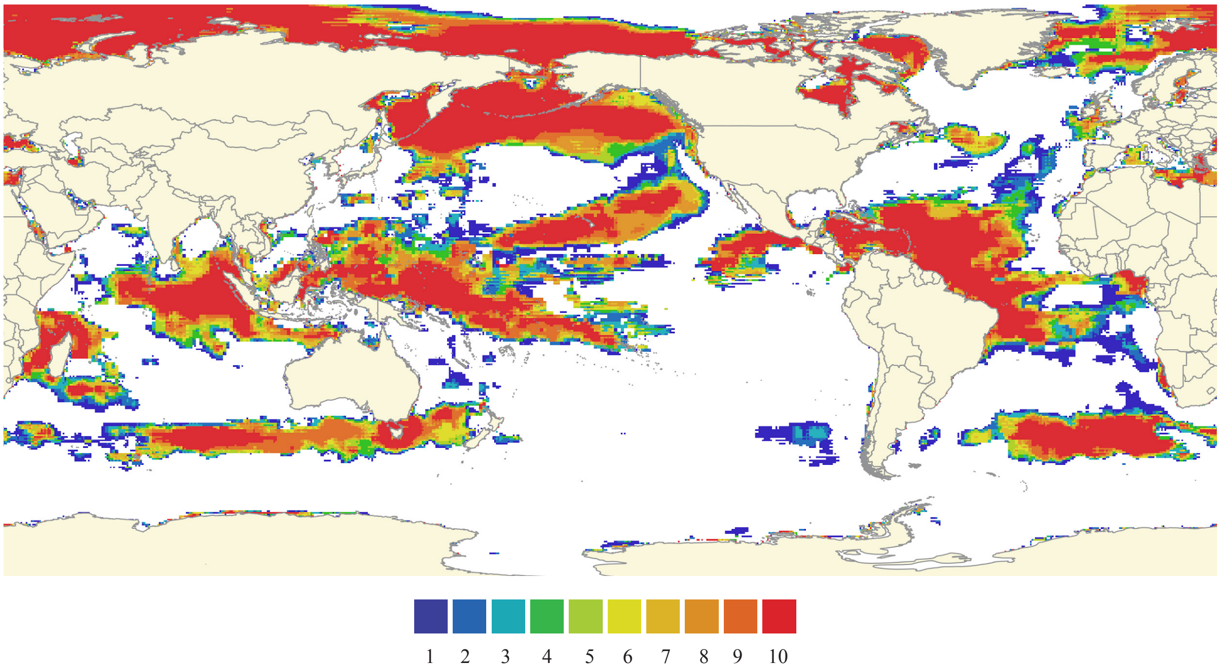


Figure 4.24. Frequency of DHM Level 2 Alert, for decade 2050 (2050-2059), under MM (RCP 4.5).



Polar Sea Ice

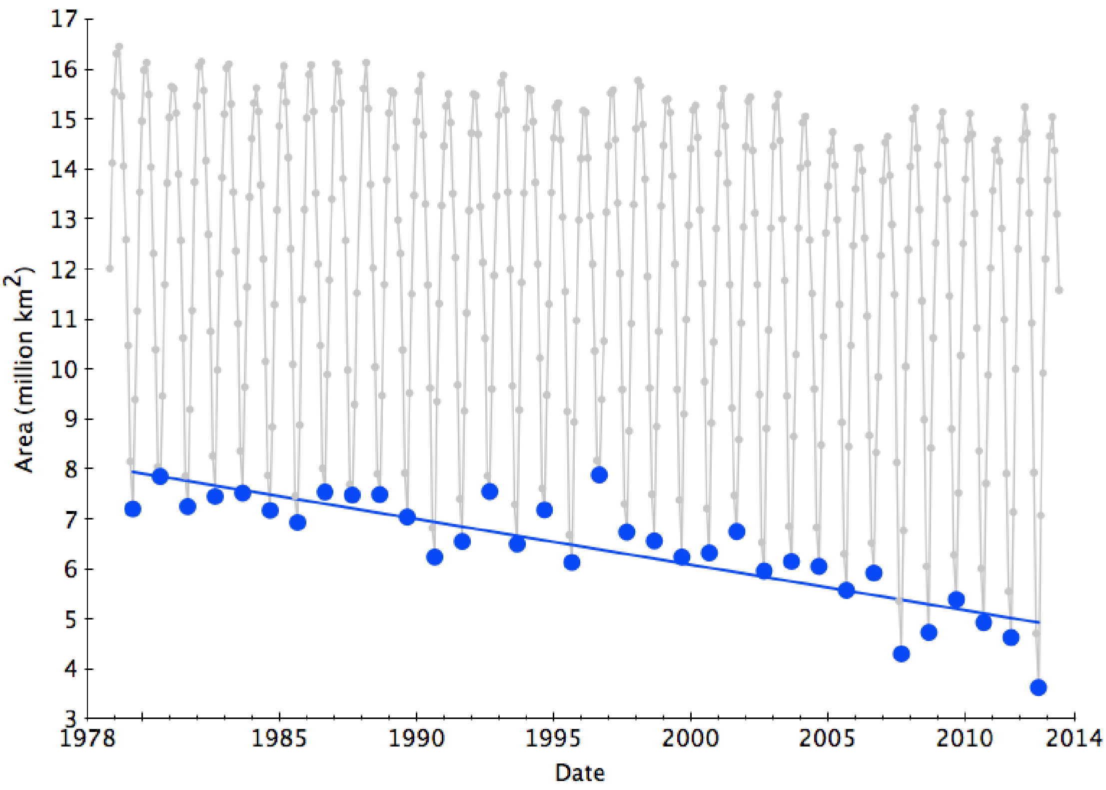
The Polar Regions are often perceived as cold, desolate and virtually devoid of all animals and plants. However, this is not the case. Every summer, a short period of sunshine (three months only) allows an explosion of life in surface waters. Under the ice, tiny algae (diatoms) capture the little light available to survive. Zooplankton also proliferates here and is an essential link in the Arctic food chain (see Chapter 5.3), which in turn feeds small invertebrates, small carnivores and the upper stages of the ecosystem web including fish, birds, whales and other marine mammals.

Sea ice also plays an important role as a barrier, forbidding access to ships during the whole winter. From a physical point of view, Polar sea ice cover reflects solar energy to space, whilst insulating the ocean from heat loss. Regional climate changes affect the sea ice characteristics and these changes can feed back on the climate system, both regionally and globally.

Sea ice cover in the Polar Regions is thus a visible signature of seasonal warming, as it expands with steeply decreasing temperatures in winter and decreases with the warmer air temperature of summer. The total extent of sea ice at both Poles is a major indicator of the effect of the global warming. However, the impacts from climate change and threat of human activities on the two Poles are not equal. International treaties protect the Antarctic, limiting human activities and settlement, whereas the Arctic is exposed to a larger human footprint. Populations (mostly in developed countries) living in Boreal regions exert a significantly higher pressure due to their close proximity to the Arctic. Decreasing Arctic sea ice cover may increase access to this Polar Region and in consequence, increasing human activities that potentially degrade the so far pristine waters. This area also lacks the international protection laws adopted for the Antarctic (see Chapter 3). For these reasons, this Chapter emphasises the Arctic more than the Antarctic.

Arctic sea ice cover varies seasonally, between 6×10^{6} km^2 (2.3×10^{6} square miles) in the summer and 15×10^{6} km^2 (5.8×10^{6} square miles) in the winter (Comiso and Nishio, 2008; Cavalieri and Parkinson, 2012; Meier et al. 2012). Mainly, the summer ice cover is confined to the Arctic Ocean basin and the Canadian Arctic Archipelago, while winter sea ice reaches south as far as 44°N, into the peripheral seas. In September, at the end of Northern Hemisphere summer, the Arctic sea ice cover consists of the ice that survived the melt period. **Figure 4.25** shows that the Arctic sea ice available at summer's end has been decreasing since 1979. The inter-annual variability is largely determined by the extent of the ice cover in the peripheral seas in winter and by the ice cover that survives the summer melt in the Arctic Basin.

Figure 4.25. Arctic sea ice area estimates from satellite imagery, by NSIDC. The sea ice grows and shrinks each year, the minimum in September. The trend of the decrease of the area observed in September is clearly negative (about 10×10^3 km² loss per year.

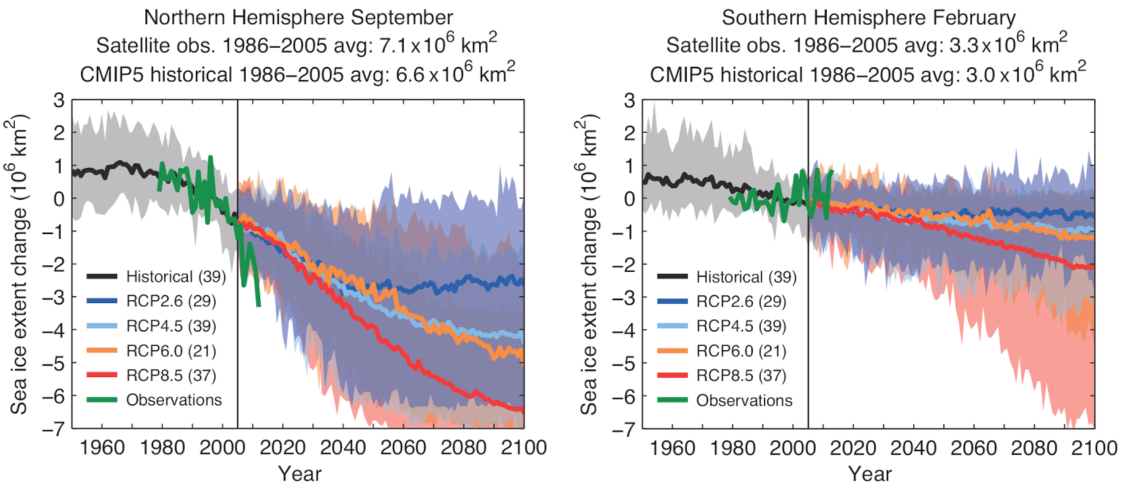


The average rate of ice loss from the Antarctic ice sheet has *likely* increased from 30 [–37 to 97] giga tons per year over the period 1992–2001 to 147 [72 to 221] giga tons per year over the period 2002 to 2011. There is *very high confidence* that these losses are mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica (IPCC, 2014).

The annual mean Arctic sea ice extent decreased over the period 1979 to 2012 with a rate that was *very likely* in the range 3.5 to 4.1 per cent per decade (range of 0.45×10^6 to 0.51×10^6 km² per decade), and *very likely* in the range 9.4 to 13.6 per cent per decade (range of 0.73×10^6 to 1.07×10^6 km² per decade) for the summer sea ice minimum (perennial sea ice). The average decrease in decadal mean extent of Arctic sea ice has been most rapid in summer (*high confidence*); the spatial extent has decreased in every season, and in every successive decade since 1979 (*high* confidence, IPCC, 2014).

IPCC WGI reported the projection of the sea ice extent using CMIP5 models the closest to the climatological mean state and 1979 to 2012 trend of the Arctic sea ice. The future sea ice extent under BAU (respectively MM) was estimated using 5 models (respectively 3). Both scenarios frame the future possible sea ice extent (see Figure 4-26). BAU predicts that the Arctic could be found in ice free condition after 2050, with less than 1×10^6 km² of sea ice in 5 consecutive years. MM also predicts ice free conditions beyond 2050, but with a larger uncertainty making the ice free condition not certain under this scenario. MM indicates that lowering the radiative forcing down to 2.6 W.m² could significantly hamper the process and allow a stabilisation of the sea ice extent around 2.5×10^6 km^2 by 2050 without significant loss beyond. However, these simulations show large uncertainty.

Figure 4.26. Changes in sea ice extent as simulated by CMIP5 models over the second half of the 20th century and the whole 21st century under RCP2.6, RCP4.5 (MM), RCP6.0 and RCP8.5 (BAU) for (left) Northern Hemisphere September, (right) Southern Hemisphere February. The solid curves show the multi-model means and the shading denotes the 5 to 95 per cent range of the ensemble. The vertical line marks the end of CMIP5 historical climate change simulations. One ensemble member per model was taken into account in the analysis. Sea ice extent was defined as the total ocean area where sea ice concentration exceeds 15 per cent and was calculated on the original model grids. Changes are relative to the reference period 1986–2005. The number of models available for each RCP was given in the legend. Also plotted (solid green curves) were the satellite data of Comiso and Nishio (2008, updated 2012) over 1979–2012. Source: IPCC AR5.



There is *medium confidence* from reconstructions that over the past three decades, Arctic summer sea ice retreat was unprecedented and SSTs were anomalously high in at least the last 1,450 years (IPCC, 2014).

It is *very likely* that the annual mean Antarctic sea ice extent increased at a rate in the range of 1.2 per cent to 1.8 per cent per decade (range of 0.13×10^6 to 0.20×10^6 km^2 per decade) between 1979 and 2012. There is *high confidence* that there are strong regional differences in this annual rate, with extent increasing in some regions and decreasing in others (IPCC, 2014). Considering the low rate of growth observed on the last decades and the models forecast showing some decrease (though less drastic than for the Arctic), the future evolution of the Antarctic sea ice is difficult to state with certainty.

Discussion and conclusions

The SST projections show that the ocean will become warmer by 2050, for both MM and BAU scenarios, with a difference smaller than 1°C in most regions. The Northern Hemisphere latitudes are expected to experience the most warming, accumulating up to 3°C under BAU.

This generalised increase in temperature is *likely* to affect the Indo-Pacific Warm Pool, causing it to become significantly larger and warmer. Such an evolution may influence the global atmospheric circulation, by increasing the thermal forcing.

the extent to which the projected temperature exceeds that observed between 1971 and 2000 is an indicator of the thermal stress to which living organisms may be exposed. This indicator shows that by 2050, most of the ocean should warm by more than 2°C in 4 months, above the climatology, every year, which is threatening both coral reefs (Chapter 5.4) and species such as pteropods (Chapter 5.5).

The mean Arctic sea ice extent decreased over the period 1979 to 2012 at a yearly rate of about 3.5 to 4.1 per cent per decade (IPCC, 2014). The Northern Hemisphere summer sea ice, the perennial ice remaining at the end of the summer melting process, decreased by about 9.4 to 13.6 per cent per decade for the same period (IPCC, 2014). According to the projections, the extent of the summer sea ice will continue decreasing to 2050 and beyond.

4.2.3 Notes on Methods

Processing Sea Surface Temperatures (SST) projections ensemble mean

The CMIP5 Sea Surface Temperatures (SST) model projections correspond to the coupled ocean-atmosphere general circulation model (OAGCM) outputs named Temperatures of Ocean Surface (TOS) with a monthly time-step (12 values per year, from 2006 to 2100), for MM and BAU (Combal and Caumont, 2016, in press). The computed data are available for download (Combal 2014a).

For a given RCP, some models can have different sets of input parameters (called input ensemble), numbered r1i1p1, r1i1p2, etc, corresponding to different input settings, resulting in an output for each rXiYpZ input. Variable 'TOS' is provided by 86 combinations of models and input ensembles (see below).

The different outputs of a single model were first averaged to compute an ensemble mean with equal weight for each model. The resulting averaged models outputs, 1 average per model, are then re-gridded to a common grid, defined as a regular grid, with a spatial resolution of ½ ° in latitude per ½ ° in longitude, from 0° to 360° in longitude, and -85° to 85° in latitude. Because of the difference in the spatial gridding, and difference in the land mass representation, some grid points were not represented in all models. Then, the re-gridded averages were averaged all together with the same weight (Oldenborgh et al. 2013).

The averaging operations are grid-cell and time independent, which means that the averaging operator is not applied along the space and time dimensions, only in-between the different models values for the same place and time.

Table 1: List of models providing "TOS" variables, for ocean SST projections, analysis, and the different input ensembles used:

ACCESS1-0	r1i1p1	FIO-ESM	r1i1p1 r2i1p1 r3i1p1
ACCESS1-3	r1i1p1	GFDL-CM3	r1i1p1
bcc-csm1-1	r1i1p1	GFDL-ESM2G	r1i1p1
bcc-csm1-1-m	r1i1p1	GFDL-ESM2M	r1i1p1
BNU-ESM	r1i1p1	GISS-E2-H	r1i1p1 r1i1p2 r1i1p3
CanESM2	r1i1p1 r2i1p1 r3i1p1 r4i1p1 r5i1p1	GISS-E2-R	r1i1p1 r1i1p2 r1i1p3
CCSM4	r1i1p1 r2i1p1 r3i1p1 r4i1p1 r5i1p1 r6i1p1	HadGEM2-AO	r1i1p1
CESM1-BGC	r1i1p1	HadGEM2-CC	r1i1p1 r2i1p1 r3i1p1
CESM1-CAM5	r1i1p1 r2i1p1 r3i1p1	HadGEM2-ES	r1i1p1 r2i1p1 r3i1p1 r4i1p1
CESM1-WACCM	r2i1p1 r3i1p1 r4i1p1	inmcm4	r1i1p1
CMCC-CESM	r1i1p1	IPSL-CM5A-LR	r1i1p1 r2i1p1 r3i1p1
CMCC-CM	r1i1p1	IPSL-CM5A-MR	r1i1p1 r2i1p1 r3i1p1
CMCC-CMS	r1i1p1	IPSL-CM5B-LR	r1i1p1
CNRM-CM5	r10i1p1 r1i1p1 r2i1p1 r4i1p1 r6i1p1	MIROC5	r1i1p1
CSIRO-Mk3-6-0	r10i1p1 r1i1p1 r2i1p1 r3i1p1 r4i1p1 r5i1p1 r6i1p1 r7i1p1 r8i1p1 r9i1p1	MPI-ESM-LR	r1i1p1
EC-EARTH	r10i1p1 r11i1p1 r12i1p1 r14i1p1 r1i1p1 r2i1p1 r3i1p1 r6i1p1 r7i1p1 r8i1p1 r9i1p1	MPI-ESM-MR	r1i1p1
		MRI-CGCM3	r1i1p1 r2i1p1 r3i1p1 r4i1p1
		NorESM1-M	r1i1p1
		NorESM1-ME	r1i1p1

Computing Degree Heating Month (DHM)

The DHM computation follows the definition in Donner (2007), although different inputs were used. The SST climatology used is the so-called Reynolds data set (climatology for the period 1971-2000), and the model time projections of SST was derived from CMIP5 ensemble means, as described in Section 2.

The SST climatology $SST^{R}(t)$, commonly known as "Reynolds climatology", is obtained from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (Data from Xue, NOAA). The analysis uses in situ and satellite SST. The climatology spans the period 1971 to 2000, with a time resolution of 1 month and a spatial resolution of 1°x1° (Reynolds et al. 2002). In the notation $SST^{R}(t)$, t is a month in the range 01 to 12 (from January to December).

The time projection of the Models $\underline{TOS}(t)$ correspond to the CMIP5 models ensembles, for scenarios RCP 8.5 and RCP 4.5. Datasets are available for download (Combal 2014b, Combal2014c).

The ensemble means of models' projections were adjusted to the climatology in order to ensure that both the model outputs and the climatology were consistent for the period 1971-2000. The "TOS climatology" of the model ensemble mean $\underline{TOS}(t)^{clim}$ for the period 1971-2000 were computed with CMIP5 "historical values", which do not depend on the forcing scenarios RCPs (Taylor et al. 2009), as they start in 2006.

The monthly difference $\Delta(t)$ between the model ensemble mean projections and the model climatology, $\Delta(t) = \underline{TOS}(t) - \underline{TOS}(t)^{clim}$, corresponds to the variation of the ensemble means projections around $\underline{TOS}(t)^{clim}$. This variation $\Delta(t)$ was added to the Reynolds climatology to obtain corrected model projections: $\underline{TOS}(t)^{corr} = SST^{R}(t) + \Delta(t)$.

Cauliflower coral pocillopora meandrina french frigate shoals

DHM represents the accumulation of temperature beyond the maximum observed in the climatology for this point maximized with the climatology standard deviation observed at the date of the climatology maximum. Only positive differences are accumulated.

A yearly DHM corresponds to the maximum 4-month-DHM observed in the year.

$$DHM = \sum_{i=t}^{t-3} \left(\underline{SST}(i)^{corr} - (SST^{R}_{max}(t) + \sigma_{max})\right) > 0$$

The DHM corresponds to a Risk Level 2 if its value is equal or above 2°C. The “Level 2 Frequency” corresponds to the number of occurrences of yearly Level 2 in ten years.

Reynolds climatology and the CMIP5 ensemble means do not represent the coastline in the same way. The ensemble means have a finer spatial resolution, and the Reynolds dataset shows values over the land for its root mean square (the dataset was spatially smoothed, ignoring discontinuity imposed by land mass). As a result, some locations close to small islands or some irregular coast, existing in both Reynolds and the ensemble means, may ignore the land mass in one case and not the other. As a result, the same pixel may show dramatically different time-series, resulting in an isolated erroneous high frequency of DHM Level 2.

In a first step, these isolated pixels were detected from an image where the DHM Frequency Level 2 was null or minimal (typically RCP 4.5, 2020). Once their locations were found, their values were replaced in all the other dates and scenarios with the most frequent values in their immediate surrounding (in a 3x3 window).

Decadal evolution of thermal stress under scenario RCP 4.5

Under scenario RCP 4.5, a Frequency Level 2 was not visible before 2040 (Figure 4-27 and Figure 4---28). Within decade 2040, some impact is visible, with a maximum frequency of eight years in the decade. In decade 2050 (Figure 4-29), the impacted areas expanded slightly, and the frequency reaches its maximal value of 10 years per decade.

Figure 4.27. Frequency (number of years of occurrence per decade) of DHM Alert Level 2, 2030 (2030-2039), MM (RCP 4.5).

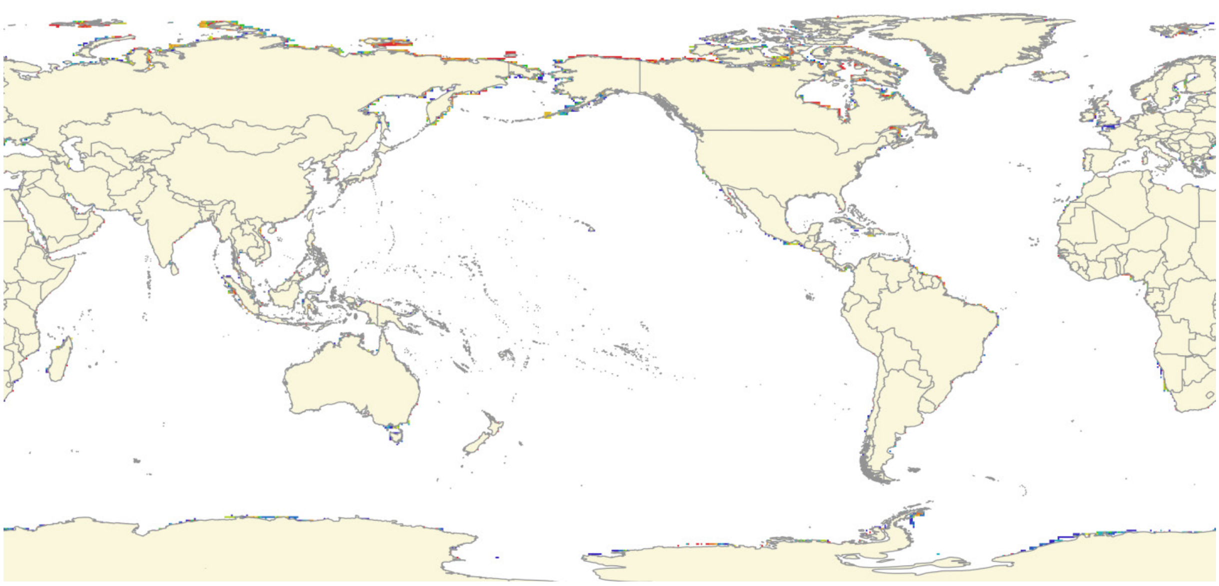


Figure 4.28. Frequency (number of years of occurrence per decade) of DHM Alert Level 2, 2040 (2040-2049), MM (RCP 4.5).

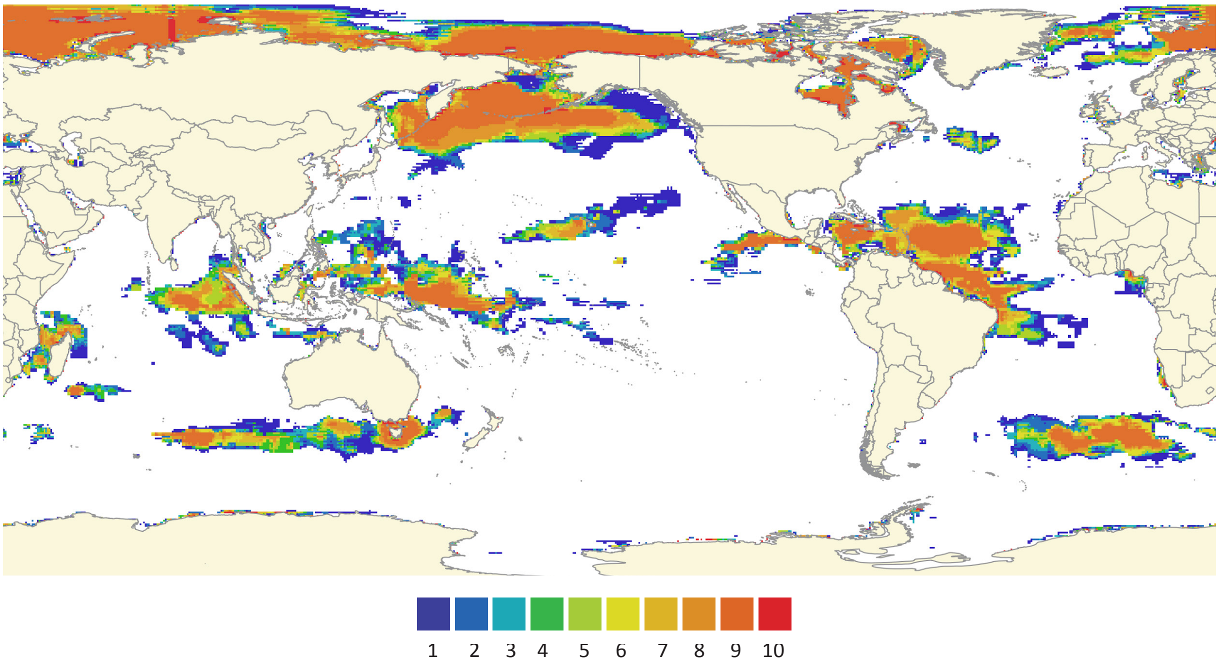
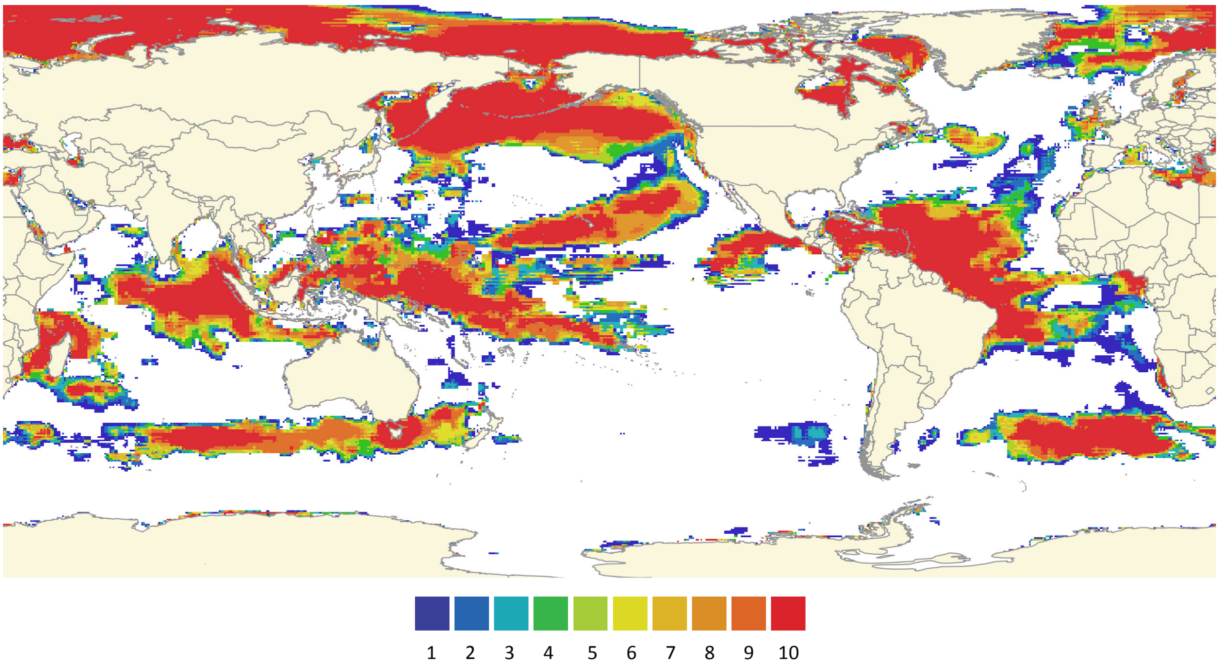


Figure 4.29. Frequency (number of years of occurrence per decade) of DHM Alert Level 2, 2050 (2050-2059), MM (RCP 4.5).



Decadal evolution of thermal stress under scenario BAU (RCP 8.5)

The evolution of the threat (demonstrated by the images below), comprises the projected frequency (number of yearly occurrence in a decade) of DHM Alert Level 2 for 2020 (Figure 4-30), 2030 (Figure 4-31), 2040 (Figure 4-32) and 2050 (Figure 4-33) under scenario BAU.

In the start of the time-series, a threat Level 2 occurs mostly in Northern Hemisphere latitudes, with some exception south of Tasmania, in the Pacific Ocean (East of Papua New Guinea and East of the Caribbean Sea). These initial locations with DHM Level 2 and a frequency between one to four per decade, significantly increased in frequency and extent throughout 2030s and 2040s. Decade 2050 shows that Alert Level 2 would occur each year in the decade, affecting virtually all seas except the Southern Ocean around the Antarctic.

Figure 4.30. Frequency (number of years of occurrence per decade) of DHM Alert Level 2, 2020 (2020-2029), BAU (RCP 8.5).

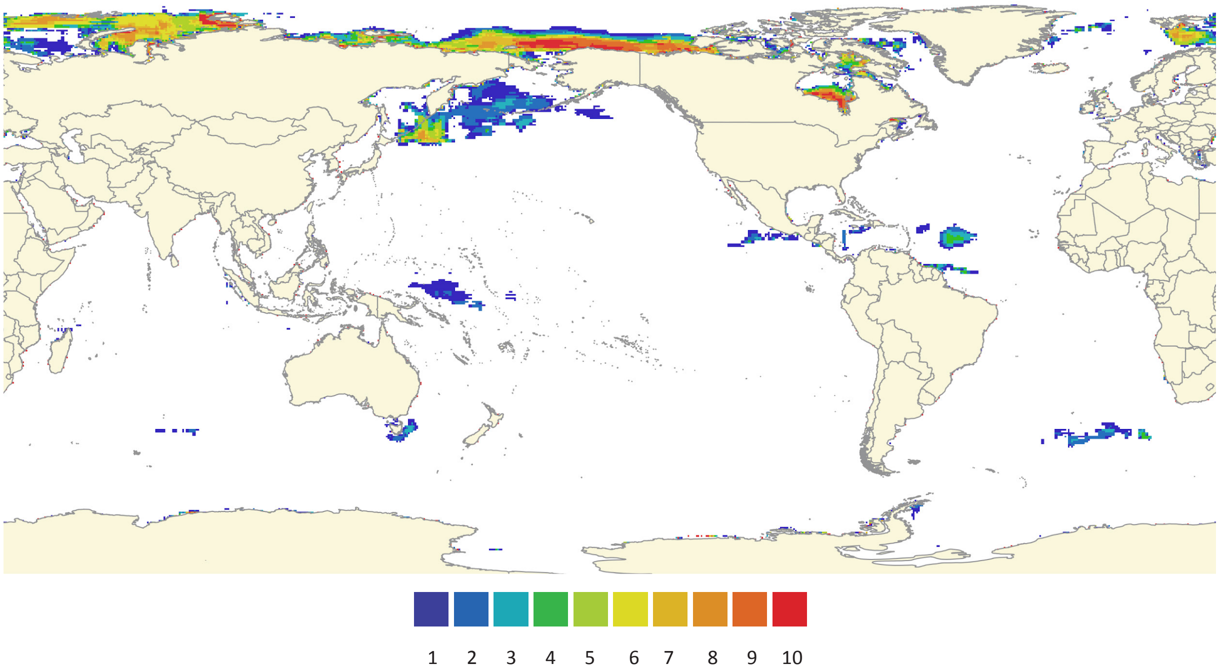


Figure 4.31. Frequency of DHM Alert Level 2, 2030 (2030-2039), BAU (RCP 8.5).

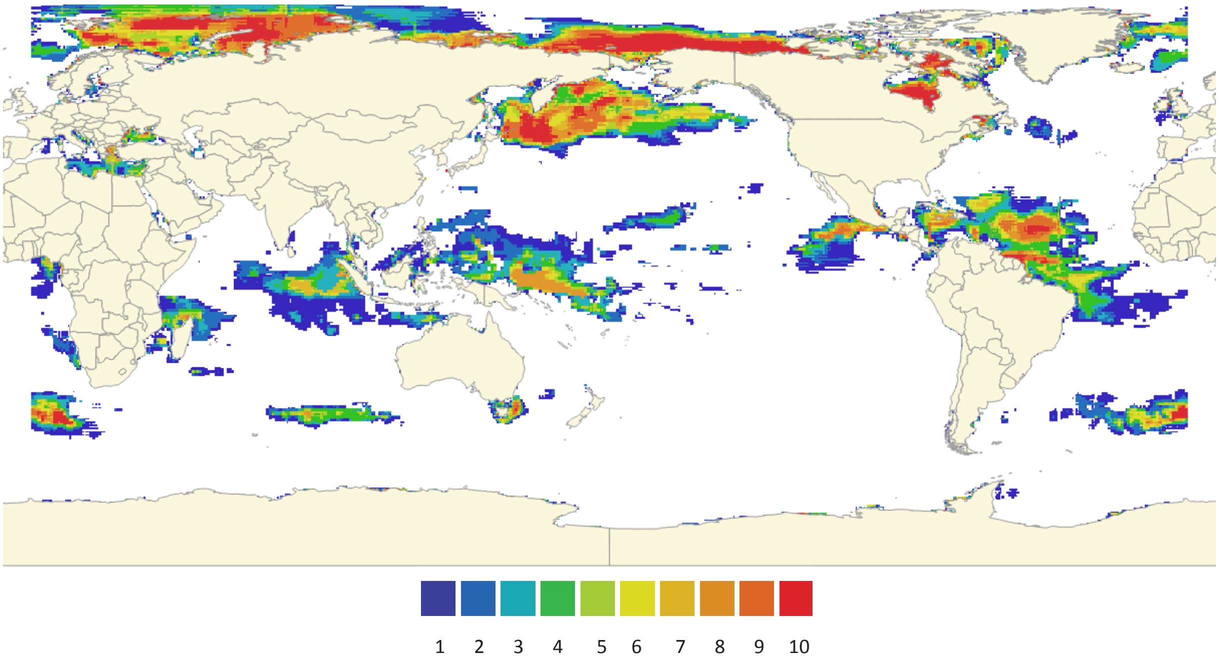


Figure 4.32. Frequency of DHM Alert Level 2, 2040 (2040-2049), BAU (RCP 8.5).

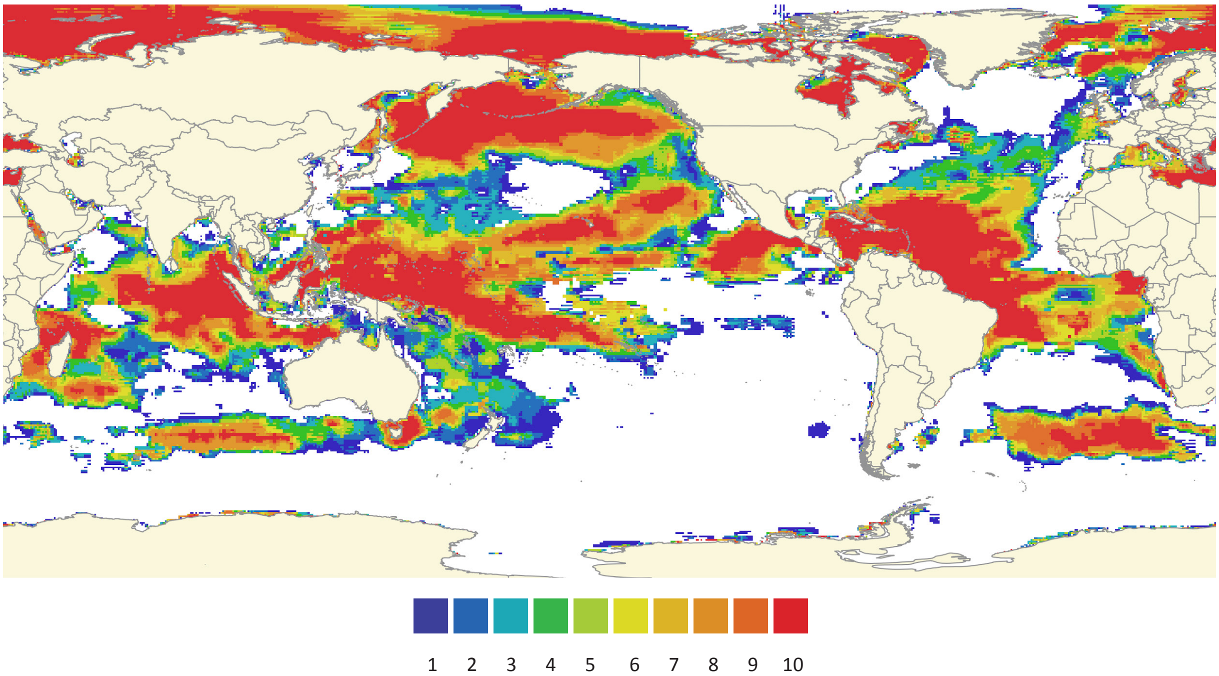
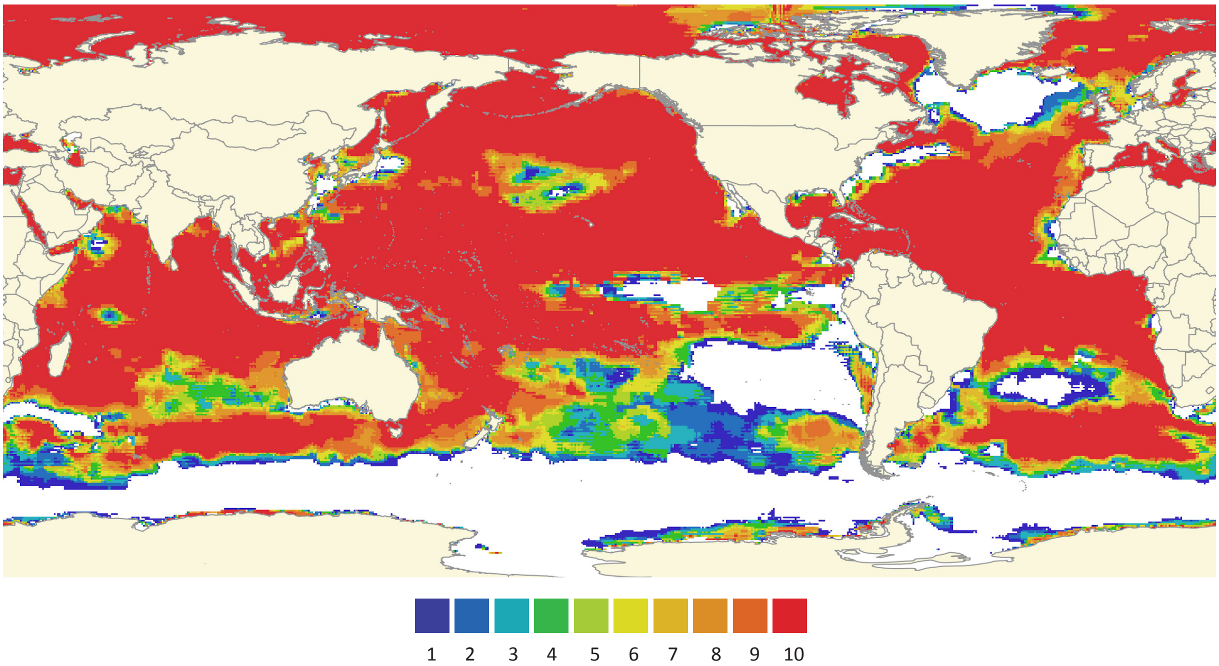
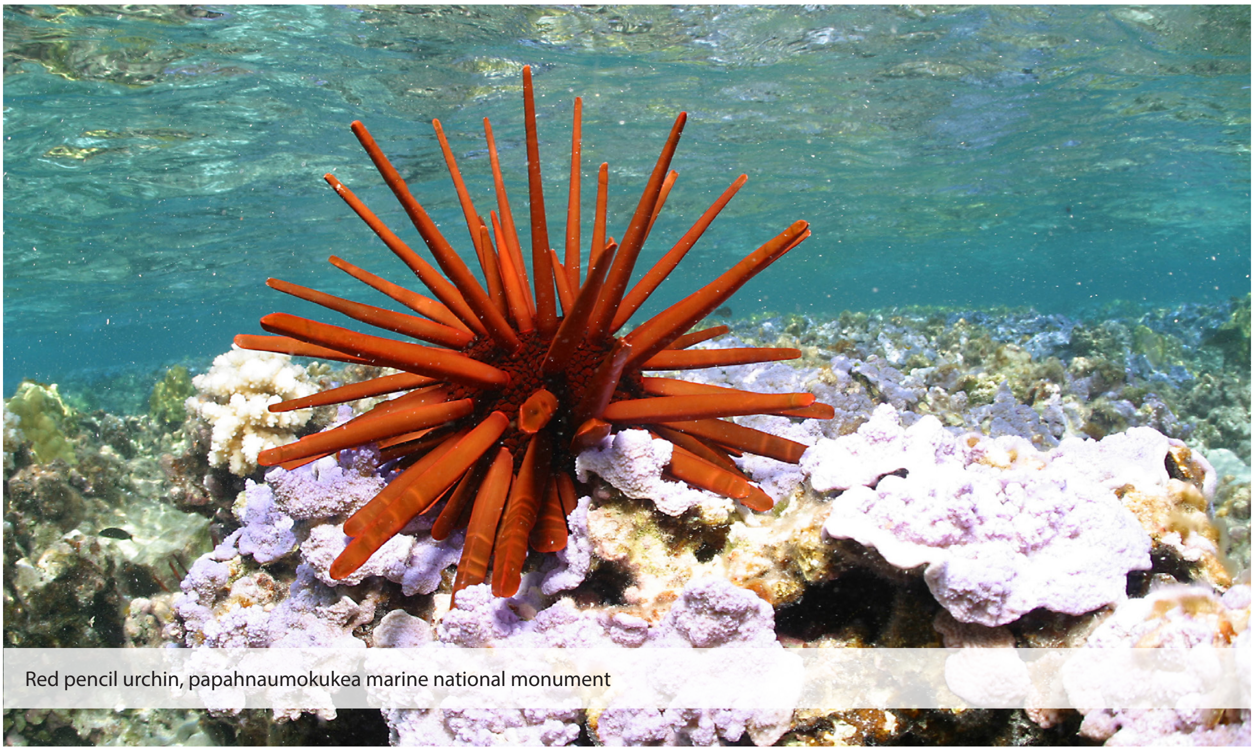


Figure 4.33. Frequency of DHM Alert Level 2, 2050 (2050-2059), BAU (RCP 8.5).





Red pencil urchin, papahnaumokukea marine national monument

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Chapter 4.3 Current and Future Ocean Deoxygenation

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4.3 Current and Future Ocean Deoxygenation

4.3.1 Summary and Key Messages

Ocean ecosystems are increasingly stressed by human-induced changes of their physical, chemical and biological environment. Among these changes deoxygenation is considered as one of the major stressors of open ocean ecosystems. Concentration of dissolved oxygen (O_2) is a major determinant of the distribution and abundance of marine species globally, and therefore deoxygenation is considered as one of the four major human-induced stressors on ocean ecosystems[24]. All these stressors emerged from significant physical, chemical and biological changes that the ocean has rapidly undergone in recent decades in response to the uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere (Doney 2010). Due to ever-increasing CO_2 emissions in the coming decades these changes will amplify with potentially significant consequences for marine organisms and ecosystems (Doney et al. 2012). Here, we use the most recent model simulations performed in the framework of the Coupled Model Intercomparison Project 5 (CMIP 5). The models simulate future climate states and dynamics to assess how ocean deoxygenation may evolve over the course of the 21st century based on four greenhouse-gas concentration trajectories (referred to as Representative Concentration Pathways or RCPs) adopted by the IPCC for its Fifth Assessment Report See Glossary Box 2.

Key Messages

- Concentration of dissolved O_2 is a major determinant of the distribution and abundance of marine species globally and therefore deoxygenation is considered as one of the four major human-induced stressors on ocean ecosystems;
- Open ocean deoxygenation has been recorded in nearly all ocean basins during the second half of the 20th century, with increased temperature responsible for approximately 15 per cent of the observed change and the remaining 85 per cent attributed to reduced O_2 supply due to increased ocean stratification and increased deep-sea microbial respiration;
- In most marine systems hypoxia alters physiological and metabolic rate processes, organism abundance, lifestyles, composition, complexity, diversity, and size structure (Levin 2003; Childress and Siebel 1998) resulting in mortality of benthic fauna, fish kills, habitat loss, and overall physiological stress;
- The biggest threat related to open ocean deoxygenation is that of decline in biodiversity through attrition of intolerant species and elevated dominance, as well as reductions in body size with impacts on organisms within the affected areas as well as in their vertical and horizontal proximities;
- We map and discuss the projected evolution of ocean deoxygenation for the 2030s and 2090s for two RCP scenarios using the latest generation of earth system models collated under CMIP5. Observations based regional and ecosystem-level impacts are discussed in relation to global O_2 change;
- Consistently with other studies, CMIP5 projections show an overall decline in oceanic dissolved O_2 concentration of 2 to 4 per cent in the 2090s relative to the 1990s depending on the complexity of a model and global warming scenario chosen;
- The North Pacific, the North Atlantic, the Southern Ocean, the subtropical South Pacific and South Indian oceans all undergo deoxygenation, with O_2 decreases of as much as $-50\ \mu mol\ kg^{-1}$ in the North Pacific by the end of the century for the RCP 8.5 scenario;
- The outcomes of these global changes are *very likely* to be influenced by regional differences such as wind stress, coastal processes, and the supply of organic matter. Global trend quantification remains a very challenging task. Projected O_2 changes in the subsurface layer (200-600 m) show a complex pattern with both increasing and decreasing trends reflecting the subtle balance of different competing factors such as circulation, production, remineralization, and temperature changes; and

24 The other three are warming, changes in primary productivity and ocean acidification.

- Significant reduction in the uncertainty of model projections is needed for informed regional management interventions and policy implementation. We recommend significant strengthening of our observational capacity in both long-term, large-scale mode and process study mode, to gain better understanding of very dynamic relationships between the major ocean stressors. This, in turn, will enhance our ability to model these systems with less uncertainty.

4.3.2 Main Findings, Discussion and Conclusions

The average dissolved O_2 concentration in the ocean is presently 162 µmol kg^{-1} (Sarmiento and Gruber 2006). Concentrations range from over 500 µmol kg^{-1} in productive Antarctic waters (Carrillo *et al.* 2004) to zero in coastal sediments and in deep layers of isolated water bodies, such as the Black Sea and the Cariaco Basin. Most organisms are not very sensitive to oxygen (O_2) levels as long as the concentrations are high enough. But once O_2 drops below a certain threshold, the organism suffers from a variety of stresses, leading ultimately to death if the concentrations stay too low for too long. Such conditions are termed hypoxic. In general terms, hypoxia results from O_2 depletion in excess of supply.

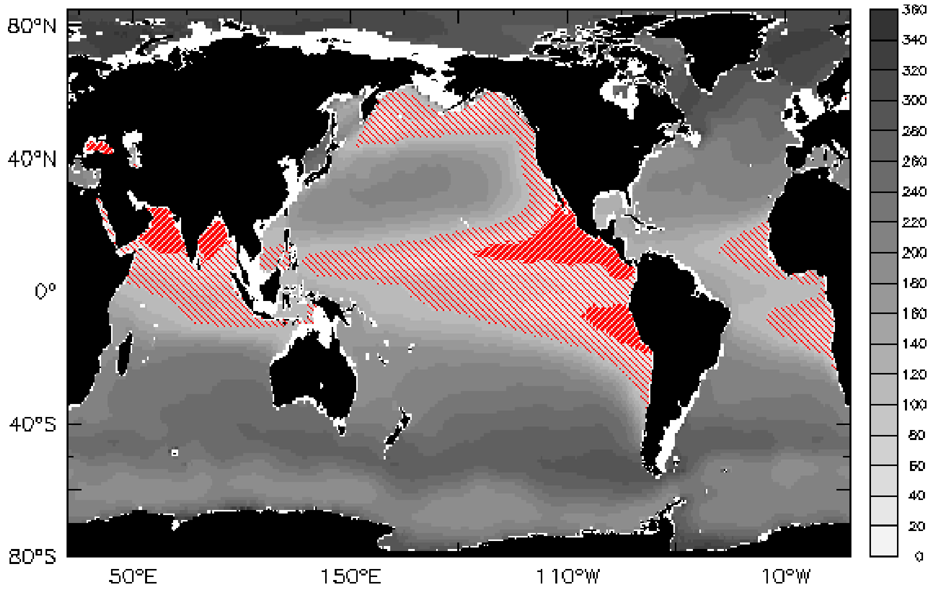
Open ocean deoxygenation has been recorded in nearly all ocean basins during the second half of the 20th century (Stramma *et al.* 2008). Still relatively sparse and localized observational studies indicate a mostly negative trend in the O_2 content over recent decades in several basins of the world's ocean (Takatani et al. 2012; Keeling et al. 2010; Stramma et al. 2008; Chan et al. 2008; Whitney et al. 2007; Mecking et al. 2006; Emerson et al. 2004; Joos et al. 2003) including Black and Baltic Seas, the Arabian Sea, and the California, Humboldt, and Benguela Current systems. A recent global-scale observational study (Helm et al. 2011) supports the evidence of a widespread ocean O_2 decrease between the 1970s and the 1990s. The reduction in O_2 concentration in these reports is consistent with that expected from higher ocean temperatures and a reduction in mixing (increased stratification). A report by Helm et al. (2011) shows that the decline in O_2 solubility with increased temperature is responsible for approximately 15 per cent of the observed change. The remaining 85 per cent is associated with reduced O_2 supply due to increased ocean stratification and increased deep-sea microbial respiration. On the contrary, greater mixing and ventilation due to strengthening wind systems in the North and South Pacific, North Atlantic and Indian oceans caused an increase in O_2 concentrations.

Thresholds for hypoxia vary greatly between marine taxa, with fish and crustaceans tending to be the most sensitive. In ecological literature the threshold for hypoxia is used for water masses with O_2 concentrations below 60 µmol kg^{-1} (Gray et al. 2002; Deutsch et al. 2011; Vaquer-Sunyer and Duarte 2008). Zones with lower O_2 are effectively "dead zones" for many higher animals. The most intense (O_2 <20 µmol kg^{-1}) and largest O_2 minimum zones (OMZs), known as suboxic layers, are mainly localized in subsurface of the upwelling regions in the Eastern Pacific (both north and south of the Equator) and Northern Indian open oceans (Figure 4.34). In the Atlantic, a slightly lesser degree of O_2 depletion is reported in relatively stagnant cyclonic gyres that exist north and south of the Equator in the east of the basin.

The O_2 minimum is typically found at depths between 400 m and 1200 m, near the base of the permanent thermocline, however they are found at depths as shallow as 100 m in the eastern tropical Atlantic and tropical Pacific oceans. In the past, OMZs have probably extended and contracted in warm (interglacial) and cold (glacial) periods, associated with high and low atmospheric CO_2 respectively. In the present, and according to the last two decades of observations, OMZs increase or intensify - and even new ones appear locally and episodically - in tune with high anthropogenic CO_2 uptake by the ocean.

The biggest threat related to open ocean deoxygenation is that of decline in biodiversity through attrition of intolerant species and elevated dominance, as well as reductions in body size, with impacts on organisms within the affected areas as well as in their vertical and horizontal proximities (Levin et al. 2009; Gooday et al. 2009). Shoaling of the tropical OMZs restricts the depth distribution of tropical pelagic fishes such as marlins, sailfish, and tuna by compressing their habitat into a narrow surface layer. Restriction of these fishes toward the surface could make them more vulnerable to over-exploitation by surface fishing gear (Prince and Goodyear 2006). For many fish and

Figure 4.34. Sub-surface O_2 concentrations averaged between 200 m and 600 m from World Ocean Atlas 2009 (µmol kg^{-1}). Light and dark red stripes indicate waters with $O_2 < 100$ µmol kg^{-1} and $O_2 < 20$ µmol kg^{-1} respectively.



crustacean species, larvae are less tolerant of hypoxia than adults, and thus expansion of hypoxic waters may create or enlarge dispersal barriers. Rapidly growing larval fish are especially susceptible to stress from hypoxic conditions as they shift from oxygenation by diffusion to active ventilation of gills. Among adults, reproducing females might also be more *likely* to experience O_2 limitations, as gonads have elevated O_2 demand (Portner and Farrell 2008).

In most marine systems hypoxia alters physiological and metabolic rate processes, organism abundance, lifestyles, composition, complexity, diversity, and size structure (Childress and Siebel 1998; Levin 2003) resulting in mortality of benthic fauna, fish kills, habitat loss, and overall physiological stress. In the future it is expected to observe overall reduced biodiversity associated with avoidance, mortality, or lowered growth and reproductive rates of hypoxia-sensitive species. OMZ expansion may also cause jelly plankton to become more prevalent in the water column. In addition, increasing jellyfish populations may promote hypoxia by preying on zooplankton, leaving unconsumed phytoplankton to sink and degrade.

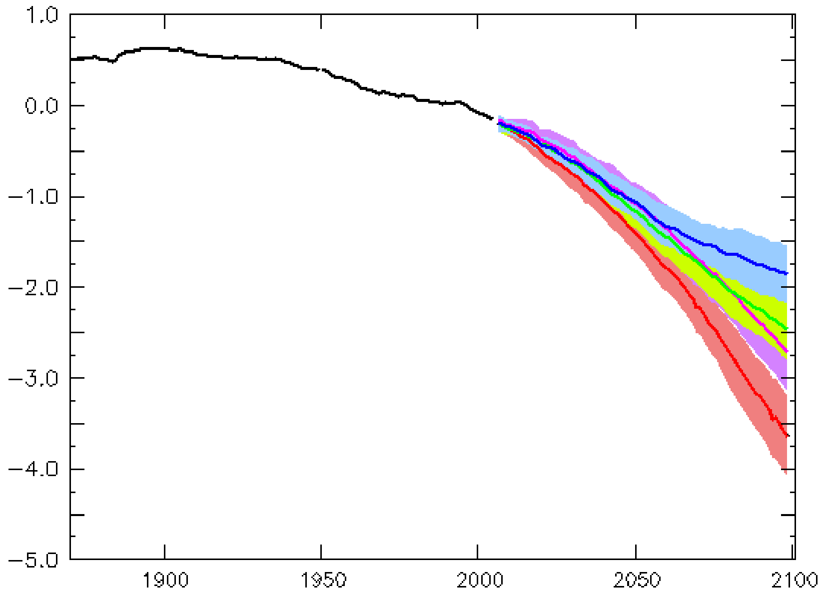
Hypoxia also influences biogeochemical cycles of elements, with perturbations to the global nitrogen cycle being the greatest current concern. Expansion of OMZ's is expected to lead to increased production of nitrous oxide (N_2O), an ozone-destroying greenhouse gas with global warming potential significantly higher than that of CO_2 (Ravishankara et al. 2009). Because of the paucity of direct measurements of N_2O production and consumption in the ocean, current rate estimates and predictions of how the N_2O budget will respond to future changes in oceanic O_2 concentration remain uncertain. However, the strongest oceanic sources of N_2O to the atmosphere are the suboxic (0 to 20 µmol l^{-1}) waters overlying the OMZs, based on measurements and models of supersaturated N_2O concentrations (Suntharalingam and Sarmiento 2000). Overall, the OMZs produce about half of all oceanic N_2O emissions (Codispoti 2010), which represents at least 20 per cent of total global emissions estimated at approximately 5.8 (+- 2) Tg N/y (Nevison et al. 2003). Concentration of dissolved N_2O is high in the tropical and northern Pacific and relatively low, although still supersaturated, in the Atlantic and Southern oceans. Subsurface N_2O in OMZs is generally supersaturated with respect to the atmosphere in the eastern tropical Pacific (ETP) and Arabian Sea. N_2O concentrations peak in the upper 500 m of the water column in the ETP, where typical maximum concentrations are 60–70 nM. In comparison, the concentration of N_2O is only 25–30 nM at equivalent depths in the tropical Atlantic, and 10–15 nM in the Southern Ocean (Nevison et al. 2003).

All this mounting evidence suggests that expanding OMZ's are a strong threat to the natural ocean ecosystem, undermining its health and indirectly negatively affecting human wellbeing. Therefore, the key indicator for ocean deoxygenation in this assessment is mapping of the predicted extent of OMZ's. Both projections of deoxygenation state in the future ocean and projected rate of deoxygenation change (trend quantification) are important indicators of change presented here to allow realistic considerations of mitigation and adaptation interventions.

Findings

Consistent with other studies (Matear et al. 2003; Bopp et al. 2002; Oschlies et al. 2008), CMIP5 projections show an overall decline in oceanic dissolved O_2 concentration of 2 to 4 per cent in the 2090s relative to the 1990s depending on the complexity of the model and global warming scenario chosen (Figure 4.35). For the so-called "business-as-usual" scenario RCP 8.5, the model mean change in the 2090s for global ocean O_2 content amounts to -3.45 (+-0.44) per cent (Bopp et al. 2013). Models support the prediction that further global warming will exacerbate hypoxia conditions mainly through reduced O_2 solubility in warmer water. All models also show a substantial additional O_2 loss resulting from enhanced upper ocean stratification and reduced winter ventilation of the water column, particularly in higher latitudes. As an additional complication, the negative trends in the O_2 content correlate not only with temperature, but also with levels of CO_2 connecting aerobic stress and calcification challenges (Hofmann and Schellnhuber 2009).

Figure 4.35. Global ocean model-mean O_2 concentration change (per cent) relative to mean concentration in the 1990s (hence 0 per cent change in the 1990s). The black line shows historical simulations tuned with available observations. Coloured lines represent four RCP scenarios: RCP 2.6 – blue, RCP 4.5 – green, RCP 6.0 – lavender and RCP 8.5 – red. Shading indicates one inter-model standard deviation.



As a consequence, CMIP5 models project an increase in a volume of the mid-depth O_2 minimum under global warming conditions. We use two thresholds (O_2<80 µmol kg^{-1} in Figure 4.36 and O_2<20 µmol kg^{-1} in Figure 4.37) to characterize time evolution of water volumes of low- O_2 waters. Suboxic waters are defined with a threshold of 20 µmol kg^{-1}, whereas hypoxic waters are defined here with a threshold of 80 µmol kg^{-1}. Figures 4.4.3-4 present the relative evolution of these two volumes as simulated by the CMIP5 models over 1870 to 2100 for all the RCP scenarios. By 2100, all models project an increase in the volume of hypoxic waters, ranging from +1 per cent to +9 per cent for individual models.

This response is more consistent than that of the previous generation of earth system models, for which changes varied from −26 to +16 per cent over 1870 to 2099 under the SRES-A2 scenario (Cocco et al. 2013). For lower O_2 levels (Figure 4.37), there is still much less agreement among the CMIP5 models. For suboxic waters, individual models project an expansion of up to 30 per cent or even a slight contraction of 4 per cent. These results for low-O_2 waters agree with those of Cocco et al. (2013), with large model–data and model–model discrepancies and simulated responses varying in sign for the evolution of these volumes under climate change.

Figure 4.36. Model-mean time series of water masses with O_2 content <80 µmol kg^{-1} over 1870-2100 using historical simulations (black line) and four RCP scenarios. Shading indicates one inter-model standard deviation. Colours represent RCP scenarios: RCP 2.6 – blue, RCP 4.5 – green, RCP 6.0 – lavender and RCP 8.5 – red. Values are plotted relative to the 1990s mean.

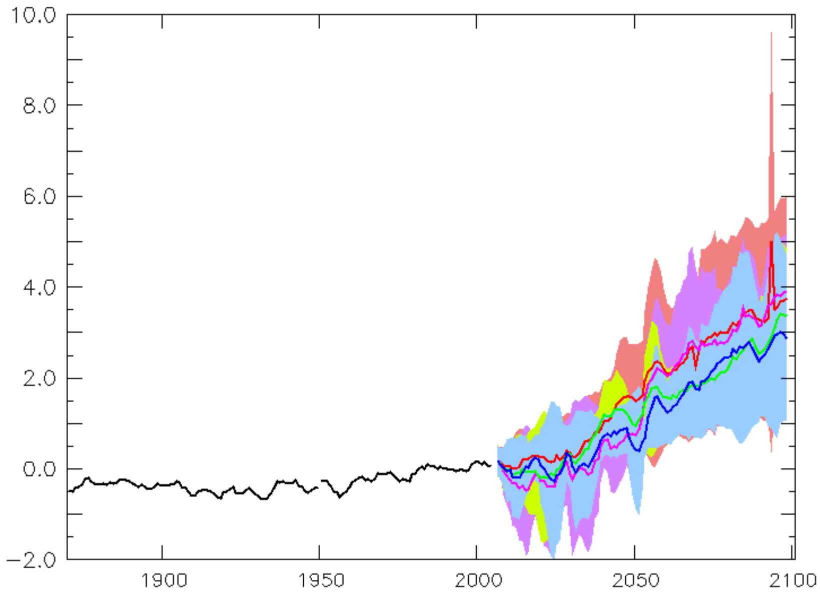
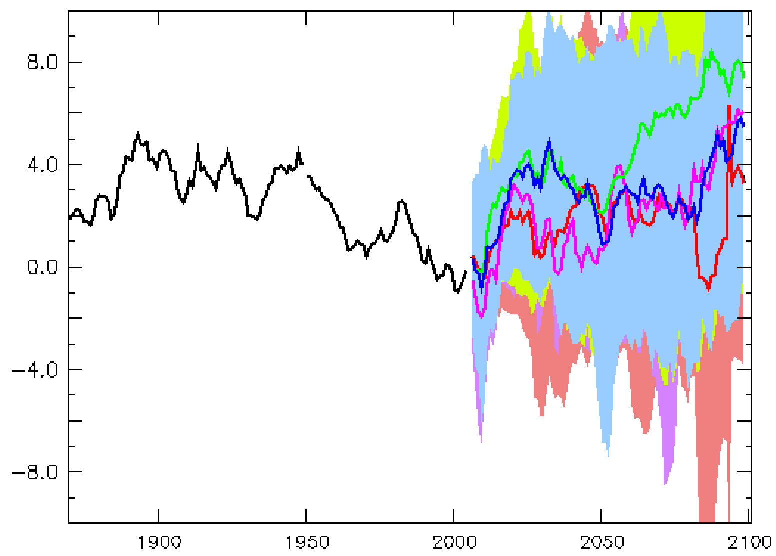
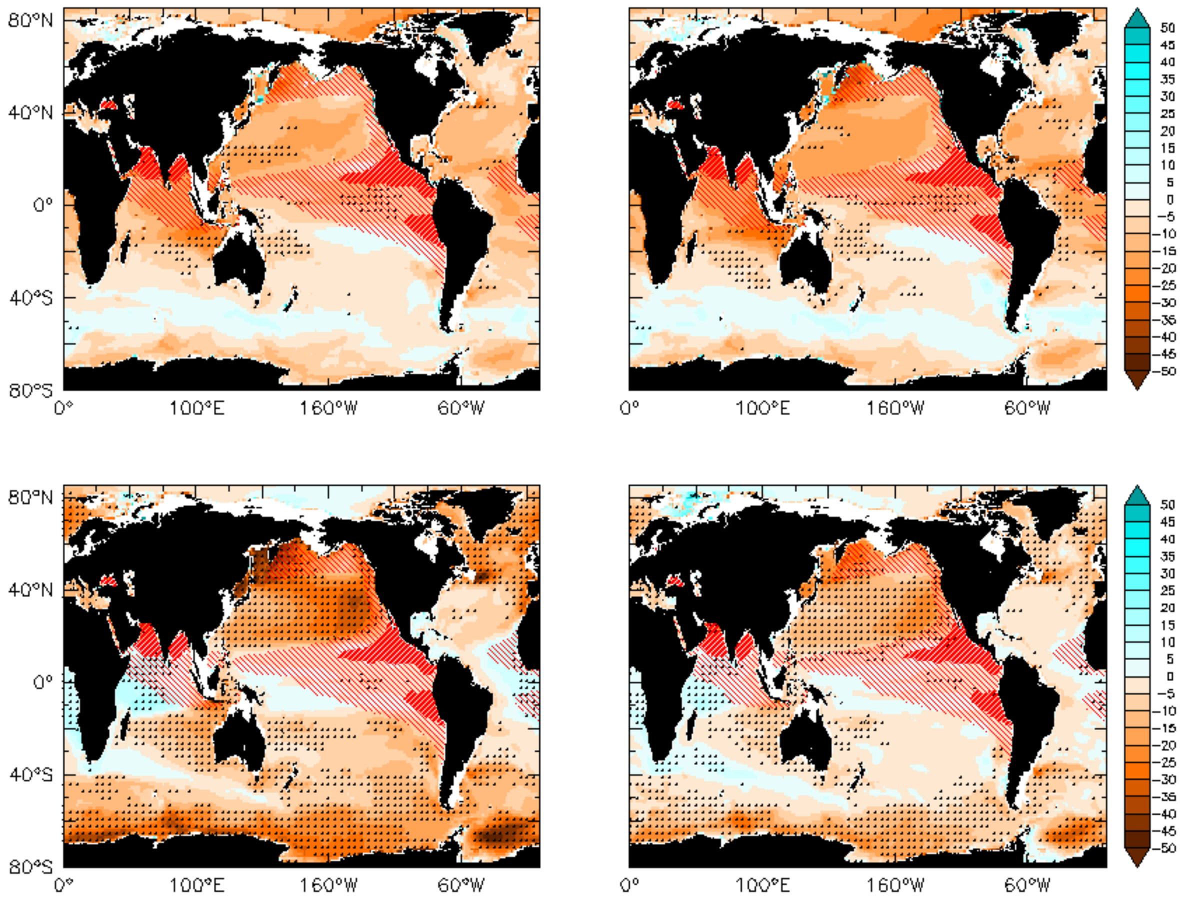


Figure 4.37. Model-mean time series of water masses with O_2 content <20 µmol kg^{-1} over 1870-2100 using historical simulations (black line) and four RCP scenarios. Shading indicates one inter-model standard deviation. Colours represent RCP scenarios: RCP 2.6 – blue, RCP 4.5 – green, RCP 6.0 – lavender and RCP 8.5 – red. Values are plotted relative to the 1990s mean.



In Figure 4.38 we show projected spatial and temporal changes in subsurface (200 m to 600 m depth) O_2 distribution for the two selected scenarios (RCP 8.5 in left column and RCP 4.5 in right column). All panels show maps of differences. Top row shows changes between the 1990s and 2030s for both scenarios and bottom row shows changes between the 1990s and 2090s, also for both scenarios. Negative values mean deoxygenation. Projected changes are also not uniform across models. Black dots marks regions with high projection robustness across models defined when at least 80 per cent of models agree on the sign of the mean change. The complex patterns of spatial changes are very similar across the two scenarios for both periods and reflect the influence of changes in several processes like ventilation, vertical mixing or remineralization on O_2 levels.

Figure 4.38. Change in subsurface (averaged for 200-600 m depth) O_2 concentration in the 2030s relative to the 1990s (top panels) and in the 2090s relative to the 1990s (bottom panels), for two RCP scenarios, RCP 8.5 on the left and RCP 4.5 on the right. Negative values mean deoxygenation. Black dots marks regions with high projection robustness across models. Red stripes indicate current OMZs as in Figure 4.34.



The North Pacific, the North Atlantic, the Southern Ocean, the subtropical South Pacific and South Indian oceans all undergo deoxygenation, with O_2 decreases of as much as −50 µmol kg^{-1} in the North Pacific for the RCP 8.5 scenario. In contrast, the tropical Atlantic and the tropical Indian show increasing O_2 concentrations in response to climate change, in both scenarios. The equatorial Pacific displays a weak east–west dipole, with increasing O_2 in the east and decreasing O_2 in the west. Apart from changes in the equatorial Pacific, these regional changes in subsurface O_2 are consistent across models under the RCP 8.5 scenario for the 2090s as indicated by black dots in Figure 4.38, and they are quite similar to those from a recent intermodel comparison of the previous generation of Earth system models (Cocco et al. 2013).

Over the mid-latitudes, patterns of projected changes in subsurface O_2 are broadly consistent with observations collected over the past several decades (Helm et al. 2011; Stendardo and Gruber 2012; Takatani et al. 2012). Yet there is no such model–data agreement over most of the tropical oceans Red stripes indicate a negative O_2 concentration trend based on observations and a blue background indicates a positive O_2 concentration trend projected by the models. Observed time series suggest a vertical expansion of the low-O_2 zones in the eastern tropical Atlantic and the equatorial Pacific during the past 50 years (Stramma et al. 2008), conversely with models that simulate increasing O_2 levels with global warming over the historical period (Andrews et al. 2013).

These results indicate a strong need for better understanding of "model-usable" physical and biogeochemical processes driving O_2-related changes at the global and regional scales. Currently, most of the data-model discrepancies are explained primarily by the fact that a number of biogeochemical ocean carbon cycle feedbacks that could also impact future trends of ocean deoxygenation are not yet included in most marine biogeochemical models (including CMIP5 models). For example, model experiments which include one of the feedbacks (namely pCO_2- sensitive C:N drawdown in primary production) suggested by some medium-scale in-situ experiments of limited duration (Riebesell et al. 2007), project future increases of up to 50 per cent in the volume of the suboxic waters by 2100 (Oschlies et al. 2008; Tagliabue et al. 2011). In addition, future marine hypoxia could be amplified by changes in the $CaCO_3$ to organic matter 'rain ratio' in response to rising seawater pCO_2 (Hofmann and Schellnhuber, 2009). CMIP5 estimates also do not take into account processes that are specific to the coastal ocean and may amplify deoxygenation.

Discussion and Conclusions

There is high agreement among CMIP5 models that O_2 concentrations will continue to decrease in most parts of the ocean due to the effect of temperature on O_2 solubility, ocean ventilation, and ocean stratification and microbial respiration rates (Andrews et al. 2013). Negative implications for nutrient and carbon cycling and ocean productivity are *very likely* (Bopp et al. 2013). The North Pacific and Atlantic oceans as well as the Southern Ocean will be the most affected by deoxygenation by the end of the century. Projections for tropical regions have *high* uncertainties and call for much caution when concluding from CMIP5 results.

Global trend quantification remains a very challenging task. Projected O_2 changes in the subsurface layer (200-600 m) show a complex pattern with both increasing and decreasing trends reflecting the subtle balance of different competing factors such as circulation, production, remineralization, and temperature changes (Cocco et al. 2013). Projected changes in the total volume of hypoxic and suboxic waters remain relatively uncertain in the current generation of earth system models. The outcomes of the global changes are *very likely* to be influenced by regional differences such as wind stress (Vecchi and Soden 2007), coastal processes, and the supply of organic matter (Snyder et al. 2003). Global earth system models such as those used in CMIP5 only start to be run at detailed-enough resolution to be able to resolve regional variability and answer questions on regional ecosystem or species level very accurately.

Biological consequences of reduced O_2 concentrations are *likely* to be most notable for the 200–400 m layer, as these waters impinge on the euphotic zone and the outer continental shelf, where these O_2-depleted waters may be upwelled into productive eastern boundary currents (Chhak and Di Lorenzi, 2007). According to an ever-growing body of literature, OMZs expanding vertically and laterally will cause habitat and abundance losses for intolerant taxa with a high O_2 demand such as fishes including top predators (Prince et al. 2010; Stramma et al. 2010; Koslow et al. 2011; Stramma et al. 2012). Expanding OMZs will probably further constrain the distribution of key zooplankton and nekton species (Ekau et al. 2010). Dissolved O_2, among other factors, plays an important role in shaping large alternating fluctuations of sardine and anchovy abundances, particularly off Peru. Where OMZs intersect the continential shelves, groundfishes (McClatchie et al. 2010) and large benthic invertebrates like crabs display high mortalities (Chan et al. 2008). Susceptibility of early life stages to hypoxia in both pelagic and benthic ecosystems (Ekau et al. 2010) threatens population survival. The upwelled OMZ waters may interact with natural or eutrophication-induced hypoxic zones on the inner shelves; this occurs for example off Peru and Chile, Namibia and the western Indian margin. In the eastern Pacific these O_2-poor upwelled waters are corrosive and under-saturated with respect to aragonite, exacerbating the stress imposed on the exposed ecosystems (Feely et al. 2008). In regions where O_2 levels decline and OMZs expand, tolerant taxa, such as anaerobic bacteria (Ulloa et al. 2012), gelatinous zooplankton (medusae, ctenophores), selected fishes (gobies, hake), and possibly selected cephalopods (Gilly et al. 2006; Bazzino et al. 2010), will respond with range expansions or population growth. A community change toward hypoxia-tolerant fauna will occur in mid-water (IPCC 2013). The diversity of macro-organisms will decrease and, finally, higher marine organisms will disappear and heterotrophic micro-organisms will dominate (IPCC 2013). In isolated water bodies like the Black Sea, warming will lead to the expansion of anoxia and hydrogen sulfide (H_2S) poisoning, reduce pelagic and bottom faunal distributions, and shape trophic relations, energy flows, and productivity (Daskalov 2003; Fashchuk 2011). All these ecosystem-related feedbacks need to be incorporated into the earth system models through better description of related physical and biogeochemical processes.

Similarly, the ability of climate models to represent O_2 concentration observations has been questioned in recent studies. Stramma et al. (2012) performed a series of model simulations over the historical period and compared the simulated subsurface O_2 trends with observations. They showed that the model was unable to reproduce the spatial patterns of observed changes. Andrews et al. (2013) compared output of two earth system models to observations over the historical period. They reported that both models fail to reproduce the pattern of O_2 loss recorded by observations in low-latitude OMZs. A more thorough analysis of the mechanisms responsible for the model–data discrepancies as well as the mechanisms driving the simulated future changes is necessary. Gnanadesikan et al. (2012) performed such an analysis with simulations carried out with a previous version of the GFDL Earth system model (GFDL-ESM2.1) under the SRES-A2 scenario. They show that the volume of suboxic waters does not increase under global warming in the tropical Pacific. A detailed analysis of the different terms contributing to the O_2 budget showed that an increase in O_2 in very low O_2 waters is associated with an enhanced supply of O_2 through lateral diffusion and increased ventilation along the Chilean coast. These results cast doubt on the ability of the present generation of models to project changes in O_2 accurately at the regional level, especially for low-O_2 waters, and stress the need for more model–data comparisons over the historical period alongside a better understanding of reasons for model biases.

Recommendations

Representation of ecosystems in earth system models such as these presented here is an evolving science. CMIP 5 models represent only a small set of the processes controlling the ecosystem and biogeochemical function. While the models are each constructed in mathematically defensible forms, they are all different in the underlying assumptions. Rather than representing discrete biological forms, they represent ecosystems as a biological continuum with infinite biodiversity in some ways (for example: the role of temperature), and an artificial rigidity in others (for example: fixed half-saturation constants). First strong recommendation would be to focus on improving the next generation of earth system models in this regard.

A related long-term recommendation would be to vastly enhance the resolution in order to represent the mesoscale phenomena such as coastal upwelling and eddies. Only models with resolution fine-enough to represent mesoscale physical and biogeochemical processes will be able to predict ecosystem changes related to anthropogenic pressures.

Finally, the existence of potential synergistic effects between the four different stressors (deoxygenetaion, warming, changes in primary productivity (NPP) and ocean acidification) strongly emphasizes the need to study them together (Boyd et al. 2008). Bopp et al. (2013) shows the temporal model-mean evolution of global surface pH, global O_2 content and global NPP vs. global sea surface warming for each of the RCPs over the 21st century. For RCP 8.5, all these relationships appear linear, implying a constant fraction of acidification, deoxygenation, and NPP reduction per degree of warming. For the other RCP scenarios, relationships are similar for surface pH vs. Sea Surface Temperature (SST) and for NPP vs. SST, but the relationship breaks down for O_2 content versus SST. That is, deoxygenation continues long after SSTs have stabilized. A recommendation would be to significantly enhance observational capacity for all four stressors. Developing a better understanding of the role of processes related to temperature (warming vs stratification), rising biological demand (especially in coastal regions) and acidification in determining O_2

concentrations will enable a more coherent understanding of the changes and potential risks to marine ecosystems. Linkages between changes occurring in the surface ocean and those associated with the deep layers are particularly important in light of a need to understand how rapidly changes are occurring and the implications for the metabolic activity and O_2 content of deep ocean habitats. Both, sensor technology and appropriate platforms exist, but need to be utilized in a much wider geographical context as opposed to the current very limited coverage offered by a couple of hundred profiling floats equipped with biogeochemical sensors. Strong emphasis has to be put on observing system simulation experiments so that the resources are distributed in the most efficient manner in terms of geographic coverage, temporal distribution and combinations of parameters observed.

Given the importance of OMZs to the physical, chemical, and biological characteristics of the ocean, it is extremely important that these systems receive greater focus, especially with regards to their response to ocean warming and acidification. Significant reduction in the uncertainty of model projections is needed for informed regional management interventions and policy implementation. Increasing our observational capacity to gain better understanding of the very dynamic relationships between the major stressors will in turn enhance our ability to model these systems more realistically and with less uncertainty.

4.3.3 Notes on Methods

For this report simulations were obtained with the latest generation of so-called earth system models collated under the Coupled Model Intercomparison Project Phase 5 (CMIP 5[25]) (Taylor et al. 2012). The models simulate future climate states and dynamics based on four greenhouse-gas concentration trajectories adopted by the IPCC for its Fifth Assessment Report. Scenarios are referred to as RCPs (Representative Concentration Pathways) and describe four possible climate futures, depending on how much greenhouse gases are going to be emitted in the years to come (RCP2.6, RCP 4.5, RCP 6.5 and RCP 8.5). In this Chapter, simulations were focused on two scenarios: RCP 4.5 in which emissions peak around 2040, then decline and RCP 8.5 in which emissions continue to rise throughout the 21st century.

Standard CMIP5 output from the Program for Climate Model Diagnosis and inter-comparison (now replaced by the Earth System Grid Federation portal[26]*)* was provided by the different modeling groups. Ten models were used to compute simulations discussed in this report based on the availability of all variables necessary to discuss the future dynamics of O_2 concentrations in the global ocean. In this report, models were used, for which the simulated volumes of hypoxic and suboxic waters over 1990–1999 fall within + 100 per cent and − 50 per cent of the observed volumes, as estimated from the WOA 2009 database (Bianchi et al. 2012). Each model includes representations of the general circulation and physics of the atmosphere and the ocean, as well as biogeochemical components, including a representation of the ocean carbon cycle and the lowest trophic level of marine ecosystems (Bopp et al. 2013). However, the models differ in many respects like architecture, with a set of components to the degree of complexity. Thus attributing the causes of differences between models to particular processes is difficult (Bopp et al. 2013) and as it is not the subject of this report, will not be discussed. Results presented in this report are the model-mean with inter-model standard deviation as an uncertainty estimate.

The projected evolution of ocean deoxygenation for the 2030s and 2090s for both RCPs were mapped and discussed as differences between projections for these decades and data-based climatology of O_2 distributions obtained from WOA 2009 for the 1990s (shown in Figure 4.34). Further, the projected evolution of global mean O_2 content of the ocean for all four RCPs was presented. Finally, the projected changes in the volumes of water with O_2 levels lower than 80 µmol kg^{-1} and lower than 20 µmol kg^{-1} were discussed.

Models are invaluable tools for studying system dynamics, generalizing discrete observations and predicting future states. Model analyses and predictions are therefore used in this assessment, however their limitations in simulating regional and local concentrations are not insignificant and therefore this data-based assessment was presented for matters un-resolvable by the current generation of earth system models.

25 http://cmip-pcmdi.llnl.gov/cmip5/index.html?submenuheader=0
26 http://pcmdi9.llnl.gov

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Chapter 4.4 Ocean acidification, projections of future state under two emission scenarios

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4.4 Ocean acidification, projections of future state under two emission scenarios

4.4.1 Summary and Key Messages

Roughly a third of the carbon dioxide (CO_2) released into the atmosphere since the 'Industrial Revolution' has been absorbed by the ocean (Sabine et al. 2004). This uptake of CO_2 is causing an ongoing change in oceanic carbonate chemistry. Oceanic pH is declining, a phenomenon commonly referred to as ocean acidification (OA). OA is causing a decline in the saturation state of calcium carbonate ($CaCO_3$) minerals such as aragonite (Doney et al. 2009). The skeletons or shells of many economically and/or ecologically important oceanic species are built from aragonite. A decline in aragonite saturation state (Ωarag) can slow down calcification and negatively impact these organisms (Kroeker et al. 2013). For example, stony corals show declined calcification with decreasing Ωarag, making them more vulnerable to damage by tropical storms and more prone to erosion (Chan and Connolly, 2013; van Hooidonk et al. 2014). Pteropods present at higher latitudes are projected to be affected severely by OA. Their distribution might be limited because of their inability to grow a shell or their shell being too weak as a defensive mechanism (Orr et al. 2005).

To project OA impacts on these and other important organisms, accurate projections of Ωarag are needed. Here Ωarag was modelled using state-of-the-art global circulation models included in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Taylor et al. 2012). Aragonite saturation state was computed by adopting standard routines from the Matlab program CO_2SYS (http://cdiac.ornl. gov/oceans/ CO_2rprt.html). To calculate Ωarag and compute all variables in the carbonate system sea surface temperature (SST), salinity and two of the following five variables are required: total alkalinity, total carbon dioxide, pH, and partial pressure of carbon dioxide or fugacity of carbon dioxide (see: Zeebe and Wolf-Gladrow, 2001). Here, SST, salinity, surface pressure of CO_2 and pH are used to calculate all the other parameters of the carbonate system. Two projections were made, one with the relative concentration pathway (RCP) 4.5, which is a scenario of rapid initial growth of greenhouse gas (GHG) concentrations, but stabilizing concentrations from 2070 onward (Thomson et al. 2011). The CO_2 equivalent concentration in 2100 is 580 ppm including all forcing agents. This pathway results in a total forcing of 4.5 W/m^2 in 2100.

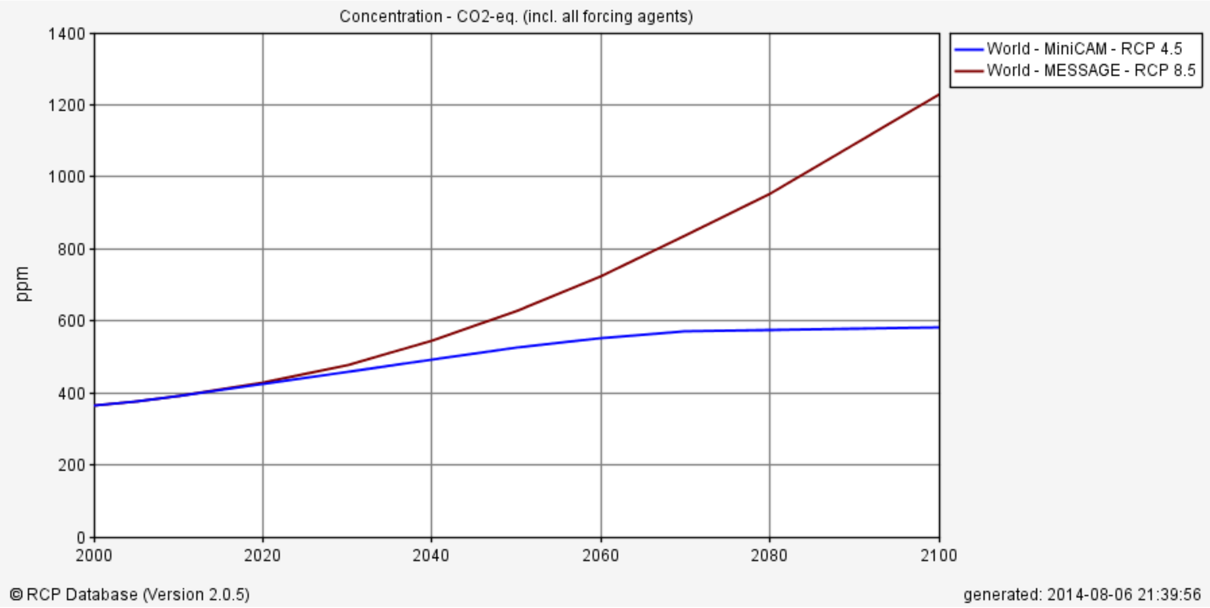
The second projection was made using the RCP 8.5: a pathway of continuing growth of GHG concentrations in the atmosphere (Figure 4.39) and one that results in an additional forcing of 8.5 W/m^2 in 2100 at a CO_2 (equivalent, including all forcing agents) concentration of 1230 ppm (Riahi et al. 2011).

Currently ,emissions track above the RCP 8.5 scenario. In all four previous generations of emission scenarios employed by the IPCC for their Assessment Reports, emissions always exceeded the worst-case scenario (Peters et al. 2012). Both pathways project a 395 ppm CO_2 concentration in 2013 as a mid-year average, which is lower than measurements of CO_2 concentration for that year (http:// www.esrl.noaa.gov/gmd/ccgg/trends/). Measurements of CO_2 in 2014 at Mauna Loa peaked above 400 ppm (http:// www.esrl.noaa.gov/gmd/ccgg/trends/).

Key Messages

- Aragonite is a calcium carbonate mineral that is an important component of shells and skeletons of marine species;
- Ocean acidification can lead to aragonite dissolution, leading to significant weakening of the shells and skeleton of many marine species;
- Global oceanic pH is expected to decrease 0.12 units by 2099 in RCP4.5; for RCP8.5 the decline is projected to be 0.32 units;
- Globally averaged aragonite saturation state is projected to decline 0.55 and 1.14 units for RCP4.5 and RCP8.5 respectively;

Figure 4.39. Concentrations of greenhouse gases in the atmosphere expressed as CO_2 equivalents including all forcing agents for the Relative Concentration Pathways RCP 4.5 (blue) and 8.5 (red).



Source: http://tntcat.iiasa.ac.at:8787

- There is a latitudinal gradient in reduction of aragonite saturation state: near the equator the reduction is largest; and
- Due to a projected weakening of easterly trade winds in the Pacific and consequently causing higher rates of SST increases in the region, aragonite saturation state is projected to decrease less in this region than surrounding areas.

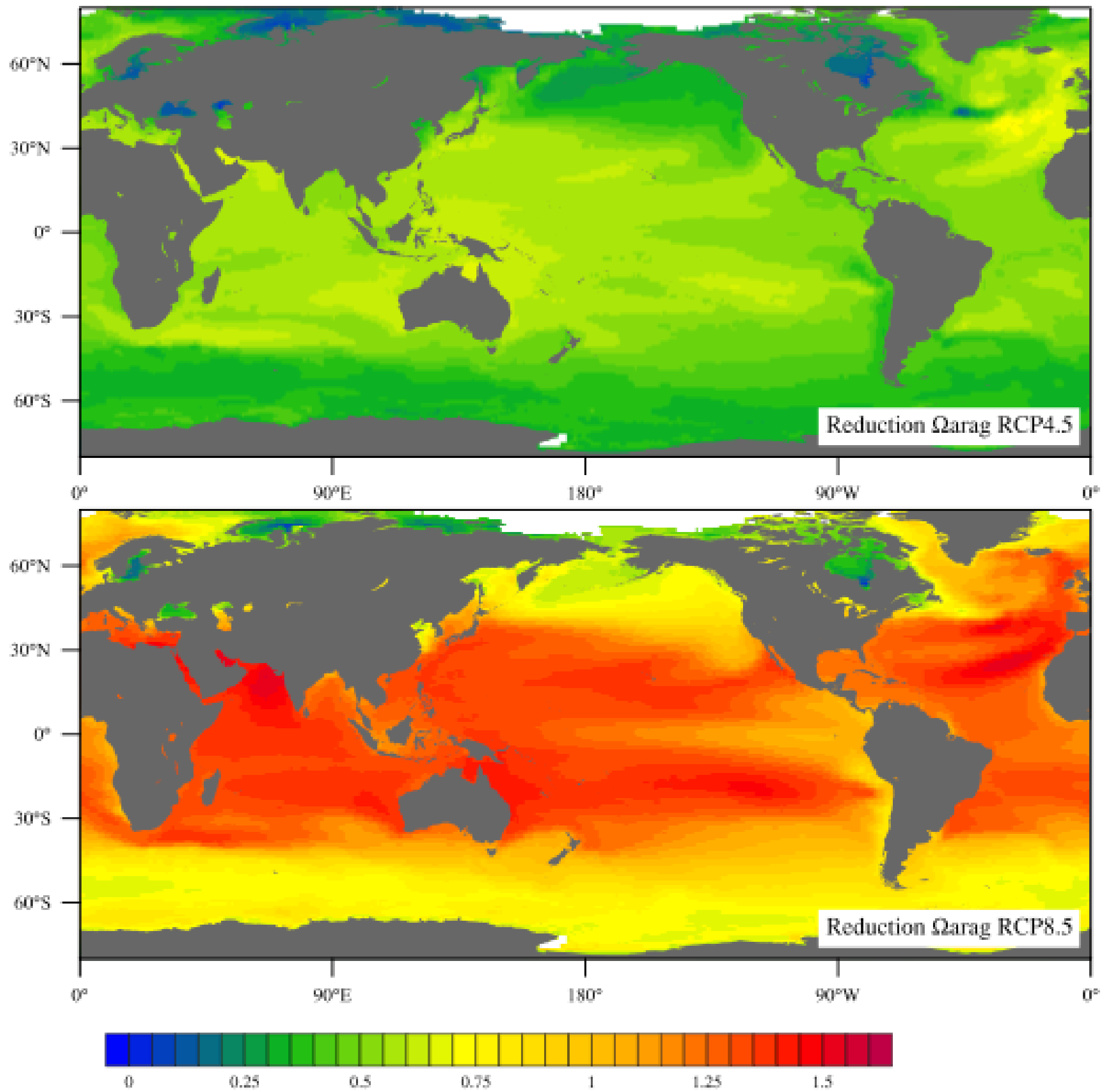
4.4.2 Main Findings, Discussion and Conclusion

Global oceanic pH in the model ensembles decreases from 8.06 in the 2006-2015 period to 7.94 in the period 2090-2099 for the stabilization scenario (RCP4.5). In the scenario that is more consistent with the current increase in greenhouse gas emissions (RCP8.5), global oceanic pH drops from 8.06 in 2006 to 7.74 in 2090-2099. Globally averaged aragonite saturation state drops from 2.75 to 2.20 in RCP4.5. Averaged over just the tropics, aragonite saturation state is projected to decline from 3.46 to 2.91 in RCP4.5. In the 'Business As Usual' scenario (RCP8.5) the reduction in the aragonite saturation state is larger, from 2.71 to 1.57 globally, and 3.43 to 2.13, in the tropics.
The reductions in aragonite saturation state are not distributed evenly across the globe: there is a clear latitudinal gradient.

The reduction in aragonite saturation state is larger near the equator and diminishes with increasing latitude (Figure 4.40), this is true for both emission scenarios. However, the equatorial eastern Pacific is an exception, where Ωarag decreases less than in surrounding waters of the Pacific. This is likely due to a projected weakening of easterly trade winds in the Pacific and consequential decreased upwelling, a flattening of the thermocline, and higher rates of SST increases in the region (Collins et al. 2010). With all else being equal, higher temperatures lead to higher Ωarag, explaining the difference seen in the equatorial eastern Pacific.

Expressed as a percentage change from 2006 values, lower latitudes experience a smaller decrease in aragonite saturation state then high latitude locations (Figure 4.41).

Figure 4.40. Absolute reduction in aragonite saturation state, projected using ensembles of GCMs. The top plot shows the reduction projected using RCP4.5, the bottom plot shows the projected reduction using the RCP8.5 scenario. Differences are calculated as the average of 2006-2015 minus the average for 2090-2099.

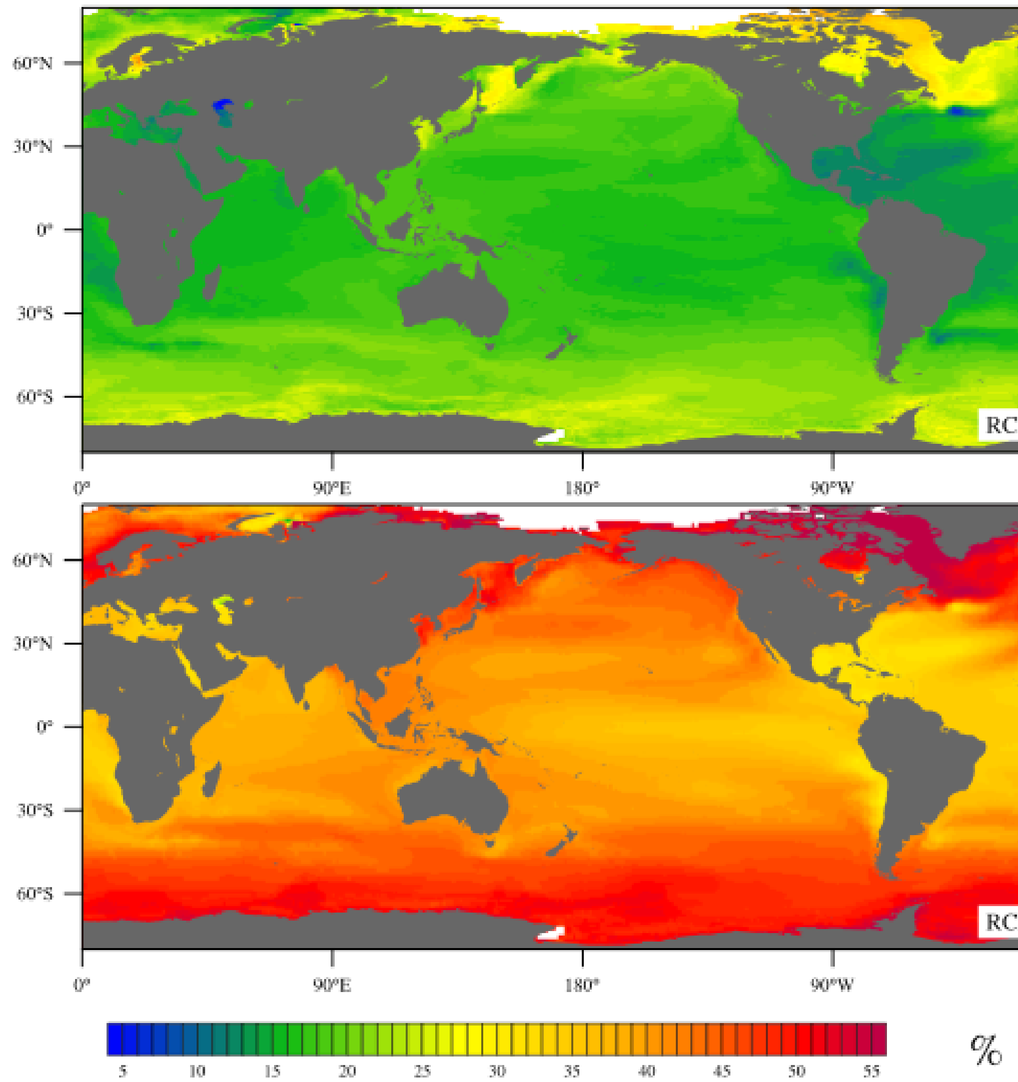


The Atlantic Ocean, of all oceans, shows the smallest reduction in Ωarag, with the Caribbean Sea and the Gulf of Mexico projected to have a ~30% reduction by 2100 in the RCP8.5 scenario. The Pacific and Indian oceans are projected to decline 37-40% by 2100 in RCP8.5. During the modeled period 2006-2099, aragonite saturation state declines globally, but the latitudinal gradient can be seen through time as well (Figure 4.42).

Discussion and Conclusion

There are assumptions and uncertainties that need to be considered when using global models to project Ωarag. Even though the most advanced suite of models has been used, uncertainties still exist. Compared to the previous generation of models the projected changes in temperature and the patterns of change are exceptionally similar.

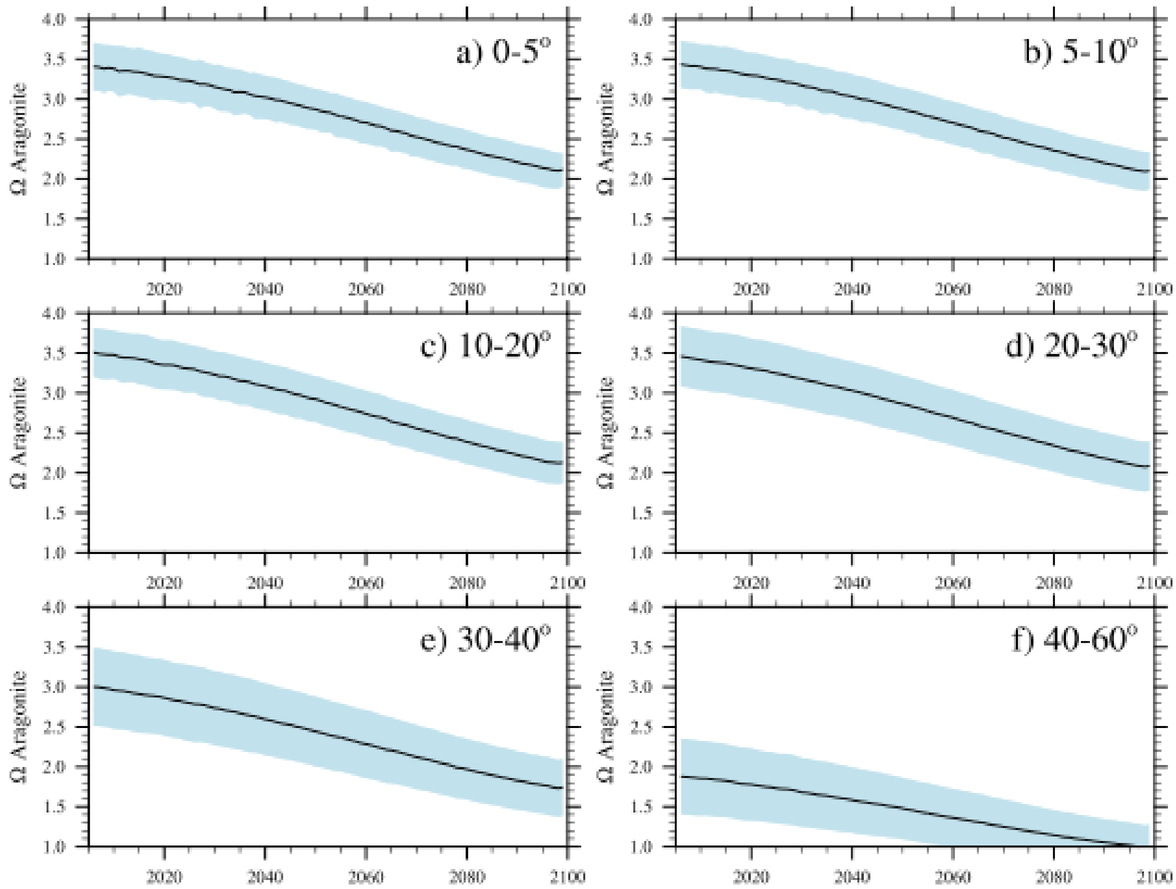
Figure 4.41. Projections of reductions in aragonite saturation state, computed from two ensembles of GCMs, one for RCP4.5, one for RCP8.5 expressed as a change in percentage from 2006 values.



The current generation of models include vastly more complex and comprehensive representations of the processes that influence climate. Therefore, although the model spread has not decreased between generations, it is more *certain* that the important processes have been included and confidence in the models should increase (Knutti and Sedláček, 2012).

Part of the model spread is inherent to internal variability in the climate system itself. Due to the coarse resolution of global models, near coastal and fine scale features such as local upwelling or run-off might not be represented accurately. Upwelling can influence the SST and run-off can alter the carbon chemistry of the surface water as well. Small local features that could influence the carbonate chemistry such as sea grass beds can also not be resolved by global models. Observations however show that these local features could have significant impact on projected functioning of ecosystems such as coral reefs (Manzello et al. 2012).

Figure 4.42. Trajectories of aragonite saturation state for the period 2006-2099 computed from the RCP8.5 ensemble. The panels show average (black solid line) and the model spread expressed as by 2100 in RCP8.5. The areas are the combination of the same latitudinal bands north and south of the equator, therefore panel a) represents from -5 to 5ºN, b) 5º to 10º on both sides of the equator, c) 10º to 20º, d) 20º to 30º, e) 30º to 40º and f) 40º to 60º on both sides of the equator.



The models do not reflect higher frequency variabilities of Ωarag, such as diurnal and weekly variability due to the monthly resolution of the outputs that are needed to compute Ωarag. Global models still have some known and unknown biases and errors, for example the representation of the annual cycle of SSTs can be under or over represented (Wu et al. 2008; van Hooidonk and Huber, 2012), which influences Ωarag considerably. A frequently used method to minimize biases and errors is to use a multi model ensemble (Tebaldi and Knutti, 2007). The spread of the models, expressed as standard deviation, can be considered as an approximation of the robustn*ess of the results (Figure 4.42*). The standard deviation increases with latitude and is on the order of 0.25-0.5 units of Ωarag. Both the standard deviations and the absolute values of Ωarag are comparable to previously published results based on measured data fro*m cruises (Feely et al. 2009).*

4.4.3 Notes on Methods

To project future ocean acidification and aragonite saturation states, ensembles of fully coupled ocean atmosphere global circulation models were used. Monthly data for the following variables were obtained from models in the Coupled Model Intercomparison Project 5 (CMIP5; http://pcmdi9.llnl.gov/ esgf-web-fe/) for all four RCP experiments (Moss et al. 2010): SST, surface pressure of CO_2 (sp CO_2), pH, and surface salinity. For this report only the results from RCP4.5 and RCP8.5 were used. For the impact of OA on tropical coral reefs under all four scenarios see van Hooidonk et al. (2014).

All modeled data were remapped to a 1x1° resolution grid. If there were multiple runs available for a model, these runs were averaged first before a multi-model ensemble was created by averaging all model outputs. Because many sites of interest are close to coastal boundaries, such as coral reef sites, missing data was filled in using an interpolation algorithm that solves Poisson's equation by relaxation. This function uses the existing data as boundaries and interpolates in the zonal direction. By filling in missing data this way, near coastal projections could be made. The models used in the RCP4.5 and RCP8.5 ensembles are documented in Table 4.1.

From SST, sp CO_2, pH and surface salinity aragonite saturation state was computed at each 1x1º pixel at each monthly timestep from 2006 until 2099. To compute aragonite saturation state, CO_2SYS Matlab routines (http://cdiac.ornl.gov/oceans/CO_2rprt.html) were ported to the NCAR Command Language (NCL 6.2.0), with K1 and K2 constants used from Mehrbach (1973), refit by Dickson and Millero (1987).

Table 4.1 Models used to compute aragonite saturation state

	RCP45	RCP85
1. CanESM2	2. 1	3. 1
4. CMCC-CESM		5. 1
6. GFDL-ESM2G	7. 1	8. 1
9. GFDL-ESM2M	10. 1	11. 1
12. HadGEM2-CC	13. 1	14. 1
15. HadGEM2-ES	16. 1	17. 1
18. MPI-ESM-LR	19. 1	20. 1
21. MPI-ESM-MR	22. 1	23. 1
24. NorESM1-ME	25. 1	26. 1
27. Total	28. 8	29. 9

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Chapter 4.5 Exploring regional coastal populations at risk of sea level rise using future socioeconomic pathways under high and low emission scenarios

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4.5 Exploring regional coastal populations at risk of sea level rise using future socioeconomic pathways under high and low emission scenarios

4.5.1 Summary and Key Messages

We estimate the risk of sea level rise (SLR) within a framework of hazard, exposure and vulnerability using internally consistent future development scenarios (or pathways) for 139 coastal countries over the time period 2010-2100. We combine socioeconomic and greenhouse gas concentration pathways into five future reference development pathways or scenarios: Shared Socioeconomic Pathway (SSP)1 (sustainable development) and SSP4 (inequality) with Representative [greenhouse gases and pollutants] Concentration Pathway (RCP) 4.5 to form low emission scenarios; and SSP2 (middle of the road), SSP3 (stalled development), and SSP5 (fossil fuel led development) with RCP8.5 to form high emission scenarios. The emission scenarios as elaborated by the Fifth Assessment Report of the IPCC provide regional estimates of sea level rise for the period 2010 to 2100, and which we use as hazard measures for estimating risk of sea level rise. The SSPs provide projections of human development metrics, including population, life expectancy at birth (health measure), mean years at school, females with tertiary education as a percentage of women of childbearing years (20-39 years) (education measures), and GDP in 2005 US$ PPP (income measure) at country scale over the same time period (2010 to 2100). We combine these human development measures into a Human Development Index (HDI) at country scale annually for the 90-year period. We take the difference between the theoretically highest level of human development and the projections called the Human Development Index Gap (i.e. 1.0-HDI) as a measure of vulnerability.

We estimate exposure to sea level rise in terms of total land area in three coastal zones defined by horizontal cumulative distances 10km, 30km and 50 km from shore, and each width intersecting with elevation data to 10 m, and greater than 10m elevations for the benchmark year 2100. The MESSAGE land use model is used to obtain total land values for each of the three coastal widths in 2100, under a high emission scenario and assume these to be the same for RCP4.5 (low emission scenario). We distribute the projected SSP populations in the three coastal widths using a reference distribution map of global population in 2100 that is based on a UN population model with medium growth variant for calibration. Both land area and population values are used as exposure metrics in calculating an SLR Risk Index.

The estimation of risk to future sea level rise is weighted equally by the hazard, exposure and vulnerability metrics above. The SLR Risk Index is calculated as the geometric mean of: (a) the projected sea level rise estimates in either RCP4.5 or RCP8.5 for the reference year 2100 (hazard measures); exposed land area and population within vulnerable zones of up to 10 m elevation at cumulative distances of 10, 30 and 50 km distance from shore (exposure metrics); and the projected Human Development Index Gaps (i.e. 1- HDI) (vulnerability measures). We report risk estimates to sea level rise within country coastal zones 50 km wide up to 10 m in elevation and compare their magnitudes across the five reference development pathways.

The analysis in this study highlights several key messages:

1. Among the three equally weighted and uncorrelated (i.e. less than correlation coefficient of 50%) measures of hazard, exposure and vulnerability used in assessing SLR risk, vulnerability correlates the most with resulting SLR risk at 79 – 85 per cent. This is evident across all five future development pathways.
2. For a country, hazard measures for low emission scenarios differ from those for high emission futures. Averaging the ranks of countries for both high and low scenarios, the list of countries facing the highest levels of SLR are: the USA, Canada, Russia, South Africa and Mozambique (tied for 4th place), Japan, Australia and New Zealand (tied for 7th place), Madagascar and Mauritius, in order of decreasing rank.

3. Exposure differs across SSP scenarios because of population differences, even with total land area in the 50km coast remaining the same under both low and high emission pathways. Averaging their exposure ranks across the five future scenarios, the countries with highest exposure in decreasing order are: the USA, Indonesia, China, India, Brazil, Viet Nam, Nigeria, Bangladesh, Egypt and Australia.
4. Using HDI Gap as vulnerability metric, the most vulnerable countries, based on their average vulnerability ranks across five future scenarios in decreasing order are: Somalia, Mozambique, Sierra Leone, Liberia, Madagascar, Guinea-Bissau, Solomon Islands, Eritrea, Papua New Guinea and Benin.
5. The ten countries most threatened by SLR indicated by the SLR Risk Index, on average and across the five reference projection pathways (in decreasing order) are: Somalia, Mozambique, Madagascar, Angola, Liberia, Sierra Leone, Papua New Guinea, Senegal, Guinea-Bissau and Mauritania. Seven of these coastal states are identified among the most vulnerable.
6. Despite an overall projected trend of increasing levels of human development among all countries and regions across all reference futures, there are scenarios, for example high emission SSP3 (stalled development) where gender-sensitive education indicators are projected to decrease, and which contribute to increasing vulnerability and risk by 2100. Even if these do not decrease, such as when the proportions of females that finish tertiary education are increasing but not fast enough, vulnerability is projected to remain significantly high for these countries.
7. Societal choices reflected in the five reference development pathways underpin hazard, exposure and vulnerability metrics of risk to SLR. They also indicate strategic ways to mitigate risk. Reducing emissions and population growth are critical, but reducing vulnerability by nurturing human development, appears the most prudent with long-term generational impacts. The reduction of risk through improved education, health and income are key to sustaining households and societies. However, human development must be pursued within a sustainability framework where clear limits in greenhouse gas emissions are capped for both developing and developed economies, despite uncertainties in projecting sea level rise, and in predicting low probability but high impact SLR scenarios.

4.5.2 Main Findings, Discussion and Conclusion

Wellbeing and future scenarios of sea level change

Sea level rise (SLR) is a cumulative response of the oceans and the cryosphere to atmospheric warming caused by the mounting concentration of greenhouse gases emitted during fossil fuel burning and from land-use changes such as deforestation. In the fifth assessment (AR5) of the Intergovernmental Panel for Climate Change (IPCC), Church et al. (2013) reported that ocean warming and glacial and ice sheet melting explain 75 per cent of the observed increase in global mean SLR from the early 1970s to 2010. Based on process-based models used in this assessment, the global mean SLR in the future Representative Concentration Pathway (RCP)8.5 reference scenario (warmest scenario) is projected, with medium likelihood, to reach a median value of 74 cm with a range of 0.52 to 0.98 m (5 to 95 per cent range) by 2100 (Table 13.5 in Church et al. 2013); for RCP4.5, the projected median value by 2100 is 53 cm with a range of 0.36 to 0.71 m (5 to 95 per cent range).

The report further indicates that toward the end of the current century, it is very likely that over 95 per cent of the global ocean will experience sea level rise, with the remaining areas located near glaciers and ice sheets very likely to experience sea level fall. Church et al. (2013) estimated that about 70 per cent of coastal areas are projected to experience relative sea level change within 20 per cent of the global mean. The sea level estimates used in the current study are obtained from AR5, for RCP4.5 (low emission) and RCP8.5 (high emission) scenarios.

The AR5 report on SLR (Church et al 2013) has triggered critical reviews of the models used to generate current and future SLR estimates, the confidence intervals around these estimates, and inability of the IPCC to evaluate ice sheet instabilities, which may underpin potentially catastrophic and rapid increases in SLR. Hinkel et al. (2015) state that low probability upper-bound scenarios are needed for risk management, and that the AR5 SLR assessment fails to provide these. While true, this criticism reflects the state of the science, and Church et al 2013, point out that what was known at the time of the fifth assessment was deemed insufficient to provide scientific guidance on upper bound SLR contributions from melting ice sheets. On the issue of the wide disparities between projections provided by semi-empirical models with those derived from processed-based models which IPCC prefers, Kopp et al (2016) very recently estimated GSL over the last 3000 years using Bayesian semi-empirical modelling, and provided 2100 projections that overlap those of Church et al 2013. Mengel et al (2016a) showed component-based contributions to 2100 GSL using Bayesian semi-empirical modelling as well, and the 5-95% ranges at component-scale likewise overlap with those of Church et al (2013). However, it is important to note that these more current semi-empirical models, like the AAR5 process-based models, are still unable to incorporate instabilities in ice sheet dynamics because of lack of prior analogues for semi-empirical models and inadequate representation of ice sheet instability in process-based models.

Because of many unknowns and large uncertainties in current knowledge about ice sheet melt and its contribution to sea level rise, Church et al. (2013) did not provide an upper bound of sea level rise by 2100. Jevrejeva et al. (2014) published a low probability upper limit of 1.8 m for sea level rise by 2100, using expert elicitation from ice sheet scientists to fill in the significant observation gaps. Though not definitive, providing an estimate of upper bound sea level rise, imperfect though it may be, fills a serious need among risk-averse coastal planners (Hinkel et al. 2015, Jevrejeva et al. 2014). Kopp et al. (2014) provides a consistent set of local sea level rise estimates, including the contribution of ice sheet melting, around a global network of tide gauges with probability distributions as an initial attempt to provide information useful for local coastal planning.

A number of studies have turned to examine past warm periods when ice sheets lost considerable mass resulting in significant sea level rises. Kopp et al (2009) showed that peak global sea level during the last interglacial stage (about 125 thousand years ago), a partial analogue of a 1-2°C warming scenario, very likely (95% probability) exceeded 6.6 m higher than today, and likely (67% probability) to have reached above 8.0 m, but was unlikely (33% probability) to have exceeded 9.4 m, with millennial SLR rates very likely exceeding 5.6 m per thousand years and unlikely exceeding 9.2 m per thousand years. Although these earlier periods might not be analogues of a future earth that is greatly anthropogenically altered relative to greenhouse emissions, pollutants, and other factors, the high uncertainty and potentially catastrophic consequences of significant ice-sheet melting leading to multi-metre sea level rise over thousand years in the future make the science and politics of sea level rise as contentious as ever. Very recently, Mengel et al (2016b), using simulations of warm water intrusion into the cavity of West Antarctica's Filchner-Ronne ice shelf over the next two centuries, showed that ice melt is determined by the strength of ocean warming, which when weak may be dominated by local ice instabilities. These findings suggest that scientists and citizens alike need to be open to low probability but high impact futures as potential scenarios of sea level change.

The uncertainty and contentiousness of SLR impacts become magnified and made more complex when linked to examining how coastal societies may respond to sea level rise in the future. The exposure of coastlines and human populations and infrastructure to coastal erosion, flooding, storm surges, saltwater intrusion to near shore aquifers, and gradual submergence of wetlands and coastal ecosystems threaten lives, livelihoods, properties and economies. Talaue-McManus and Estevanez (2016) estimate that about 40 per cent of the global population, or 2.7 thousand million people, lived within the 100 km coastal zone, which account for 22 per cent of the global land area, in 2010. Compared to inland areas, the global coastal zone is crowded, with nearly 60 per cent of coastal inhabitants living in urban centres. The increase in economic activity and wealth in the coastal zone accounts in full for the increases in losses in areas susceptible to land-falling tropical cyclones in the past six decades (Weinkle et al. 2012; Mendelsohn et al. 2012). However, there is also unevenness in the distribution of wealth so that, on average, one in five coastal dwellers worldwide is considered poor on the basis of national poverty standards (Talaue-McManus and Estevanez 2016). Given these baseline conditions of today's global coast, one may ask how these will change in the years leading to 2100, the reference year for projections of a warming planet and a rising sea. How may the present day sources of vulnerabilities persist, and if so, be mitigated, to enhance the capacity of coastal societies to cope with climate change, including sea level rise?

Previous studies have examined impacts of sea level rise. Nicholls et al (1999) and Nicholls (2004) examined flood risk and wetland losses under various SLR and socioeconomic scenarios. Dasgupta et al. (2011) analysed the exposure of 84 developing countries to modelled storm surges and sea level rise of 1 m using six indicators of exposure (exposed land area, population, economic activity, urban extent, agricultural extent and wetlands), but were limited to using current conditions of land use, population and GDP. Hinkel et al (2014) analyzed coastal inundation damage and adaptation costs at global scale under 21st century sea level rise. Neumann et al. (2015) examined coastal population growth and exposure to sea level rise and coastal flooding for 2000 (baseline), 2030 and 2060 using scenario guidelines developed by the UK's Foresight Project on Migration and Global Environmental Change. The current study focuses on the RCP scenarios that influence land use and sea level rise changes for the period 2010 to 2100; and the SSP scenarios that prescribe the trends in population and well-being among coastal states and their resulting vulnerability to sea level rise over the same period.

The study aims to provide scenarios of spatially distributed coastal populations and land area in the coastal zone to 2100. To make these estimates computationally feasible, we chose two physical pathways (RCP4.5 and RCP8.5) and five socioeconomic pathways, combined to form internally consistent development scenarios: SSP1 and SSP4 combined with RCP4.5 to form low emission development scenarios; and SSP2, SSP3 and SSP5 combined with RCP8.5 to form high emission development scenarios.

The high emission pathway chosen for this exploratory study is RCP8.5, with radiative forcing reaching >8.5 W/m^2 by 2100, then increasing further. This pathway features increasing greenhouse gas emissions which lead to high concentrations of greenhouse gases (1 370 ppm CO_2 equivalent) with a projected median temperature increase of 4.9°C above the pre-industrial level by 2100 (Riahi et al. 2007, Riahi et al. 2011, Rogelj et al. 2012).

The low emission pathway is RCP4.5, with radiative forcing reaching 4.5 W/m^2 by 2100, stabilizing at this level after 2100 without overshoot. In this pathway, the median temperature increase reaches 2.4°C above pre-industrial level, and with an equivalent CO_2 emission of 650 ppm in 2100 (Thomson et al. 2011, Rogelj et al. 2012).

Both radiative forcing pathways set the sea level rise values used in this study following the IPCC Fifth Assessment of sea level change (Church et al. 2013). For total land areas, we processed the RCP8.5 land-use model data layer (Hurtt et al. 2006) to obtain the total land area at elevations ≤10 and higher, co-located in ≤10 km, ≤30km and ≤50 km coastal widths. We assumed that the total coastal land areas in 2100 under RCP4.5 to be the same as those in RCP8.5.

A second objective of this study is to explore wellbeing and vulnerability to sea level rise using modelled time series of metrics from 2010 to 2100. These models follow the reference characteristics of the Shared Socioeconomic Pathways developed by the IPCC Working Group II (O'Neill et al. 2014; O'Neill et al. 2015). The RCP pathways are combined with appropriate SSP development pathways to make coherent physical-socioeconomic future narratives as a context for exploring risk to climate-related phenomena including sea level rise. For this study, low emission-based scenarios SSP1-RCP4.5 and SSP4-RCP4.5 and high emission-based scenarios SSP2-RCP8.5, SSP3-RCP8.5 and SSP5-RCP8.5, provide the integrated internally coherent reference contexts for the analysis of hazard, exposure, and vulnerability to evaluate overall risk.

Main Findings, Discussion and Conclusions

Sea level rise to 2100 under RCP4.5 and RCP8.5. Figure 4-43 shows the changes in sea level in 2010 and 2100 under RCP4.5 and RCP8.5. Table 4-2 provides the ranges of country-scale maximum SLR projections aggregated by regions for both low and high emission scenarios.

Under the low emission scenario (RCP4.5), the United States and Canada have the highest projected SLR by 2100 at 0.725 m and 0.694 m, respectively. The Caribbean (0.628 m), Eastern Europe (Russia and Poland only) (0.624 m), Eastern Africa (0.617 m), Southern Africa (0.609 m), Eastern Asia (0.604 m) and Oceania (0.601 m) have the highest projected SLR at regional scale.

Under the high emission scenario (RCP8.5), the United States in Northern America and Russia in Eastern Europe are projected to experience the highest SLR at over 0.9 m. The tropical coastal regions of Africa, Asia, Oceania, Central America and the Caribbean are projected to have high SLR maxima at or higher than 0.8 m. About 131 countries or 94 per cent of 139 coastal states examined face projected SLR of 0.6 m and higher by 2100. Under a low emission scenario (RCP 4.5), 128 countries of 139 assessed are projected to experience SLR levels below 0.6 m by 2100.

The SLR estimates above require further fine-scale calibration. At the coast, what is critical is 'total' relative sea level change which is the net sum of (1) sum of global mean rise and the regional variability; (2) static factors (e.g. solid earth responses such as land uplift with melting of overlying ice and icequakes triggered by fracturing ice) causing regional sea level change, and (3) local vertical land movement (Cazenave and Le Cozannet 2013). While global models can help elucidate global mean sea level change and regional variability, these require complementary analysis of additional sources of relative sea level rise and an assembly of fine-scale data and analysis by national communities of scientists to resolve static factors and local vertical land motion so that the estimated magnitude of SLR that would impact coastal communities may be further constrained. The RCP projections above are therefore coarse estimates that finer-scale studies need to fine-tune for these to become relevant to the needs of local coastal planning.

Equally important to stress is the uncertainty introduced by rapid ice-sheet melting dynamics which Church et al. (2013) could not evaluate during the IPCC AR5 because of inadequate knowledge at the time. The low probability upper bound of global mean sea level rise of 1.8 m as proposed by Jevrejeva et al. (2014), together with other estimates from other models, such as semi-empirical approaches (Vermeer and Rahmstorf 2009), also need to be systematically examined and regionalized. Kopp et al. (2014) provide local SLR estimates with probability distributions for a global tide gauge network, incorporating the influences of ice-sheet dynamics and groundwater extraction, among others. For this current study focusing on global comparisons of local SLR, the use of what may appear as conservative estimates of regional sea level rise by Church et al. (2013) are considered first approximations and work in progress.

Figure 4.43. Hazard metrics. RCP 4.5 total ensemble mean sea surface height for (a) 2010 and (b) 2100, and RCP 8.5 total ensemble mean sea surface height for (c) 2010 and (d) 2100. Maps were plotted using the University of Hamburg Integrated Climate Data Center Live Access Server at http://www.icdc.zmaw.de/las/getUI.do. Note that the color legend for each map differs in values as the range of minimum and maximum sea level rise estimates increases with time.

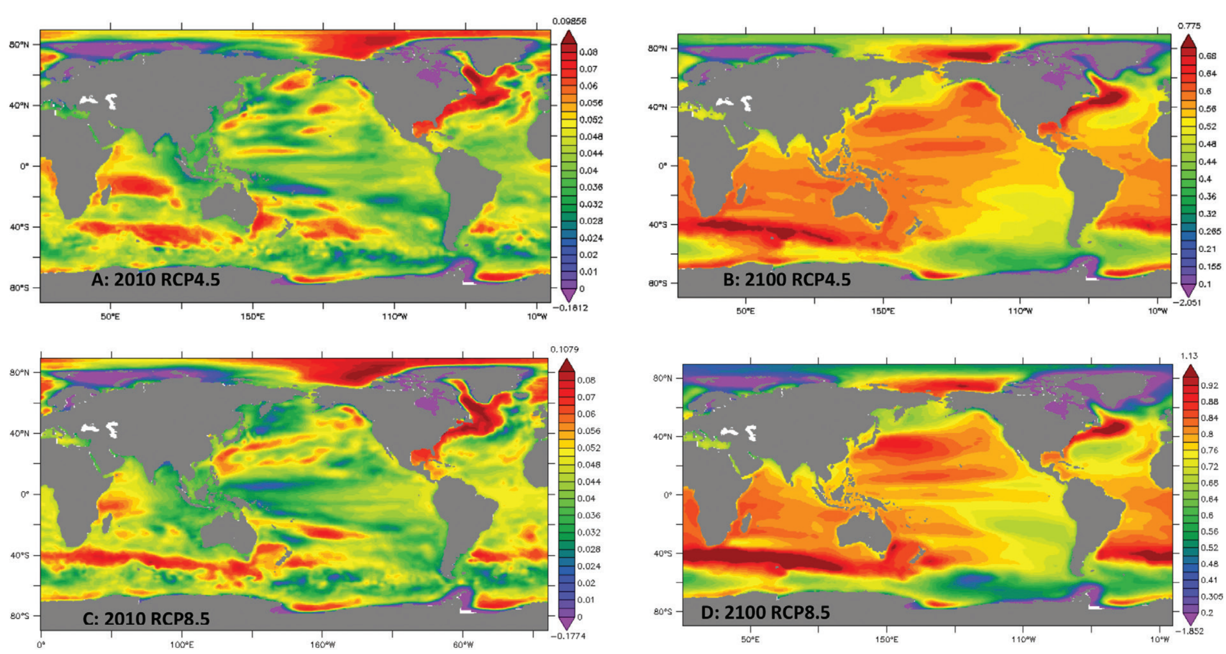


Table 4.2 Hazard metrics using ranges of country-scale maximum sea level rise derived from RCP8.5 projections of Church et al. (2013) in the IPCC AR5.

Region	RCP 8.5		RCP4.5	
	Low Maximum SLR (Country-scale, m)	High Maximum SLR (Country-scale, m)	Low Maximum SLR (Country-scale, m)	High Maximum SLR (Country-scale, m)
Northern Africa	0.675	0.743	0.463	0.485
Western Africa	0.750	0.836	0.524	0.562
Middle Africa	0.785	0.836	0.552	0.595
Southern Africa	0.828	0.851	0.578	0.609
Eastern Africa	0.702	0.845	0.465	0.617
Western Asia	0.402	0.778	0.380	0.559
Southern Asia	0.669	0.801	0.392	0.572
Southeastern Asia	0.716	0.814	0.528	0.596
Eastern Asia	0.750	0.830	0.523	0.604
Oceania	0.784	0.861	0.580	0.601
Northern America	0.890	0.960	0.694	0.725
Central America	0.734	0.800	0.506	0.592
Southern America	0.691	0.784	0.475	0.580
Caribbean	0.732	0.805	0.550	0.628
Northern Europe	0.293	0.742	0.070	0.508
Western Europe	0.677	0.759	0.485	0.539
Southern Europe	0.587	0.710	0.393	0.556
Eastern Europe*	0.625	0.904	0.365	0.624

**No sea level rise data for Bulgaria, Georgia, Romania and Ukraine, around the Black Sea.*

Legend:		Countries RCP8.5	Countries RCP4.5
SLR ≥ 0.900	Very high SLR	2	0
0.800 ≤ SLR < 0.900	High SLR	27	0
0.700 ≤ SLR < 0.800	Medium SLR	70	1
0.600 ≤ SLR < 0.700	Low SLR	32	10
SLR<0.600	Very low SLR	8	128
	No SLR data	4	4

Total land areas and RCP8.5 land uses in the coastal zone in 2100. For both land use area and population distribution in the coastal zone, we define those co-located within the ≤10 m elevation and within the ≤50 km from shore to be the most susceptible to the adverse impacts of SLR and associated phenomena such as coastal storm surges and episodic coastal inundation. The chosen elevation ranges are dictated by the overall vertical resolution of the ACE2 DEM of about 5 m, which varies with location and the extent to which altimeter and Shuttle Radar Tomography Mission (SRTM) readings, which provided digital elevation data at near global scale, have been blended. The estimated land and population distribution in coastal space, defined by intersecting elevation and distance from shore for the 50 km global coastal width, is the first global data set of its kind. Other global data sets provide distribution estimates by elevation independently of those by distance from shore, as in the case of CIESIN population data layers (2013). The use of three-dimensional spatial distribution of population and land use is required for modelling physical and socioeconomic impacts of coastal processes such as flooding. At a global scale, the GIS implementation is computer-intensive and at best coarse. However, the approach is invaluable for comparing magnitudes of potentially affected populations and areas along the global coast notwithstanding the variable widths of floodplains.

For the current study, we use total land areas in the 10 m elevation intersecting the 50 km coast as land exposure metrics. The computer-intensive land use analysis was done only for RCP8.5, results for which are presented in Annex Table 1. Comparison of land use between low and high emission scenarios will be done when analysis of RCP4.5 data is completed. Values for total area include inland waters, ice, and desert areas in addition to the three evaluated land-use areas, as applicable. For RCP8.5 agricultural land use in 2100, areas within the coastal zone (10 m elevation X 50 km from shore) are widest in Southeastern Asia (99 296 km^2), Southern America (74 538 km^2), Oceania (mostly Australia, 62 447 km^2), Central America (57 268 km^2), Southern Asia (46 534 km^2) and Eastern Africa (33 841 km^2). These areas may be widened as locally and regionally appropriate, depending on the widths of the coastal floodplains. Approximate areas for coastal widths ≤ 10 km and ≤ 30 km from shore and up to 10 m elevation are provided in Annex Table 1.

Urban land use within the ≤ 10m elevation - 50 km coastal space is highest in Eastern Asia (10 963 km^2), Southeast Asia (7 988 km^2), Northern America (4 993 km^2), Southern Asia (3 894 km^2), Western Africa (3 878 km^2), and Western Europe (3 784 km^2).

Primary and secondary vegetated areas in the coastal zone are most extensive in Southeast Asia (162 827 km^2), Northern America (148 946 km^2), Eastern Europe (79 697 km^2), Southern America (79 181 km^2), Oceania (51 181 km^2), Central America (45 585 km^2) and Northern Europe (44 370 km^2).

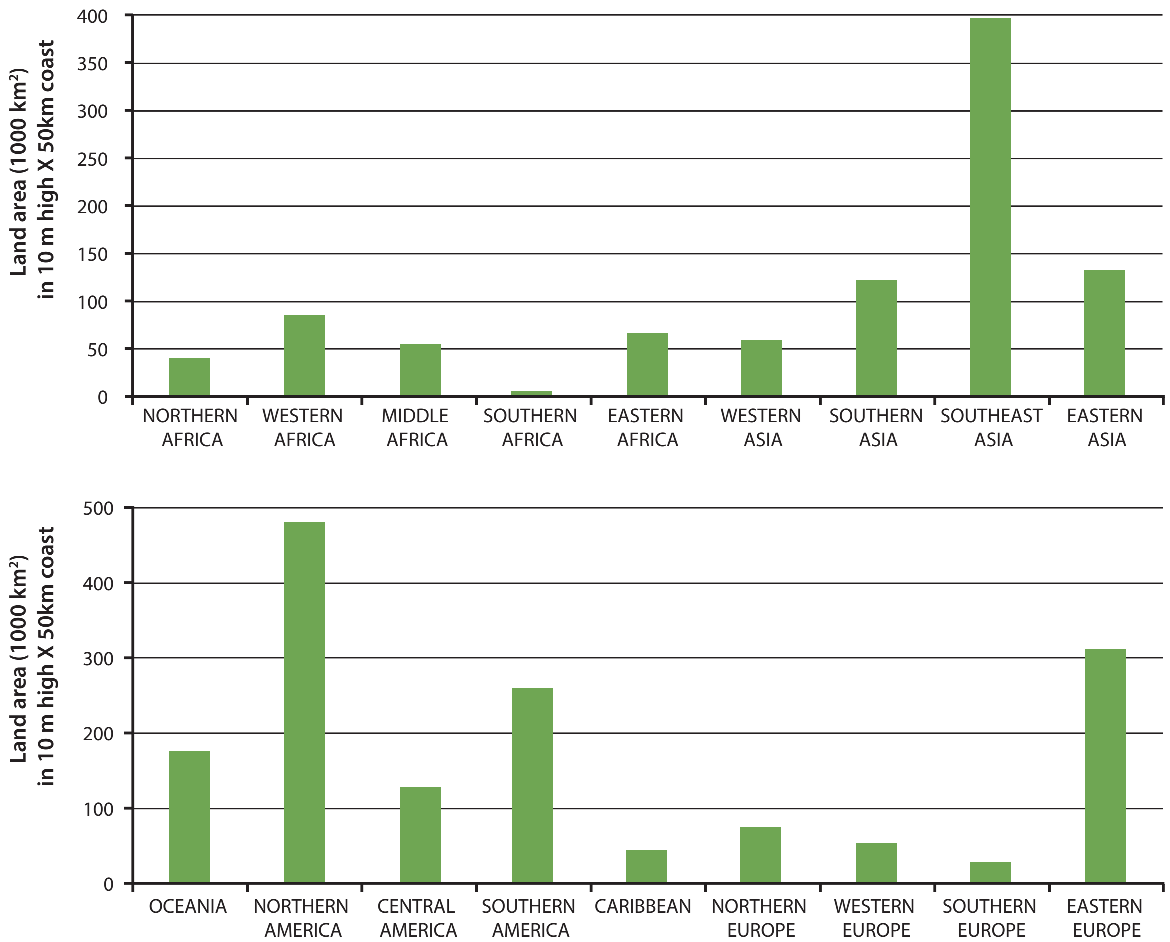
Figure 4.44 shows coastal land areas in the 10 m elevation co-located in the 50 km coast for 139 countries aggregated into 18 regions, and which are the same for both low and high emission reference futures in 2100. Northern America (480 049 km^2), Southeastern Asia (397 495 km^2), Eastern Europe (330 654 km^2), and Southern America (260 002 km^2) have the highest land exposure (in decreasing order).

SSP populations in the coastal zone in 2100. In analysing population trends to 2100, the modelled data for SSP 1-5 narratives are used. Figure 4-45 shows the regional populations in 2100 totals by SSP pathways, grouped into low emission (SSP1 and SSP4) and high emission (SSP2, SSP3, and SSP5) scenarios. Population increase is most pronounced for SSP3 (Regional Rivalry) where population growth rates and fertility rates are high for both high and low fertility countries, and low for rich OECD countries (O'Neill et al. 2015). Major population centres in Southern Asia (22 per cent), Southeastern Asia (15 per cent), Western Africa (11 per cent), Eastern Asia (8 per cent) and Northern Africa (8 per cent) account for 64 per cent of the most susceptible coastal inhabitants.

SSP2 (Middle of the Road) and SSP4 (Inequality) follow similar patterns. SSP2 features moderate growth rates. SSP4 exhibits high population growth and high fertility rates for high and low fertility countries, and low population growth and low fertility rates for rich OECD countries. SSP5 (Fossil-fuel led development) has the second to lowest population growth rates with low growth and fertility rates for both high and low fertility countries, and low growth but high fertility for rich OECD nations. SSP1 (Sustainable World) has the lowest population growth where fertility is maintained low for both High and Low Fertility countries, and kept at medium for rich OECD states.

Table 2 shows the spatial distribution of the coastal population within 10 m elevation by 10, 30 and 50 km coastal zone by SSP. The spatially explicit distributions in co-located elevation and width coastal spaces allow for comparisons, and may be customized to actual widths of floodplains in refining exposure at finer scales. Because the SSP country populations are time-series values and not geo-referenced data sets, the populations are distributed spatially following national ratios obtained when the CIESIN (2013) population data layer is wrapped on the ACE2 DEM. The ratios of populations by distance from shore are therefore constants across SSPs. There is no reason to believe that population distribution will follow a single pattern across reference SSPs. In the absence of geo-referenced population data layers for the SSPs, we use the resulting populations in the 10 m high X 50 km distance from shore as coarse and proxy measures of exposure. Highly exposed populations, or those within the 10m high X 10 km distance from the coast, make up 55 per cent of the total SSP global population within the 50 km coastal zone. Those projected to be within 10 m high X 30 km distance account for 85 per cent of the projected SSP global population in the 50 km wide coastal zone. Under a low emission scenario, exposed population in the 10 m X 50 km coast in 2100 for 139 countries varies from 574 million for SSP1 to 645 million for SSP4. Under a high emission scenario, exposed population is least in SSP5 at 631 million, increasing to 697 million in SSP2 and is largest at 937 million in SSP3.

Figure 4.44. Exposure metrics. Land area up to 10 m elevation co-located within 50 km distance from shore in 2100 for 139 SSP countries. Land areas are assumed to be the same across the five reference futures. Northern America, Southeastern Asia, Eastern Europe and Southern America, have the highest land exposure, in decreasing order.



Global Trends in well-being and vulnerability for 2010-2100. In this section, we explore the trends in well-being metrics, some of which we use to construct Human Development Indices (HDI) over the same period as a way of comparing capacities of countries and regions to deal with climate change including sea level rise.

The influence of individual metrics at the global scale are explored in this section (Figure 4): life expectancy at birth (E0), mean years at school, the proportion of females of childbearing ages (20-39 years) with tertiary education, and per-capita gross domestic product over the next 90 years, across the five reference socioeconomic pathways (SSP1-5). Figures 4-46B to 4-46F show the global trends. Life expectancy at birth for SSPs 1 and 5 follow almost the same pattern, with very long life expectancies resulting from high investments in health (Annex Table 2) (Figure 4-46B). By

Figure 4.45. Exposure metrics. Regional population under low emission SSPs (SSP1 and SSP4) and high emission SSPs (SSP2, SSP3 and SSP5) within the 10 m elevation intersecting the 50 km coast in 2100.

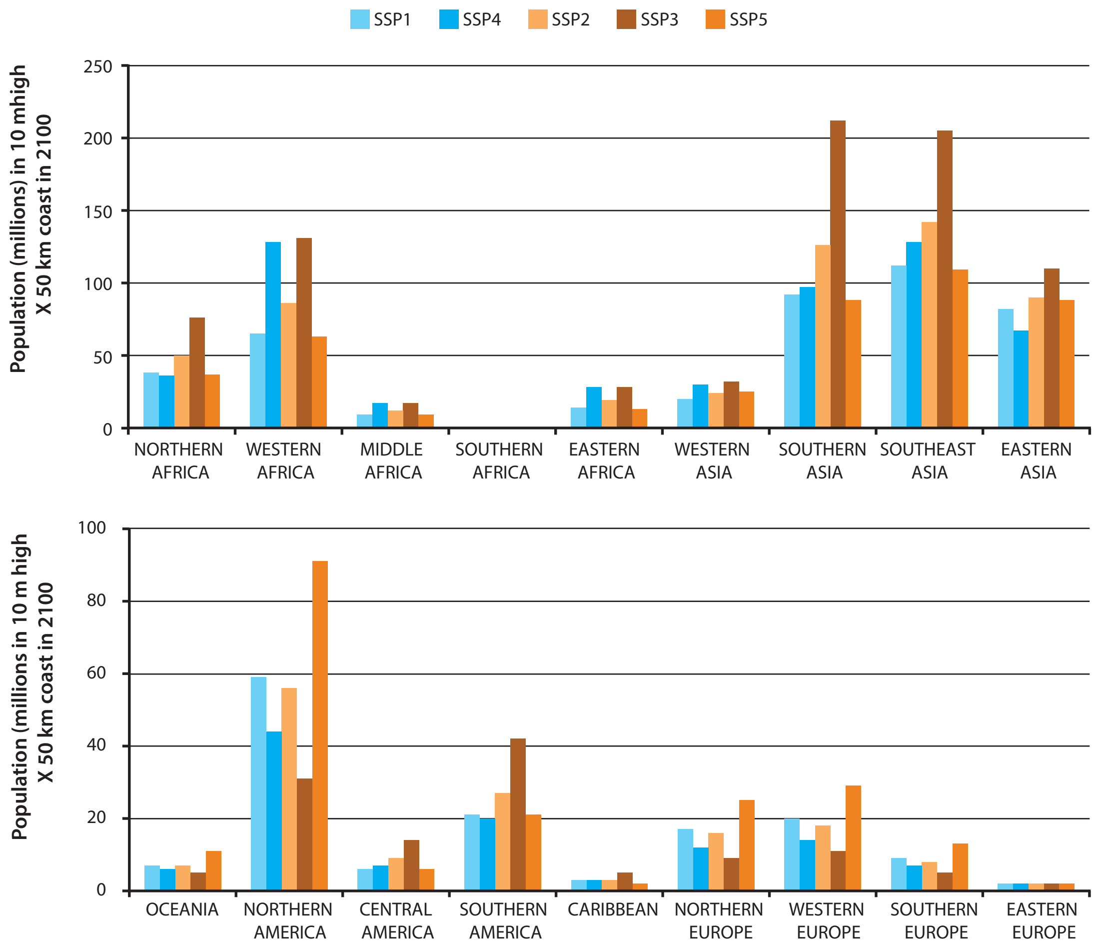


Table 4.3 Exposure metrics. Distribution of population in 2100 at 10 m elevation by SSP and by distance from shore. SSP1 and SSP4 are consistent with low emission scenarios (RCP4.5); SSP2, SSP3, and SSP5 are consistent with high emission scenarios (RCP8.5).

Region	SSP	Population 2100 at 10 m elevation			Region	SSP	Population 2100 at 10 m elevation		
		≤ 10 km	≤ 30 km	≤ 50 km			≤ 10 km	≤ 30 km	≤ 50 km
Northern Africa	SSP1	18 921 508	28 377 924	37 638 229	Oceania	SSP1	5 672 756	6 842 438	6 947 599
	SSP4	18 282 806	27 251 694	35 930 284		SSP4	4 984 728	6 009 662	6 107 938
	SSP2	25 274 792	37 941 185	50 361 098		SSP2	5 540 517	6 673 059	6 777 230
	SSP3	38 339 921	57 515 168	76 259 132		SSP3	3 750 129	4 475 109	4 547 566
	SSP5	18 336 766	27 510 562	36 512 449		SSP5	8 928 994	10 799 733	10 964 779
Western Africa	SSP1	27 664 878	49 551 338	64 508 737	Northern America	SSP1	34 306 200	55 983 986	59 151 247
	SSP4	55 143 310	98 186 754	128 248 835		SSP4	25 531 097	41 680 349	44 038 619
	SSP2	37 409 759	66 391 509	86 293 608		SSP2	32 195 829	52 560 434	55 534 294
	SSP3	56 095 045	100 016 761	130 719 691		SSP3	17 997 647	29 414 365	31 079 084
	SSP5	26 908 880	48 268 466	62 883 565		SSP5	52 901 299	86 235 760	91 113 188

Region	SSP	Population 2100 at 10 m elevation			Region	SSP	Population 2100 at 10 m elevation		
		≤ 10 km	≤ 30 km	≤ 50 km			≤ 10 km	≤ 30 km	≤ 50 km
Middle Africa	SSP1	6 344 423	8 803 852	9 123 719	Central America	SSP1	3 554 787	5 492 797	6 448 535
	SSP4	11 523 934	16 171 508	16 721 602		SSP4	4 399 961	6 500 707	7 468 287
	SSP2	8 409 515	11 773 382	12 188 677		SSP2	4 809 296	7 416 771	8 699 621
	SSP3	11 448 807	16 074 659	16 629 143		SSP3	7 936 055	12 233 985	14 350 346
	SSP5	6 399 044	8 879 108	9 199 010		SSP5	3 264 004	5 020 239	5 881 681
Southern Africa	SSP1	300,143	304 665	304,684	Southern America	SSP1	15 135 693	19 896 410	21 261 404
	SSP4	255,042	258 610	258,626		SSP4	14 419 048	18 984 376	20 328 187
	SSP2	355,352	360 694	360,717		SSP2	19 497 096	25 653 055	27 436 107
	SSP3	428,258	434 641	434,669		SSP3	29 729 748	39 209 220	42 036 736
	SSP5	316,358	321 146	321,167		SSP5	14 674 964	19 295 648	20 616 200
Eastern Africa	SSP1	12 266 097	13 680 955	13 882 315	Caribbean	SSP1	2 311 275	2 604 206	2 641 798
	SSP4	24 462 134	27 155 641	27 522 832		SSP4	2 689 449	2 999 490	3 035 534
	SSP2	17 199 837	19 138 480	19 408 497		SSP2	2 825 665	3 196 285	3 245 600
	SSP3	25 188 042	27 939 072	28 312 678		SSP3	4 480 926	5 094 307	5 177 595
	SSP5	11 755 896	13 131 036	13 328 041		SSP5	2 047 991	2 307 726	2 341 681
Western Asia	SSP1	15 902 381	18 286 937	19 863 776	Northern Europe	SSP1	11 836 856	14 984 688	16 535 033
	SSP4	23 130 757	27 543 133	29 749 206		SSP4	8 261 444	10 488 256	11 581 930
	SSP2	19 443 580	22 559 362	24 532 687		SSP2	11 212 176	14 219 741	15 684 222
	SSP3	24 839 674	29 403 468	32 336 333		SSP3	6 636 674	8 493 075	9 328 686
	SSP5	20 530 491	23 204 401	25 012 617		SSP5	17 885 491	22 606 353	24 961 713
Southern Asia	SSP1	47 976 665	76 228 125	92 106 690	Western Europe	SSP1	9 231 124	16 780 785	19 813 852
	SSP4	52 428 398	81 201 138	97 219 482		SSP4	6 591 287	11 978 638	14 143 319
	SSP2	65 988 530	104 572 861	126 203 985		SSP2	8 566 617	15 564 839	18 370 727
	SSP3	111 427 754	175 957 292	211 985 040		SSP3	5 049 534	9 195 880	10 848 562
	SSP5	45 952 038	72 747 852	87 725 184		SSP5	13 382 293	24 248 090	28 624 289
Southeastern Asia	SSP1	60 049 935	95 171 376	111 593 598	Southern Europe	SSP1	6 881 471	8 040 619	8 500 623
	SSP4	73 914 139	111 693 973	128 196 473		SSP4	5 311 805	6 204 957	6 558 300
	SSP2	76 809 254	121 518 967	142 233 682		SSP2	6 431 026	7 525 358	7 952 876
	SSP3	110 946 639	175 218 072	205 088 823		SSP3	3 969 060	4,684,651	4 939 313
	SSP5	58 693 429	92 811 127	108 817 286		SSP5	10 178 438	11 841 677	12 521 245
Eastern Asia	SSP1	33 200 207	65 879 638	82 014 203	Eastern Europe	SSP1	1 028 245	1 860 839	2 495 193
	SSP4	26 548 726	53 133 901	66 679 327		SSP4	876 574	1 626 795	2 187 617
	SSP2	35 533 367	71 545 648	90 051 796		SSP2	1 193 064	2 233 035	3 005 348
	SSP3	41 001 230	85 533 444	110 253 682		SSP3	1 326 848	2 563 169	3 450 585
	SSP5	36 998 973	71 961 049	88 395 612		SSP5	1 187 312	2 114 644	2 835 841

2100, modelled results indicate that 88 countries in SSP1 (Sustainable World) and 83 countries in SSP5 (Fossil-fuel led development) are projected to reach the aspirational goalpost of 100 years life expectancy. SSP2 (Middle of the Road) prescribes medium health investment resulting in a global mean of 86.1 years compared to 97.6 years for SSP1 and 97.7 for SSP 5. SSP4 (Inequality) features unequal health investments within regions with lower inputs in low-income countries, and medium investments in high-income countries, achieving a global mean life expectancy of 73.4 years by 2100. SSP3 is projected to reach the lowest life expectancy with a global mean of 71.8 years by 2100 given the low health investment in its narrative. For perspective, the 2014 HDI maximum goalpost for health is 85 years and the minimum is 20 years.

The mean years-at-school (MYS) metric is a contemporary measure of educational achievement and a useful gauge in future well-being scenarios (Figure 4-46C). In the SSP1 and SSP5 narratives, educational achievements are projected to be high, reaching 12.5 years and 12.4 years, respectively by 2100, allowing for completion of secondary education. For SSP2, moderate education levels are achieved with MYS reaching 11 years, a little short of the time required to obtain a high-school diploma. In SSP4 (Inequality), high fertility countries achieve very low education goals with uneven distribution; low fertility countries reach low education goals with uneven distribution; and OECD countries achieve medium goals, also with uneven distribution. The resulting projected global mean for SSP4 is 6.7 years, which is slightly longer than required to complete elementary education. SSP3 (Stalled development) is projected to achieve very low levels of education with a global MYS of 6.3 years.

A gender-sensitive education metric that has not yet been integrated in contemporary HDI is the proportion of females of childbearing age with tertiary level of education relative to the female population of the same age group (20-39 years of age) (Figure 4.46D). Because of the strong correlation between high female educational achievement and low fertility (Samir and Lutz 2014; Lutz et al. 2014), the role of female education in increasing well being and resilience at the household level appears as a logical policy target. We set a maximum goal post of 70 per cent for the 90-year period, with the highest proportion reached across the 5 SSP scenarios by 2100. SSP1 and SSP5 follow identical trajectories, SSP1 reaching a global mean of 64 per cent by 2100, and SSP5 reaching 65 per cent. SSP2 is projected to lag, at 50 per cent. The Inequality World of SSP4 is projected to achieve a global mean of 23 per cent and the Stalled Development scenario of SSP3 shows a reduced global mean of 11 per cent compared to the 2010 mean of 16 per cent, a decrease in female education achievement 90 years into the future. In this study, this measure is used as a second education metric in the construction of the HDI, replacing the measure Expected Years at School used in present HDI, for which projections by SSP are not available.

A third education measure is the Gender Gap in Education Attainment, which is the ratio of male to female 25 years and older (Figure 4.46E). Like the metric above, gender-sensitive indicators focus on the abilities of the female populations to assume their critical reproductive and quality-of-life enhancing roles at household and societal levels. Both SSP1 and SSP5 reach a global mean ratio of 0.97 (males/female) by 2100, meaning that females exceeded males in education for the age group 25 years and older. For the Middle of the Road scenario of SSP2, a global mean ratio of 0.99 males/female is achieved. For the Inequality narrative of SSP4, a sizeable gender gap is projected to exist at 1.06 males per female. For the Stalled Development pathway of SSP3, the ratio increases to 1.09 males per female.

The education metrics examined above show that in the narratives of SSP4 (Inequality) and SSP3 (Stalled Development), MSY and educational accomplishment of the female population are projected to decrease, as well as increases in the education gender gap. The manifestations of these will be more pronounced among developing countries and is discussed in greater detail below.

Per-capita GDP is a standard metric of human development. Figure 4.46F shows that wealth is projected to increase across all 5 reference SSPs. The Fossil-led Development scenario of SSP5 is projected to have the highest mean global GDP at 2005 US$1 X 1015 PPP by 2100. The Sustainable World scenario of SSP1 is projected to have high per-capita growth in low-income and medium-income countries and medium growth in high-income countries, all resulting in a global mean GDP of 2005 US$570 X 1012 PPP in 2100. The Middle of the Road SSP2 scenario has medium and uneven growth, reaching 2005 US$540 X 1012 PPP by 2100. The SSP4 Inequality scenario has low per-capita growth in low-income countries and medium in other countries, leading to a low global mean of 2005 US$360 X 1012 PPP by 2100. Finally for the SSP3 Stalled Development World, per-capita growth is slow, reaching a global mean of 2005 US$280 X 1012 PPP in 2100.

Figure 4.46. Vulnerability metrics. Global estimates of (a) population, (b) life expectancy at birth, (c) mean years at school, (d) %females of childbearing ages (20-39 years) with tertiary education, (e) gender gap in educational attainment, and (f) per capita GDP for the five reference Shared Socioeconomic Pathways (SSPs). SSPs are cohesive descriptions of socioeconomic development pathways that are used to examine future long-term scenarios in the search for effective measures to adapt to and mitigate climate change. SSP1 is called the Sustainability Pathway, SSP2 is Middle of the Road, SSP3 features regional rivalry, SSP4 highlights inequality, and SSP5 is fossil-fueled development (O'Neill et al 2015). Except for the average proportion of females with tertiary level education that is based on 143 modeled countries, the average metrics are based on 185 modeled countries (including coastal and landlocked).

Regional HDI Patterns in 2100. To examine the regional texture of the well-being metrics discussed above, a HDI is constructed at country scale annually over the period 2010-2100, combining life expectancy at birth, mean years at school, proportion of females of childbearing age with tertiary level education, and per-capita GDP, as discussed in the methods section. The country-scale HDIs are aggregated to derive the mean regional HDIs to conform with the coarse scale of land use and sea level rise measures, and are presented as time series. The current HDI classification scheme is used to compare the regions: 0.8+ (Very high); 0.7 ≤ HDI <0.8 (High); 0.55 < HDI < 0.7 (Medium); and HDI < 0.55 (Low) (HDR 2014).

Figure 4.47 shows the regional HDI time series for each SSP and regions in Oceania, the Americas, the Caribbean and Europe. In all SSPs, HDIs at country and regional scales are projected to increase during the 90-year period at varying rates depending on the SSP narrative. In SSP5, all regions reach Very high HDI by 2100, with very high carbon footprint and little attention to alternative fuel sources. In contrast, SSP1 also projects Very high HDI for countries to be achieved with low carbon footprint, using technology to increase efficiency and harnessing energy from renewables. In SSP2, HDIs range from 0.798 (High, Caribbean) to 0.938 (Very high, Western Europe), by 2100, a trend reflecting the medium investments made in human development. SSP4, the Inequality development pathway, projects HDI ranges in 2100 to reach 0.597 (Caribbean) to 0.804 (Western Europe)(classified as Medium to Very high). The wide disparity in 2100 HDI values exemplify the inequality that marks this scenario. Finally, the Stalled Development Scenario SSP3 has the worst projections for 2100: from 0.52 (Caribbean, Low) to 0.786 (Western Europe, High).

Figure 4.47. Vulnerability metrics. Regional HDI from 2010 to 2100 for Oceania, the Americas, Caribbean and Europe, integrating country-scale metrics for life expectancy at birth, mean years at school, percentage of females achieving tertiary education relative to total female population for ages 20-39 years, and per capita gross domestic product at 2005 PPP US$. A country's national population relative to the regional total population weights the country HDI each year. The sum of weighted country HDIs for a region provides the regional HDI per year.

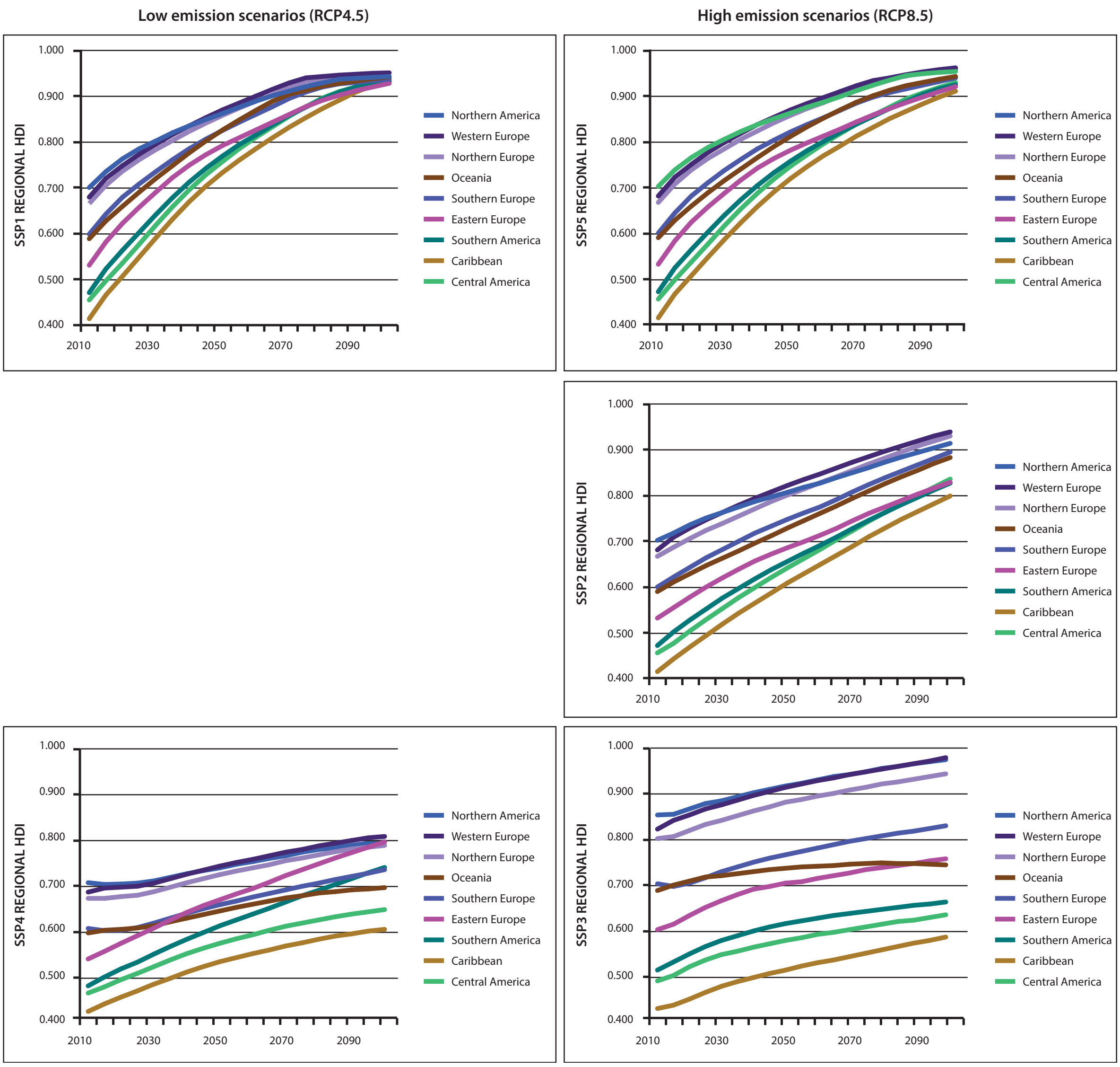
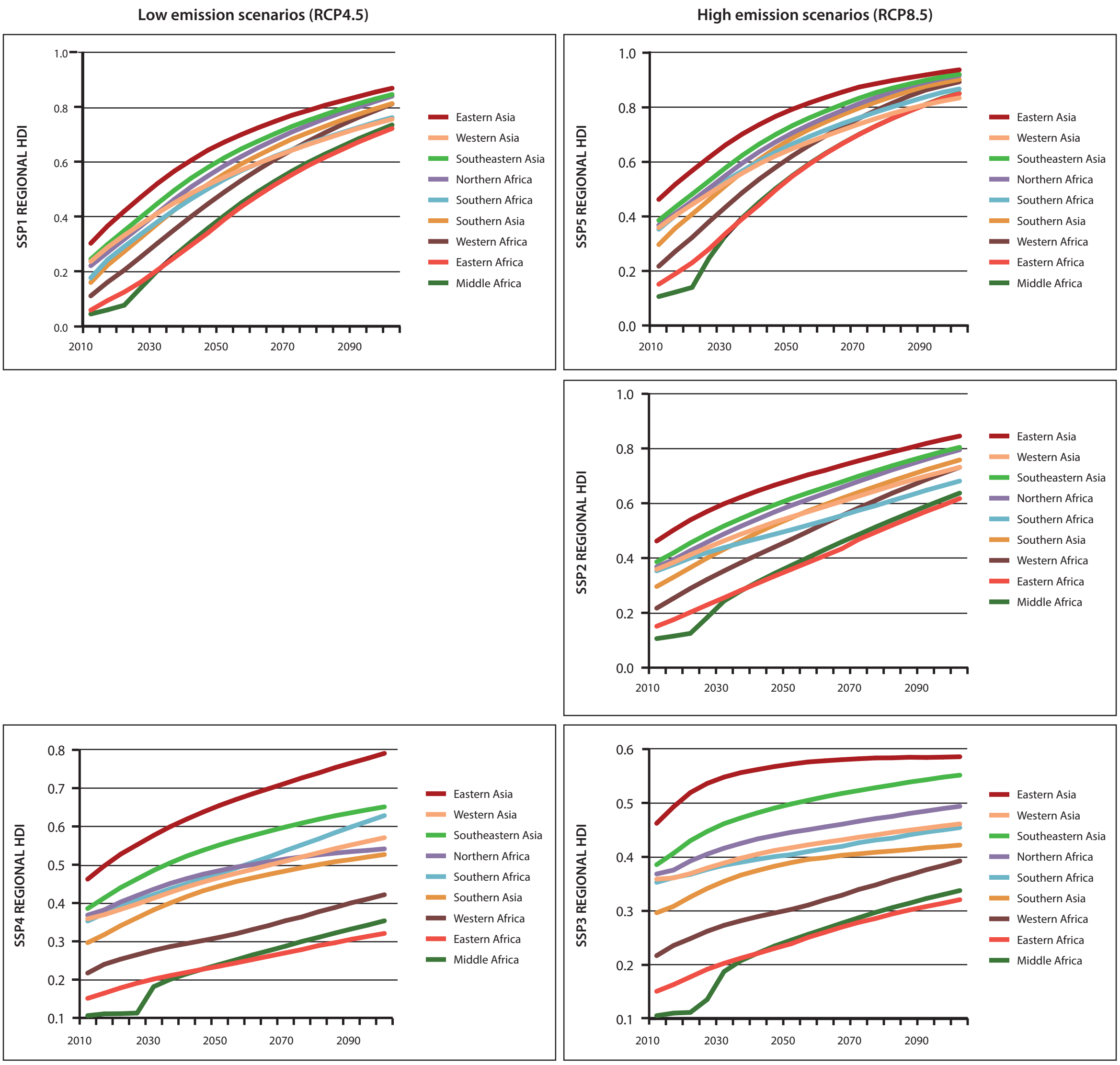


Figure 4.48 shows the HDI time series across all five SPPs for regions in Africa and Asia. Like their counterparts in the West, all countries and regions across all SSP narratives are projected to increase in HDI, albeit at varying rates consistent with the SSP features. Across all five SSP scenarios, during the 90-year projection period, Eastern and Southeastern Asia are projected to be consistently in the lead, and with Middle and Eastern Africa projected to be the least developed. SSP1 and SSP5 are both projected to bring all regions to Very high HDI levels by 2100. In the Inequality Pathway of SSP4, Eastern Africa, Middle Africa, Western Africa, Southern Asia and Northern Africa, in the order of increasing HDI values, are projected to be Low HDI countries, i.e. with HDI levels lower than 0.55. Under the Stalled Development narrative of SSP3, all regions have decreased rates of HDI progress, with Eastern and Southeastern Asia reaching Medium level, while Eastern Africa, Middle Africa, Western Africa, Southern Asia, Southern Africa, Western Asia and Northern Africa, in increasing HDI values, are all projected to be Low HDI by 2100.

Figure 4.48. Vulnerability metrics. Regional HDI from 2010 to 2100 for Africa and Asia, integrating country-scale metrics for life expectancy at birth, mean years at school, percentage of females achieving tertiary education relative to total female population for ages 20-39 years, and per capita gross domestic product at 2005 US PPP$. A country's national population relative to the regional total population weights the country HDI each year. The sum of weighted country HDIs for a region provides the regional HDI per year.



Regional patterns in the educational achievements of the female population to 2100. As a new metric in the calculation of HDI, we examine the trends in the proportion of females at childbearing age (20-39 years) in each of the SSPs, as shown in Figures 4.49 (Western regions) and 8 (Eastern Regions). Like the global patterns of the education metrics within the 90-year projection period, we note that the proportion of females with tertiary education increases in SSP1, 2, and 5, and are projected to come close to or meet the aspirational goal of 70 per cent. In SSP 4, developed regions show projected decreases while developing regions show increases, though nowhere near the goal standard of 70 per cent. In SSP3, all regions with the exception of Southeastern Asia are projected to decrease in this metric. Thus despite the overall projected trend of increasing HDI in all countries and regions for all SSPs, there are scenarios where gender-sensitive education indicators are projected to decrease, which may contribute to an increase in socioeconomic vulnerability. Female educational attainment has been shown to have profound impacts on household capacities and choices relevant to child health and mortality, household energy consumption and adaptation, and even the quality of participation in governance and democratic processes (Samir and Lutz 2014; Lutz et al. 2014). Enabling and empowering women is strategic in enhancing adaptive capacities to environmental risks including that resulting from SLR, at household and country scales.

Figure 4.49. Vulnerability metric. The proportion of females with tertiary education among females 20-39 years old (childbearing years), is examined for its role in increasing wellbeing and reducing overall socioeconomic vulnerability across all SSP futures. This panel series shows trends for the period 2010 to 2100 in the Americas, Europe, Oceania, and the Caribbean.

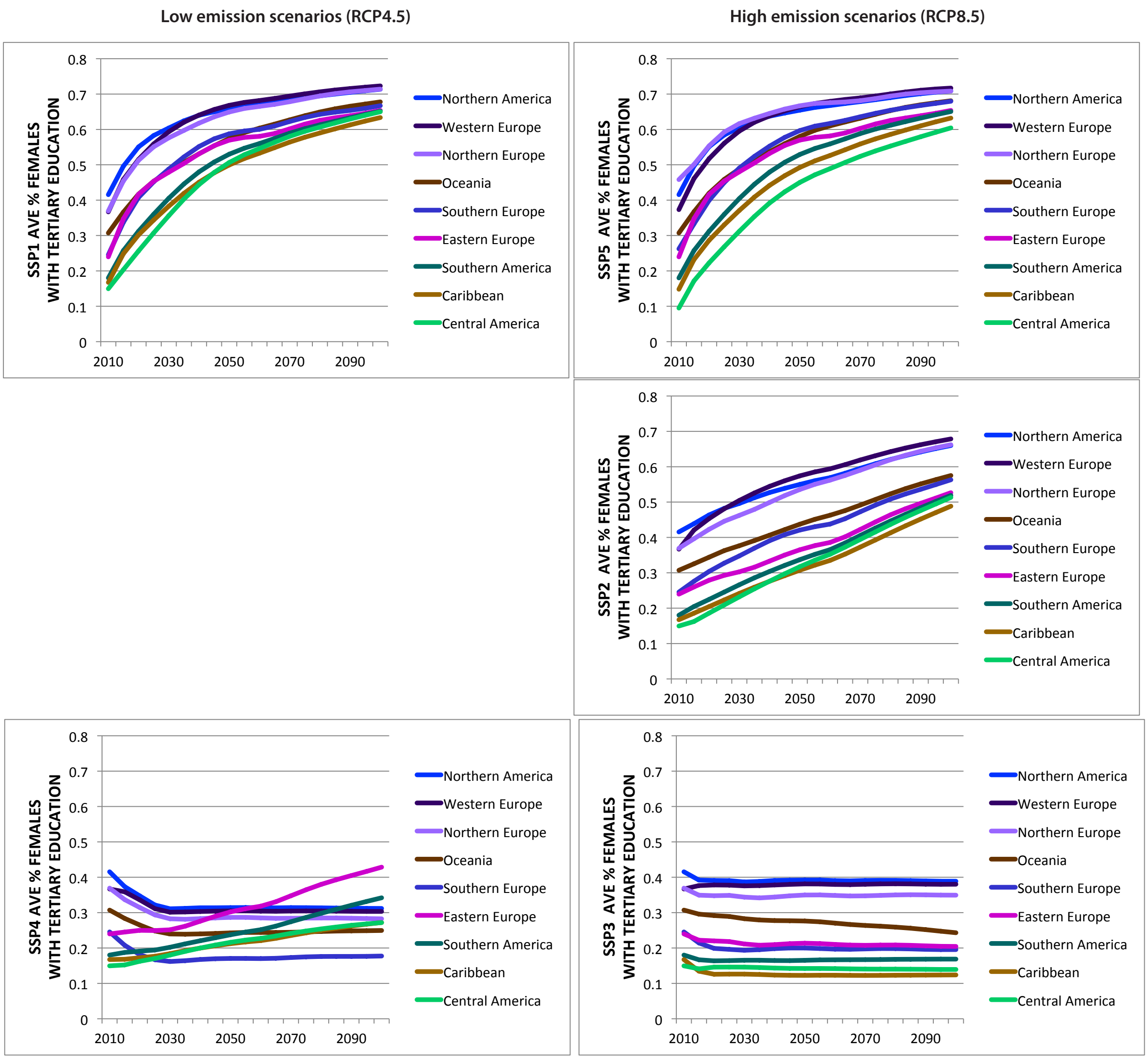
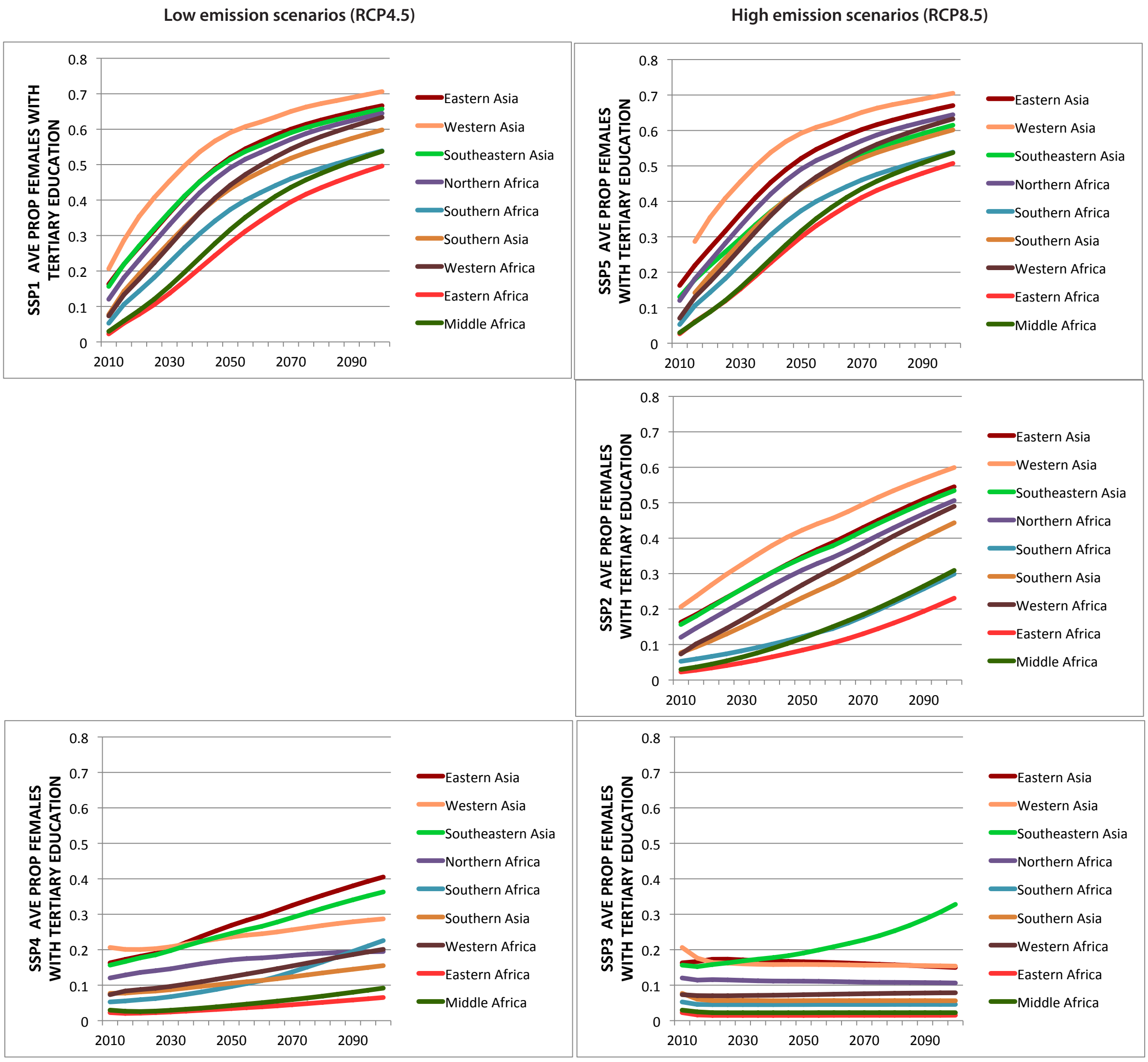


Figure 4.50. Vulnerability metric. The proportion of females with tertiary education among females of childbearing ages (20-39 years old) is examined for its role in increasing wellbeing and reducing overall socioeconomic vulnerability across all SSP futures. This panel shows trends for the period 2010 to 2100 in Africa and Asia.

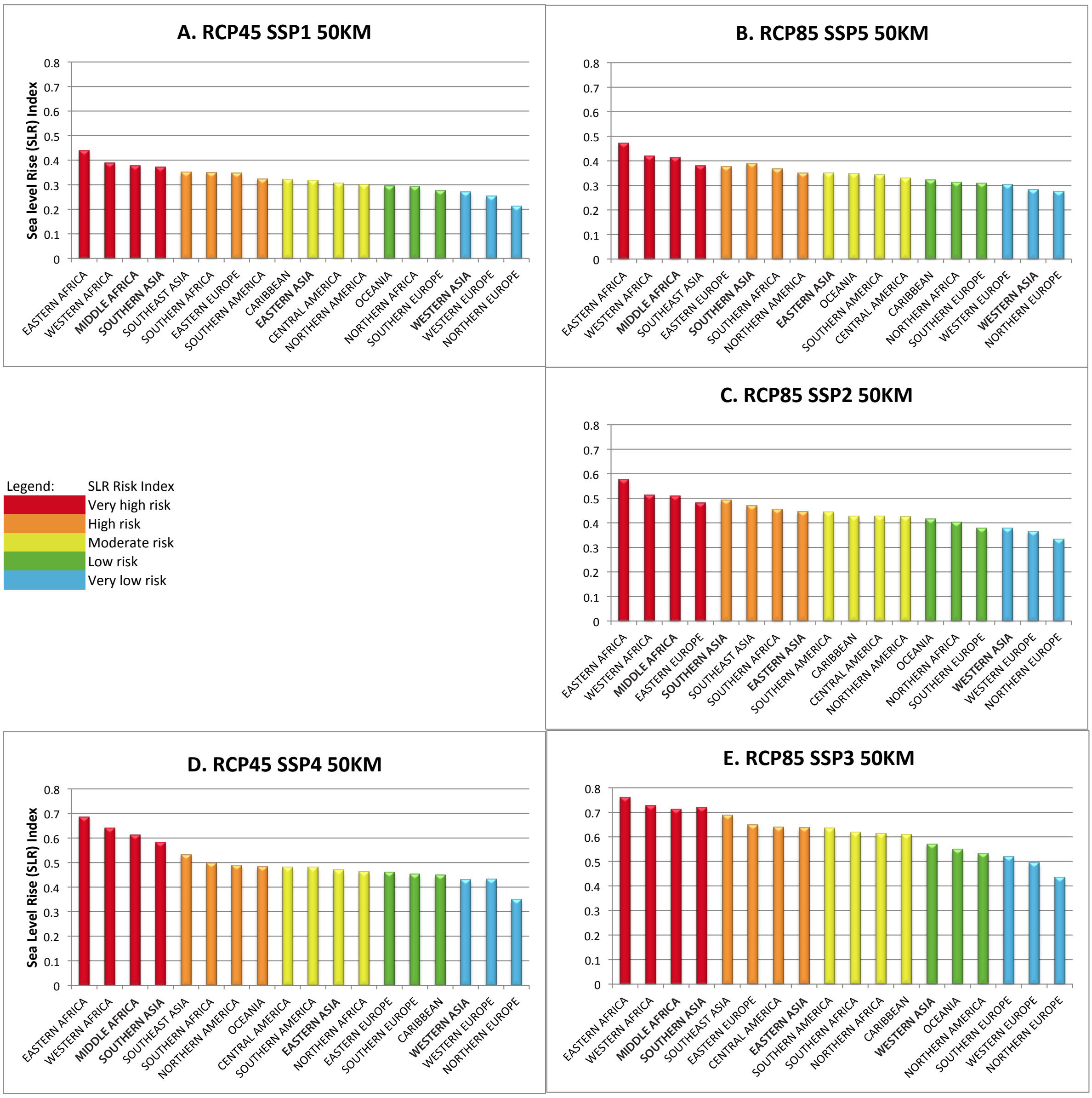


Regional patterns in SLR risk index. Within a hazard-exposure-vulnerability framework, the estimated SLR, populations and land-use areas under two emission scenarios (RCP 8.5 and RCP4.5) and the levels of development explored under the five SSP narratives (SSP1 to 5) are used to examine risk to SLR (Figure 4.51). Correlation analyses show that the hazard, exposure and vulnerability metrics are not correlated (none exceeding 36%) across the five reference scenarios (Table 4.4). Their geometric means are used to compute risk, which are significantly influenced by HDI Gap at 78 to 81%, despite its equal computational weight with hazard and exposure metrics.

Risk in this assessment integrates the combined measure of exposed population and total land area within the 10 m elevation X 50 km distance from shore, the estimated SLR, and the HDI Gap. Across SSPs, land area and maximum SLR are the same for a country or region, while population and HDI GAP vary in conformity with the SSP elements. The inclusion of the HDI Gap in risk index construction follows the concept that exposure and hazard metrics are necessary but insufficient determinants of risk. An important consideration is that risk is borne differently by populations at different levels of human development and wellbeing. Climate-related risks are additional burdens for development-compromised populations.

In a low emission scenario, SSP1 risk levels were consistently lower than SSP4 risk levels, and consistently the lowest across all five SSPs. In a high emission scenario, SSP5 consistently has the lowest risk values compared to SSP2 and SSP3. Across all five SSPs, SSP5 is a close second to SSP1. The interplay between emissions and sea level and the ability to localize the SLR estimates are key to refining the SLR risk associated with each scenario. Greenhouse gas emissions therefore serve as the ultimate reference point for what is sustainable, including the extent to which human wellbeing may be enhanced. SSP5, with a high emission scenario, is less sustainable than SSP1 without any policy intervention, even if all SSP5 HDI elements are virtually identical with their SSP1 counterparts, except SSP5 GDP, which is significantly higher than SSP1 GDP. Thus the only significant difference between SSP1 and SSP5 is the emission scenario associated with each.

Figure 4.51. The Sea Level Rise (SLR) Index by region, sorted from highest to lowest for each of the five development scenarios. The regions are grouped into five relative risk levels, with the top 4 classified as Very High Risk; the next 4 regions as High Risk; the next 4 as Moderate Risk; the next 3 as Low Risk; and the last 3 as Very Low Risk. Eastern, Western and Middle Africa consistently rank as the top three most vulnerable regions across all 5 scenarios.



In a low emission scenario, SSP4 has significantly increased risk levels, and is second highest in magnitude. Thus, even if emissions are low, the larger differences in human development among countries increase overall risk, which will impede the abilities of societies to adapt to climate change.

Across the five SSPs examined here, Eastern, Western and Middle Africa show the highest risk levels (Figure 4.51). Countries ranked from highest to lowest risk on average across 5 scenarios, are shown in Annex Table 3. The ten countries most at risk in 2100, in decreasing order, are: Somalia, Mozambique, Madagascar, Angola, Liberia, Sierra Leone, Papua New Guinea, Senegal, Guinea-Bissau and Mauritania. Seven of these countries also rank among the top 10 most vulnerable, validating the high correlation between vulnerability and risk. The reduction of risk through improved education, health and income are key. At the same time, the fundamental physical triggers of ocean warming and sea level rise highlight that reduction of carbon emissions is equally critical. Given the lag time between emissions and the earth's response to them, an integrated strategy would be one where human development is pursued not in isolation but within a framework of a sustainable planet where clear limits to greenhouse gas emissions have to be primary and central to any development strategy for both developing and developed economies.

Table 4.4. Correlation matrices among SLR Risk component metrics for each future development pathway, n=139 coastal countries. Among the 3 metrics, vulnerability measured by the Human Development Index Gap (i.e. 1-HDI), correlated the most with SLR Risk at 79 per cent at SSP3 pathway (Stalled Development) to 85 per cent at SSP4 pathway (Inequality).

RCP 4.5					RCP8.5				
SSP1	**Hazard**	**Exposure**	**Vulnerability**	**SLR Risk**	**SSP5**	**Hazard**	**Exposure**	**Vulnerability**	**SLR Risk**
Hazard	1.0000	0.1493	0.2791	0.5096	Hazard	1.0000	0.2246	0.3395	0.5302
Exposure	0.1493	1.0000	0.0065	0.4989	Exposure	0.2246	1.0000	0.0443	0.5671
Vulnerability	0.2791	0.0065	1.0000	0.8140	Vulnerability	0.3395	0.0443	1.0000	0.8127
SLR Risk	0.5096	0.4989	0.8140	1.0000	**SLR Risk**	0.5302	0.5671	0.8127	1.0000
					SSP2	**Hazard**	**Exposure**	**Vulnerability**	**SLR Risk**
					Hazard	1.0000	0.2523	0.3436	0.5533
					Exposure	0.2523	1.0000	0.0406	0.5969
					Vulnerability	0.3436	0.0406	1.0000	0.7909
					SLR Risk	0.5533	0.5969	0.7909	1.0000
SSP4	**Hazard**	**Exposure**	**Vulnerability**	**SLR Risk**	**SSP3**	**Hazard**	**Exposure**	**Vulnerability**	**SLR Risk**
Hazard	1.0000	0.1723	0.2704	0.4978	Hazard	1.0000	0.2793	0.3553	0.5692
Exposure	0.1723	1.0000	0.1397	0.5780	Exposure	0.2793	1.0000	0.1053	0.6544
Vulnerability	0.2704	0.1397	1.0000	0.8459	Vulnerability	0.3553	0.1053	1.0000	0.7883
SLR Risk	0.4978	0.5780	0.8459	1.0000	**SLR Risk**	0.5692	0.6544	0.7883	1.0000

To avert dire sea level rise scenarios in 2100 as evaluated by Church et al. (2013), and notwithstanding a potential for higher sea level rise resulting from unquantified and abrupt melting of significant masses of ice sheets, the explorations of basic scenarios of human development point to key strategies. Steering away from conditions prescribed by SSP3 (high emission, Regional Rivalry), SSP4 (low emission, Inequality) and SSP2 (medium to high emission, Middle of the Road) appears prudent. Burke et al. (2015) project that 5 per cent of countries may become poorer in 2100 than today in RCP 8.5 and SSP5, and 43 per cent may become so in RCP 8.5 and SSP3. The SSP1 narrative cohesive with a low emission scenario appears to fulfil both the biophysical requirement to maintain low concentrations of greenhouse gases and the socioeconomic requirement to enhance human well being among least developed countries.

In evaluating the RCP options and sea level rise, Hansen et al. (2015) stress that a 2°C warming above pre-industrial level is beyond the radiative forcing the earth has faced in previous glacial-interglacial cycles, implying a target emission scenario that must necessarily be lower than prescribed by RCP 4.5, i.e. RCP 2.6. In the latter scenario, radiative forcing reaches 3.1 W/m^2 by 2050, stabilizing to 2.6 W/m^2 by 2100, with a CO_2 equivalent greenhouse concentration of 490 ppm and a resulting temperature increase of 1.5°C. Sanford et al. (2014) warn that current emissions are tracking dangerously close to RCP 8.5. To initiate a climate policy that must address high emission scenarios, science needs to convey that RCPs and SSPs cannot be weighted in the same way by virtue of the risks they carry for the planet. In addressing the increasing probability of high emissions, climate policies at national, regional and global scales must weigh the costs and benefits of human development, alongside climate mitigation and adaptation, as well as all trade-offs necessary to meet very low emission targets, despite huge uncertainties. In addition, the time frames of concern must go beyond the reference year of 2100, because contemporary emissions underpin climate changes thousands of years into the future, including SLR. Clark et al (2016) envisions the evolution of energy infrastructure that features net-zero emissions so that climate change 10,000 years hence may be contained within the planet's habitable range. While climate science provides an analytical framework for the study of earth system change spanning geologic time, the social sciences would need to define plausible scenarios through which human societies can evolve an ethos for sustaining the earth system long-term that is across millennia.

4.5.3 Notes on methods

Table 4.5 describes the spatial data layers and tabular data used in this study.

2100 RCP 4.5 and RCP8.5 Regional Sea Level Change. Using the University of Hamburg Integrated Climate Data Center Live Access Server at http://www.icdc.zmaw.de/las/getUI.do, data and maps of the RCP4.5 and RCP8.5 total ensemble mean sea surface heights used in the IPCC AR5 (2013) were obtained. A geo-referenced sea surface height data layer at 1° resolution was analysed, together with a country population data layer, to obtain the minimum and maximum sea level change data for the nearest coastal grid cells adjacent to littoral states using GIS analysis for RCP4.5 and RCP8.5.

2100 Land areas in coastal areas distribution. To obtain estimates of total land area in coastal spaces defined by co-located elevations and distances from shore in 2100, we obtained the harmonized land-use data layer for RCP8.5 developed by Hurtt et al. (2011) using the MESSAGE Integrated Assessment Model. The RCP8.5 MESSAGE land-use model features gridded 0.5° X 0.5° land use transition time series for the period 2005-2100, and includes crop, pasture, and urban fractions for each 0.5° grid cell.

For this study, we focused on estimating total coastal land areas, while also obtaining land use data. However, the greatest drawback of the data set is that the coastlines of littoral states are not resolved within the outermost 0.5° grid cells other than the assignment of a country code. A major corrective exercise is implemented by this study to resolve borders of coastal states and minimize the inclusion of ocean water outside country borders before areas of land use could be derived at country scale. To do this, the population layer prepared by CIESIN (2013) with resolved coastlines was used to remove oceanic water from coastal grid cells of the land-use map in 2100. The remaining inland waters within the country borders were reconciled with the Global Lakes and Wetlands Database (GLWD) 3.0 data layer for lakes and wetlands. Reductions in water content of border cells created unclassified land fractions that were reallocated to cropland, pastureland, and primary and secondary vegetated land, following the land ratios after removal of excess oceanic water. For locations with permafrost and desert areas, we used permafrost and desert and dry (i.e. low moisture) biome maps to delineate these areas before allocating remaining fractions to land-use areas. The GLWD3.0 data layer, permafrost and desert maps reflect present-day conditions, which are assumed to remain constant to 2100, given the lack of projected data for these features. Details of the GIS analyses to obtain land areas by land use are in Annex Figure 1.

Table 4.5. Spatial data layers and tabular data used in this study.

Indicator Sub-theme	Indicator	Time Period	Underlying metrics	Data sources
I. Regional Sea Level change	Maximum sea level change at country scale	2100	Total ensemble mean sea surface height	http://www.icdc.zmaw.de/las/getUI.do
II. Population and Land Use	Coastal population by elevation up to 10 m and higher and by distance from shore up to 50km (spatial)	2100	Populations at ≤1, ≤2, ≤3, ≤4, ≤5, 5-10 m, ≥10m elevation; at 0-2km, 2-4km, 4-6km, 6-10km, 10-15km, 15-20km, 20-30km, 30-40km, 40-50km from shore; Resolution at 1 km (30 arc-seconds) with coastlines resolved	http://sedac.ciesin.columbia.edu/data/set/lecz-urban-rural-population-land-area-estimates-v2. (registration required);
	Country population	2010-2100 for all SSPs	Tabular data	Wittgenstein Centre for Demography and Global Human Capital 2014 at http://witt.null2.net/shiny/wittgensteincentredataexplorer/
	ACE2 Digital Elevation Model	2009	Used 1 km resolution	http://tethys.eaprs.cse.dmu.ac.uk/ACE2/ (registration required); Available at 3,9 and 30 sec and 5 min resolution; registration required
	Land Use Change RCP85 Scenario	2005-2100	Crop, Pasture, Urban, Primary and Secondary Vegetation; Resolution at 0.5 °	Hurtt et al. 2011; Data download at http://luh.umd.edu
	Global Lakes and Wetlands Database GLWD3.0 Layer	Present day	Inland water bodies to resolve coastal cells within national boundaries; resolution at 1 km	Lehner and Döll (2004); available for free download at http://www.worldwildlife.org/pages/global-lakes-and-wetlands-database
	Permafrost layers	Present day	Circum-arctic, Canada, China, Russia, USA Alaska	Global Geocryological Data System, University of Colorado National Snow and Ice Data Center; data downloads at http://nsidc.org/data/ease/data_summaries.html - frozen
	Desert layer	Present day	Desert and xeric biomes	Olson and Dinerstein. 2002. The Global 200: Priority ecoregions for global conservation.
III. Human wellbeing	HDI Metrics for 2100 using SSP pathways	2010-2100	Geometric Mean of Female Tertiary Education Achievement (20-39 years old), GDP per capita, Life expectancy	These metrics are used to compute country- and regional scale Human Development Index.
	Tertiary education for women of childbearing years (20-39 yrs old)	SSP1-5 for 2010-2100	Modelled population data	IIASA Population Model, SSP Database, 2012 Available at: https://secure.iiasa.ac.at/web-apps/ene/SspDb
	Gender Gap in Educational Attainment as ratio of males to females (25 yrs+ of age group with post secondary educational achievement) (Global averages)	2010-2100	Modelled data	Wittgenstein Centre for Demography and Global Human Capital 2014 at http://witt.null2.net/shiny/wittgensteincentredataexplorer/
	Mean years at school	SSP1-5 for 2010-2100	Modelled data	IIASA Population Model, SSP Database, 2012 Available at: https://secure.iiasa.ac.at/web-apps/ene/SspDb
	GDP per capita	SSP1-5 for 2010-2100	Modelled data on National GDP and Population	OECD GDP Model, SSP Database, 2012 Available at: https://secure.iiasa.ac.at/web-apps/ene/SspDb
	Life expectancy from birth	SSP1-5 for 2010 to 2100	Modelled data	Wittgenstein Centre for Demography and Global Human Capital 2014 at http://witt.null2.net/shiny/wittgensteincentredataexplorer/
IV. 2100 Sea Level Rise Risk Index	Geometric Mean of 2100 Area and Population in (10m X 10 km), Maximum sea level rise and HDI Gap	2100	Metrics derived from Modelled data and Index constructed as a natural disaster Index (risk =hazard X exposure X vulnerability)	As above

Because of the major data correction for coastal grid cells, and the two-dimensional (elevation by distance from shore) derivation of land and population distributions that demanded significant computer resources and supervised area reallocation algorithms, we focused on processing land-use data for one RCP pathway: RCP8.5. There is no other global land use data set for 2100 that could be used to calibrate the data we derived, and comparisons of coastal land uses under different RCPs may be possible in future.

We determined total land areas and area distribution at ≤1 m, ≤2 m, ≤3 m, ≤4 m, ≤ 5 m, 5-10 m, and >10 m elevation and, each of which were co-located at 0-2 km, 2-4 km, 4-6 km, 6-10 km, 10-15 km, 15-20 km, 20-30 km, 30-40 km, and 40-50 km from the shore, following the same protocol for obtaining population distributions. For reporting, we aggregate land-use areas by elevation to ≤10 m and >10 m, and by total elevation; and are intersected within ≤10 km, ≤30 km and ≤50 km coastal widths.

We used the total land area within the 10 m elevation and cumulative distances from shore to 10 km, to 30 km and to 50 km in the sea level risk calculation for RCP8.5, and assumed that the total cumulative land areas would be the same for RCP4.5. We use the total land area within the 10 m elevation co-located within the cumulative 50 km coastal width as area exposure for this global SLR risk assessment. Impacts of physical processes associated with SLR such as coastal erosion, floodplain inundation, storm surge are assumed to take place within this coastal space.

2100 Population distribution. Using the 1 km resolution 2100 population layer (CIESIN 2013) superimposed on the 1 km ACE2 Digital elevation model, we determined population distribution at ≤1 m, ≤2 m, ≤3 m, ≤4 m, ≤5 m, 5-10 m, and >10 m elevation and each elevation bin intersecting with widths at 0-2 km, 2-4 km, 4-6 km, 6-10 km, 10-15 km, 15-20 km, 20-30 km, 30-40 km, and 40-50 km from shore. Note that the spatially explicit location of population estimates by intersecting elevation and distance from shore allows for global comparisons by explicit location, which is not possible when coastal segments are defined at floodplain scales (Neumann et al. 2015). However, we note that the vertical resolution of the ACE2 Digital Elevation Model is coarser than the 1 m elevation intervals used in this study. Thus we report the results by ranges in elevations ≤10 m and >10 m and which conform with the 10 m elevation used by McGranahan et al. (2007) to discriminate low elevation coastal zones. For ease of tabulation, the distances from shore are aggregated to ≤10 km, ≤30 km and ≤50 km. The population distribution using the CIESIN (2013) data layer at coastal segment and country scales are used to distribute the SSP populations spatially in the 10m elevation - 50 km coastal space for 2100. We note that there are inherent uncertainties in spatially explicit population projections to 2100 and that current estimates may be refined with better spatial data in future.

Human well being by Shared Socioeconomic Pathway (1-5) from 2010 to 2100. Annex Table 2 details the elements of the five SSPs used in the study to determine trends in well being from present to the end of the century (O'Neill et al. 2104, 2015). For cohesive future scenarios, we combine SSP1 and SSP4 with RCP4.5 as future low emission scenarios, and SSP2, SSP3 and SSP5 with RCP8.5 as future high emission scenarios.

SSP1 features low population growth rate, and high achievements in education, health and economic growth. It has low challenges to mitigation, and the high degree of well being implies low challenges to adaptation.

SSP2 is called the Middle of the Road pathway, where conditions do not change significantly from historic trends. Progress in reaching sustainable development goals is slow, with no fundamental breakthroughs in technology. Global population growth is moderate, but education investments are not adequate to allow transition to low fertility rates in developing countries. This pathway has moderate challenges to mitigation and adaptation, with significant variance between and within countries.

SSP3 features a Regional Rivalry pathway. States focus on domestic needs for energy and food security. Education and technological development take a back seat, along with environmental concerns. Population growth is uneven: low in developed and high in developing economies. This pathway has high challenges to both adaptation and mitigation.

SSP4 features Inequality within and among countries. It has a widening gap between a globalized society and a group of low-income and poorly educated societies engaged in low-technology economies. This pathway has low challenges to mitigation but indicates high adaptation challenges as many remain at low levels of development.

SSP5 highlights Fossil Fuel led Development. It has strong investment in health and education, but also a preference for continued exploitation of fossil fuels, all factors leading to rapid economic growth. It features high challenges to mitigation, and low challenges to adaptation.

For each of the five reference SSPs, we obtain the modelled well-being metrics to compute a country-scale Human Development Index annually for each of 139 coastal countries over 2010-2100. The metrics include life expectancy at birth as a health metric, mean years at school and the percentage of women of childbearing age (20-39 years) with tertiary level education as education metrics, and per capita GDP as an economic metric (Dellink et al. 2015, Crespo 2015). These metrics are used to compute country-scale HDI as an indicator of well-being, and the resulting HDI Gap (1-HDI) as a metric of vulnerability.

We followed the current methods of computing HDI (HDR 2014), adjusting the current minimum and maximum metric goal posts to what may be relevant aspirational goals in 2100. We chose a gender-sensitive education metric, the percentage of females of childbearing age with tertiary education instead of expected mean years at school, the latter being one of the metrics for current HDI not quantitatively modelled within the SSP narratives.

The computations of the three sub- indices that make up the 2010-2100 HDI are:

Index	Normalized Metric	Minimum Goal Post	Maximum Goal Post	Data Sources
Health = Normalized E0	Life expectancy at birth or year 0, E0 = (E0 -20)/ (100-20)	20 years	100 years	Lutz et al. 2014 (eds). http://www.oeaw.ac.at/vid/dataexplorer/
Education Index = Average (MYS, % Fem_Tert)	Mean years at school (= MYS /18)	0 years	18 years	Lutz et al. (2014) (eds). http://www.oeaw.ac.at/vid/dataexplorer/
	% Females of childbearing age with tertiary education (= % Fem_Tert / 70%)	0%	70%	Lutz et al. (2014) (eds). http://www.oeaw.ac.at/vid/dataexplorer/
Income = Normalized Per capita GDP	Per capita GDP in 2005 US$ PPP = (LN Income – LN 700) / (LN $100 000 – LN 700)	$700	$100 000	Dellink et al. 2015, Crespo 2015. https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about

As a measure of well being, we compute the HDI as:

Human Development Index = Geometric Mean (Health Index, Education Index, Income Index)

We use HDI Gap as a measure of vulnerability caused by unfulfilled development potential, computed as:

HDI Gap = 1- HDI

2100 Sea Level Rise Risk Index by SSP. We develop the 2100 Sea Level Rise Risk Index to integrate the exposure of population and land area to sea level rise in the 10 m X 10, 30 and 50 km coastal zone, the maximum sea level rise for either RCP 4.5 (low emission scenarios) or RCP8.5 (high emission scenarios) at country scale, and the HDI Gap. The three metrics are not correlated at 36% and higher (Table 4).

For low emission scenarios (SSP1 and SSP4 with RCP4.5 sea level rise):

2100 Country Sea Level Rise Risk Index = (Natural logarithm (LN) of Total Area + LN Population)$_{\text{normalized across all 5 RCP-SSP combination scenarios}}$ X (RCP 4.5 Maximum Sea Level Rise) X (HDI Gap)

For high emission scenarios (SSP2, SSP3 and SSP5 with RCP8.5 sea level rise):

2100 Country Sea Level Rise Risk Index = (LN Total Area + LN Population)$_{\text{normalized across all 5 RCP-SSP combination scenarios}}$ X (RCP 8.5 Maximum Sea Level Rise) X (HDI Gap)

Since HDI Gap is derived from HDI values which were previously normalized, and sea level rise values are between 0 and 1, only the combined LN values for area and population were normalized prior to risk index computation. The natural logarithms of the combined land use and populations were normalized using the minimum and maximum values across the five RCP-SSP combination scenarios, so that the risk values are comparable across the five reference development pathways.

Scales for reporting results. All input and derived data for hazard, exposure and vulnerability metrics are at country scale, including associated rank scores. For ease of presentation, regional averages for SSP wellbeing metrics and risk were also computed using either country coastal populations or land areas as weighting factors, where appropriate. Annex Table 4 lists the 139 SSP countries and regions used in the analysis.

Within a combination RCP-SSP scenario, the country-scale and regional scale SLR Risk Indices increases between 0 and 5 percentage points, and between 0 and 3 percentage points, respectively, when the coastal width is increased from 10 km to 50 km since the natural logarithms of both area and population are used in risk calculations. Here we report the risk indices for the 50 km coast where exposure to and risk of sea level rise would subsume appropriate scales of physical (e.g. erosion, storm surge, flooding) and socioeconomic processes (e.g. coastal livelihoods, daily migrations). Refinements of spatial scales to widths and elevations of coastal floodplains may be done at finer scale analysis since the explicit co-location of elevation, area and populations provides analytical flexibility.

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Annex Table 1. Exposure metrics showing projected future land use and total land areas in 2100 at RCP8.5 derived from harmonized land use transition mapping by Hurtt et al (2011) using the RCP8.5 MESSAGE Integrated Assessment Model (http://luh.umd.edu). Total land area at 50km is used in the SLR Risk Index calculations.

REGION	Elevation	Agricultural Land (distance from shore, km²)			Urban Land (distance from shore, km²)			Vegetated Land (distance from shore, km²)			Total Area (distance from shore, km²)		
		≤10km	≤30km	≤50km	≤10km	≤30km	≤50km	≤10km	≤30km	≤50km	≤10km	≤30km	≤50km
NORTHERN AFRICA	≤10m	9 069	16 009	19 389	900	1 641	2 140	4 525	7 212	8 569	20 273	34 291	39 956
	>10m	37 868	124 408	205 400	3 072	8 826	13 353	24 760	102 671	190 831	68 788	243 289	420 648
	TOTAL	46 937	140 417	224 789	3 972	10 467	15 492	29 285	109 883	199 400	89 060	277 580	460 604
WESTERN AFRICA	≤10m	9 156	19 216	24 328	1 459	3 049	3 878	8 744	15 829	20 250	35 826	68 117	84 989
	>10m	7 698	40 956	85 029	955	4 687	9 439	7 661	28 628	52 488	19 594	81 319	155 861
	TOTAL	16 854	60 172	109 357	2 414	7 735	13 317	16 405	44 458	72 739	55 420	149 436	240 851
MIDDLE AFRICA	≤10m	5 312	14 881	20 294	456	1 211	1 379	4 969	14 886	24 342	14 786	38 962	55 123
	>10m	9 422	30 196	55 331	701	2 122	4 105	8 089	21 103	36 257	19 538	55 705	98 610
	TOTAL	14 733	45 077	75 626	1 157	3 333	5 484	13 058	35 989	60 599	34 325	94 667	153 733
SOUTHERN AFRICA	≤10m	1 309	1 514	1 517	33	39	39	2 075	2 136	2 136	4 327	4 779	4 789
	>10m	19 494	62 282	108 643	623	1 577	2 473	11 507	37 761	64 048	32 936	103 965	177 983
	TOTAL	20 803	63 797	110 160	656	1 616	2 512	13 582	39 897	66 184	37 264	108 744	182 772
EASTERN AFRICA	≤10m	23 186	31 872	33 841	718	855	869	3 713	5 443	6 379	43 355	60 917	65 577
	>10m	72 449	246 029	417 626	2 922	8 063	13 062	15 565	53 999	93 095	97 621	324 140	547 395
	TOTAL	95 636	277 901	451 467	3 639	8 918	13 931	19 278	59 441	99 474	140 976	385 057	612 972
WESTERN ASIA	≤10m	8 890	12 386	13 392	1 186	1 345	1 428	17 009	23 829	25 490	43 872	57 792	62 025
	>10m	33 983	128 328	230 252	4 567	13 839	19 767	58 321	196 675	322 504	107 708	358 396	596 875
	TOTAL	42 872	140 714	243 644	5 752	15 184	21 196	75 330	220 504	347 994	151 579	416 188	658 901
SOUTHERN ASIA	≤10m	18 005	35 072	43 950	1 763	3 123	3 833	11 154	17 261	19 507	60 165	101 583	122 198
	>10m	15 787	61 296	112 117	1 949	7 056	12 401	22 040	70 697	122 545	44 597	158 172	284 539
	TOTAL	33 791	96 369	156 067	3 713	10 179	16 234	33 194	87 958	142 052	104 762	259 755	406 737

REGION	Elevation	Agricultural Land (distance from shore, km^2)			Urban Land (distance from shore, km^2)			Vegetated Land (distance from shore, km^2)			Total Area (distance from shore, km^2)		
		≤10km	≤30km	≤50km	≤10km	≤30km	≤50km	≤10km	≤30km	≤50km	≤10km	≤30km	≤50km
SOUTHEASTERN ASIA	≤10m	47 270	82 264	99 296	4 600	7 161	7 988	78 772	133 981	162 827	189 821	327 242	397 495
	>10m	123 654	308 493	436 010	9 948	26 396	38 961	256 168	606 289	858 655	438 254	1 018 674	1 422 119
	TOTAL	170 924	390 757	535 306	14 547	33 557	46 950	334 939	740 270	1 021 482	628 075	1 345 915	1 819 614
EASTERN ASIA	≤10m	14 933	31 971	44 427	3 377	7 755	10 963	19 628	36 654	47 450	53 331	101 846	131 532
	>10m	31 315	83 950	129 408	5 831	14 946	21 771	92 045	233 337	343 097	136 056	341 228	504 346
	TOTAL	46 248	115 921	173 835	9 208	22 701	32 734	111 672	269 992	390 547	189 388	443 073	635 877
OCEANIA	≤10m	35 287	56 755	62 447	1 099	1 442	1 490	30 040	46 955	51 181	107 551	163 083	176 628
	>10m	114 829	355 536	587 152	3 813	9 955	13 330	173 696	389 655	527 916	323 322	797 276	1 175 341
	TOTAL	150 116	412 290	649 599	4 912	11 397	14 820	203 736	436 610	579 097	430 873	960 358	1 351 968
NORTHERN AMERICA	≤10m	6 885	10 688	15 092	3 169	4 653	4 993	140 717	146 984	148 946	299 803	420 097	480 049
	>10m	23 290	49 303	71 008	6 640	15 364	21 222	861 505	1 643 182	2 116 398	1 195 594	2 428 197	3 257 609
	TOTAL	30 175	59 991	86 099	9 809	20 017	26 215	1 002 223	1 790 166	2 265 343	1 495 397	2 848 294	3 737 658
CENTRAL AMERICA	≤10m	23 709	47 218	57 268	663	1 178	1 392	19 650	37 474	45 585	58 835	108 614	128 015
	>10m	40 200	149 896	257,598	1 375	5 044	8 323	39 750	141 232	225 882	87 843	306 914	504 477
	TOTAL	63 909	197 115	314,866	2 038	6 223	9 715	59 401	178 706	271 468	146 679	415 528	632 492
CARIBBEAN	≤10m	9 001	10 839	11 285	729	787	803	11 434	13 032	13 168	36 511	43 593	44 339
	>10m	24 584	74 981	103 427	2 731	6 493	7 409	18 642	43 916	52 345	47 537	127 345	165 207
	TOTAL	33 585	85 820	114 711	3 459	7 280	8 213	30 076	56 948	65 513	84 048	170 938	209 546
SOUTHERN AMERICA	≤10m	35 244	59 996	74 538	1 775	2 795	3 202	37 433	63 317	79 181	112 336	204 139	260 002
	>10m	91 138	295 765	500 487	4 350	13 844	21 551	149 528	346 001	514 825	257 336	682 767	1 077 492
	TOTAL	126 382	355 761	575 025	6 125	16 639	24 753	186 961	409 317	594 006	369 673	886 907	1 337 494
NORTHERN EUROPE	≤10m	13 864	19 009	21 780	1 395	1 901	2 103	35 893	42 653	44 370	56 955	70 172	75 158
	>10m	53 387	134 911	190 630	4 097	10 076	13 432	150 066	347 094	500 861	219 052	510 220	728 552
	TOTAL	67 251	153 920	212 410	5 492	11 977	15 535	185 959	389 747	545 231	276 007	580 392	803 710

REGION	Elevation	Agricultural Land (distance from shore, km²)			Urban Land (distance from shore, km²)			Vegetated Land (distance from shore, km²)			Total Area (distance from shore, km²)		
		≤10km	≤30km	≤50km	≤10km	≤30km	≤50km	≤10km	≤30km	≤50km	≤10km	≤30km	≤50km
WESTERN EUROPE	≤10m	11 003	20 133	24 284	1 650	3 152	3 784	9 281	15 432	17 924	27 608	46 037	53 405
	>10m	14 377	45 203	74 214	1 533	4 222	6 269	18 099	49 996	76 703	34 608	100 244	158 171
	TOTAL	25 380	65 336	98 498	3 182	7 373	10 053	27 380	65 428	94 627	62 216	146 281	211 576
SOUTHERN EUROPE	≤10m	7 800	11 257	12 820	813	1 065	1 144	7 120	9 362	10 016	18 583	25 752	28 280
	>10m	64 599	148 012	210 553	4 854	9 763	11 738	67 852	163 889	235 417	140 564	325 749	462 057
	TOTAL	72 399	159 268	223 373	5 667	10 828	12 883	74 972	173 250	245 433	159 147	351 502	490 337
EASTERN EUROPE	≤10m	5 700	10 592	14 807	284	516	662	54 172	71 221	79 697	187 303	284 795	330 654
	>10m	12 283	42 284	74 590	680	1 805	2 572	244 629	680 683	1 079 815	461 732	1 203 701	1 867 421
	TOTAL	17 983	52 876	89 397	964	2 320	3 234	298 801	751 904	1 159 512	649 035	1 488 496	2 198 075

Annex Table 2. Elements of Shared Socioeconomic Pathways (SSPs) (O'Neill et al 2015). Country groupings by fertility are based on Samir and Lutz (2014) and by income are defined by the World Bank at http://data.worldbank.org/about/country-and-lending-groups.

SSP Element	Sustainable World Pathway (SSP1)	Middle of the Road (SSP2)	Fragmented World/ Stalled Development (SSP3)	Inequality (SSP4)	Fossil-fuel Led Development (SSP5)
Demographics – Population (by age, sex, education)					
Growth	Relatively low	Medium	High for High and Low fertility countries; Low for Rich OECD countries	Relatively high	Relatively low
Fertility	Low for High and Low fertility countries; Medium for Rich OECD countries	Medium	High for High and Low fertility countries; Low for Rich OECD countries	High for High fertility countries; Low for Low fertility countries, Low for OECD countries	Low for High and low fertility countries; High for Rich-OECD countries
Mortality	Low	Medium	High	High for High fertility countries; Medium for Low fertility countries; Medium for OECD countries	Low
Migration	Medium	Medium	Not prescribed	Medium	High
Demographics – Urbanization					
Level	High	Medium	Low	High for High Fertility countries; High for Low fertility countries; Low for OECD countries	High
Type	Well managed	Continuation of historical patterns	Poorly managed	Mixed across and within cities	Better management overtime, some sprawl
Human Development					
Education	High	Medium	Low	High Fertility – very low/ uneven, Low Fertility – low/ uneven, OECD – medium, uneven	High
Health investments	High	Medium	Low	Unequal within regions, lower in Low Income Countries (LICs), medium in High Income Countries (HICs)	High
Access to health facilities, water and sanitation	High	Medium	Low	Unequal within regions, lower in LICs, medium in HICs	High
Equity	High	Medium	Low	Medium	HIgh
Social cohesion	High	Medium	Low	Low, stratified	HIgh
Societal participation	High	Medium	Low	Low	High
Economy & Lifestyle					
Per capita growth	High in LICs & MICs; medium in HICs	Medium, uneven	Slow	Low in LICs, medium in other countries	High
Inequality	Reduced across and within countries	Uneven moderate reductions across and within countries	High, especially across countries	High, especially within countries	Strongly reduced, especially across countries
Consumption & Diet	Low growth in material consumption, low-meat diets, first in HICs	Material-intensive consumption, medium meat consumption	Material-intensive consumption	Elites: high consumption lifestyles; Rest: low consumption, low mobility	Materialism, status consumption, tourism, mobility, meat-rich diets

SSP Element	Sustainable World Pathway (SSP1)	Middle of the Road (SSP2)	Fragmented World/ Stalled Development (SSP3)	Inequality (SSP4)	Fossil-fuel Led Development (SSP5)
Policies and institutions					
Environmental Policy	Improved management of local and global issues: tighter regulation of pollutants	Concern for local pollutants but only moderate success in implementation.	Low priority for environmental issues	Focus on local environment in Medium Income Countries (MICs), HICs; little attention to vulnerable areas or global issues.	Focus on local environment with benefits to well-being, little concern with global problems
Policy orientation	Toward sustainable development	Weak focus on sustainability	Oriented toward security	For the benefit of the political and business elite	Toward development, free markets, human capital
Institutions	Effective at national & international levels	Uneven modest effectiveness	Weak global institutions/ national governments dominate societal decision making	Effective for political and business elite, not for the rest of society	Increasingly effective, oriented toward fostering competitive markets
Environment & Natural Resources					
Fossil constraints	Preferences shift away from fossil fuels	No reluctance to use unconventional resources	Unconventional resources for domestic supply	Anticipation of constraints drives up prices with high volatility	None
Environment	Improving conditions over time	Continued degradation	Serious degradation	Highly managed and improved near high/middle-income living areas, degraded otherwise.	Highly engineered approaches, successful management of local issues
Land Use	Strong regulations to avoid environmental tradeoffs	Medium regulations lead to slow decline in the rate of deforestation	Hardly any regulation; continued deforestation due to competition over land	Highly regulated in MICs, HICs; largely unmanaged in LICs leading to tropical deforestation	Medium regulation lead to slow decline in deforestation rate
Agriculture	Improvements in agricultural productivity; rapid diffusion of best practices	Medium pace of technological change in agricultural sector; entry barriers to agricultural markets reduced slowly	Low technology development, restricted trade	Agricultural productivity high for large scale industrial farming, low for small-scale farming	Highly managed, resource-intensive; rapid increase in productivity
Technology					
Development	Rapid	Medium, uneven	Slow	Rapid in high-tech economies and sectors; slow in others.	Rapid
Transfer	Rapid	Slow	Slow	Little transfer within countries to poorer populations	Rapid
Energy tech change	Directed away from fossil fuels, toward efficiency and renewables	Some investment in renewables but continued reliance on fossil fuels	Slow tech change, directed toward domestic energy sources	Diversified investments including efficiency and low-carbon sources	Directed toward fossil fuels; alternative sources not actively pursued
Carbon intensity	Low	Uneven, higher in Least Industrialized Countries (LICs)	High in regions with large domestic fossil fuel resources	Low/medium	High

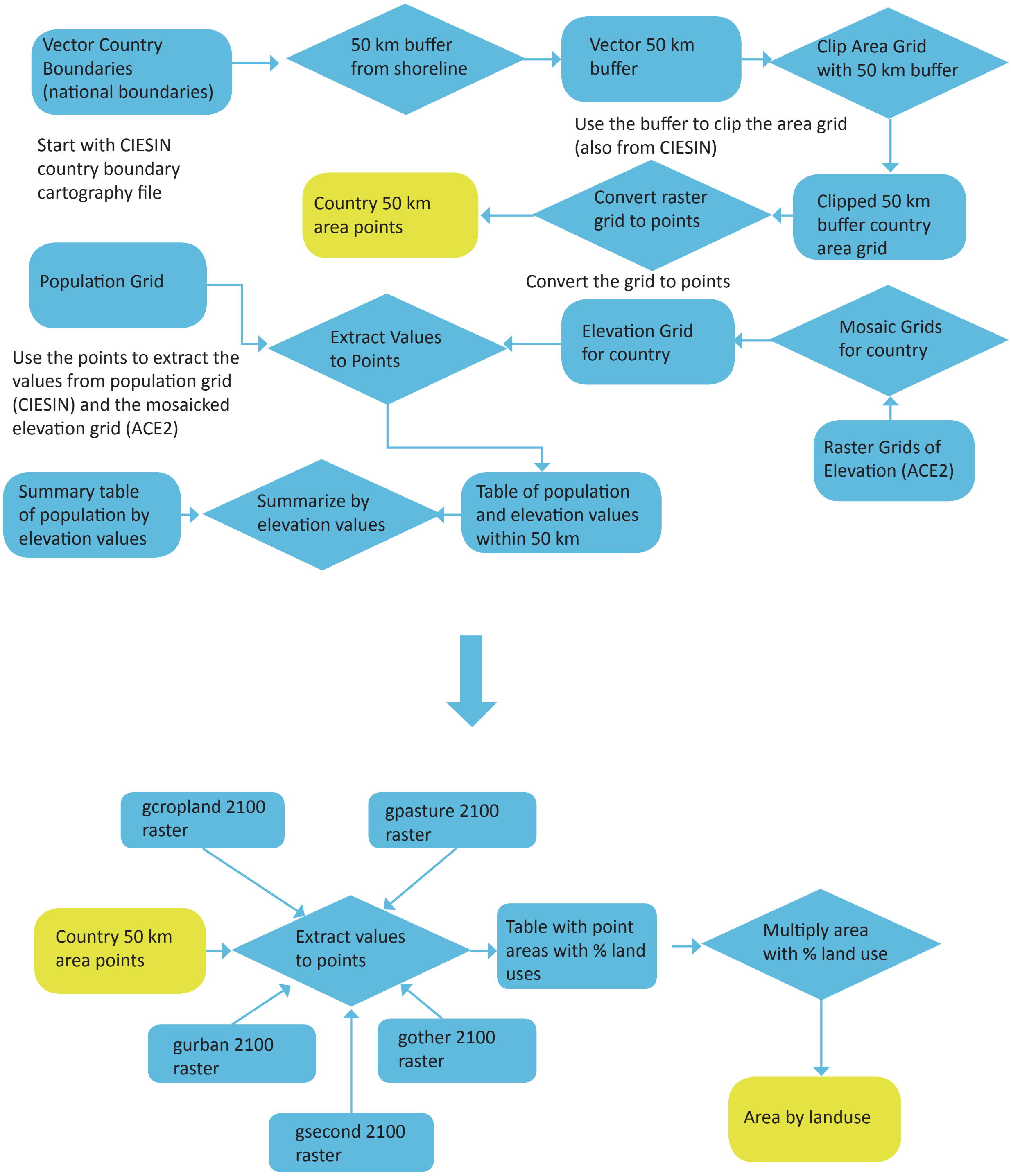
Annex Table 3. Coastal countries and their mean ranks for hazard (over RCP4.5 and RCP8.5), exposure (over 5 scenarios), vulnerability (over 5 scenarios), and SLR Risk Index (over 5 scenarios). For each metric, the top quintile is assigned very high risk (in red); second quintile is at high risk (in orange); third quintile is at moderate risk (in yellow); fourth quintile is at low risk (in green), and the last quintile is at very low risk (in blue). The countries are finally sorted from highest to lowest risk to SLR. The influence of vulnerability on SLR risk is most pronounced.

Country	Average hazard rank	Average exposure rank	Average vulnerability rank	Average slr risk rank	Country	Average hazard rank	Average exposure rank	Average vulnerability rank	Average slr risk rank
Somalia	19	66	1	1	Philippines	27	12	62	36
Mozambique	4	19	2	2	Sudan	112	82	18	37
Madagascar	9	29	5	3	Honduras	62	66	40	38
Angola	19	21	11	4	China	58	3	75	39
Liberia	60	42	4	5	Russian Federation	3	14	78	40
Sierra Leone	58	43	3	6	Djibouti	102	107	15	41
Papua New Guinea	19	37	9	7	Guatemala	86	94	30	42
Senegal	71	25	16	8	Haiti	77	83	38	43
Guinea-Bissau	67	56	6	9	Guyana	65	64	47	44
Mauritania	82	31	13	10	United States of America	1	1	111	45
Tanzania United Rep	60	34	19	11	Sri Lanka	53	33	58	46
Benin	50	55	10	12	Suriname	57	49	54	47
Myanmar	89	15	24	13	Nicaragua	28	86	50	48
Guinea	76	41	20	14	Namibia	22	110	36	49
Nigeria	41	7	43	15	Belize	64	78	48	50
India	44	4	45	16	Morocco	84	53	55	51
Togo	33	93	14	17	Thailand	49	17	80	52
Yemen	46	58	22	17	Timor-Leste	12	118	29	53
Congo Dem	28	99	12	19	Equatorial Guinea	17	117	33	54
Cameroon	50	68	26	20	Comoros	41	122	21	55
Solomon Islands	16	103	7	21	Mexico	24	13	101	56
Indonesia	11	2	61	22	Bahamas	14	69	70	57
Ghana	40	51	31	23	Cuba	15	44	77	58
Pakistan	120	28	23	24	Venezuela (Bolivarian Republic of)	52	26	82	59
Gabon	25	35	41	25	Egypt	103	9	81	60
Congo REP	37	59	31	26	Sao Tome and Principe	17	128	17	61
Viet Nam	62	6	49	27	Fiji	32	116	44	62
Eritrea	104	91	8	28	Colombia	36	36	86	63
Cambodia	87	76	27	29	Turkey	108	47	65	64
Bangladesh	113	8	42	30	Vanuatu	26	121	39	65
Gambia	75	72	24	31	Argentina	95	23	91	66
Brazil	33	5	57	32	Cape Verde	47	119	35	66
Côte d`Ivoire	54	51	37	33	Italy	98	30	92	68
South Africa	4	100	34	34	Netherlands	72	20	108	69
Kenya	35	84	28	35	Costa Rica	92	87	66	70
Maldives	30	114	53	71	Germany	80	27	127	106
Iraq	123	70	69	72	Bahrain	120	88	103	107
El Salvador	90	104	63	73	Samoa	31	127	59	108

Table (contd.)

Country	Average hazard rank	Average exposure rank	Average vulnerability rank	Average slr risk rank	Country	Average hazard rank	Average exposure rank	Average vulnerability rank	Average slr risk rank
Dominican Republic	70	79	85	73	Tunisia	105	65	117	109
Mauritius	10	124	45	75	Japan	6	16	137	110
Portugal	82	89	73	76	New Caledonia	12	109	115	111
Denmark	100	39	97	77	Syrian Arab Republic	119	125	55	112
Libyan Arab Jamahiriya	108	50	88	78	Sweden	133	45	120	113
Uruguay	94	81	76	79	Croatia	128	119	82	114
Ecuador	77	48	95	80	Belgium	97	92	121	115
Trinidad and Tobago	66	111	59	80	Barbados	56	133	51	116
Albania	118	102	52	80	Puerto Rico	54	106	130	117
Spain	68	45	104	83	Norway	129	63	124	118
Iran (Islamic Republic of)	115	40	93	84	Singapore	79	96	133	119
Jamaica	44	113	71	85	Aruba	37	128	100	120
United Kingdom of Great Britain and Northern Ireland	91	22	114	86	Korea Rep	69	57	138	121
Australia	7	10	127	87	Latvia	136	80	123	122
Oman	88	95	90	87	Lebanon	115	123	115	122
Algeria	111	90	74	89	Cyprus	107	115	124	124
Canada	2	17	134	90	Ireland	105	85	135	125
Peru	93	60	105	91	Saint Vincent and the Grenadines	43	136	68	126
Brunei Darussalam	74	105	87	91	Estonia	137	98	109	127
Malaysia	39	11	129	93	Montenegro	125	132	66	128
Poland	129	73	84	94	Lithuania	135	108	126	129
Israel	117	101	78	94	Saint Lucia	48	135	89	130
Qatar	127	71	94	96	Slovenia	124	131	95	131
New Zealand	7	62	121	97	Occupied Palestinian Territory	122	134	98	132
Chile	110	61	110	98	Finland	139	53	112	133
Greece	98	75	106	99	Hong Kong Special Administrative Region of China	80	112	138	134
France	100	32	118	100	Macao Special Administrative Region of China	84	130	131	135
Saudi Arabia	114	24	119	100	Iceland	138	97	131	136
Panama	73	77	113	102	Malta	95	137	136	137
Kuwait	125	74	99	103	Jordan	129	138	107	137
Tonga	23	126	64	104	Bosnia and Herzegovina	129	139	72	139

Annex Figure 1. GIS Methods for analyzing spatial data



Use the country 50 km area points from top flowchart. Use these points to extract the values from land use raster data. Each of the area points will have the % of landuse type. Multiply the % of landuse type by area to get area by land use.

1. For countries with no permafrost within 50 km from shore, we reallocated "iced areas" to other land uses, using **Equation 1:**

   [grid code]*(([specific land use 2100] + ([specific land use 2100] / [total land use area %]) * [ice %])) = new specific land use area

   Where:

   grid code = area for the grid
   total land use area % =% cropland 2100 + % urban2100 +% pasture 2100 + %secondary2100 + % others 2100

   ice % = 1 – total land use area %
2. For countries with permafrost:
   a. We extracted values from the regional permafrost maps from the Global Geocryological Data System, University of Colorado National Snow and ice Data Center (Table 4), assigning 100% of area for delineated permafrost areas
   b. We extracted the values for the remaining areas for cropland, urban, pastureland, secondary land, and other land uses using **Equation 1**

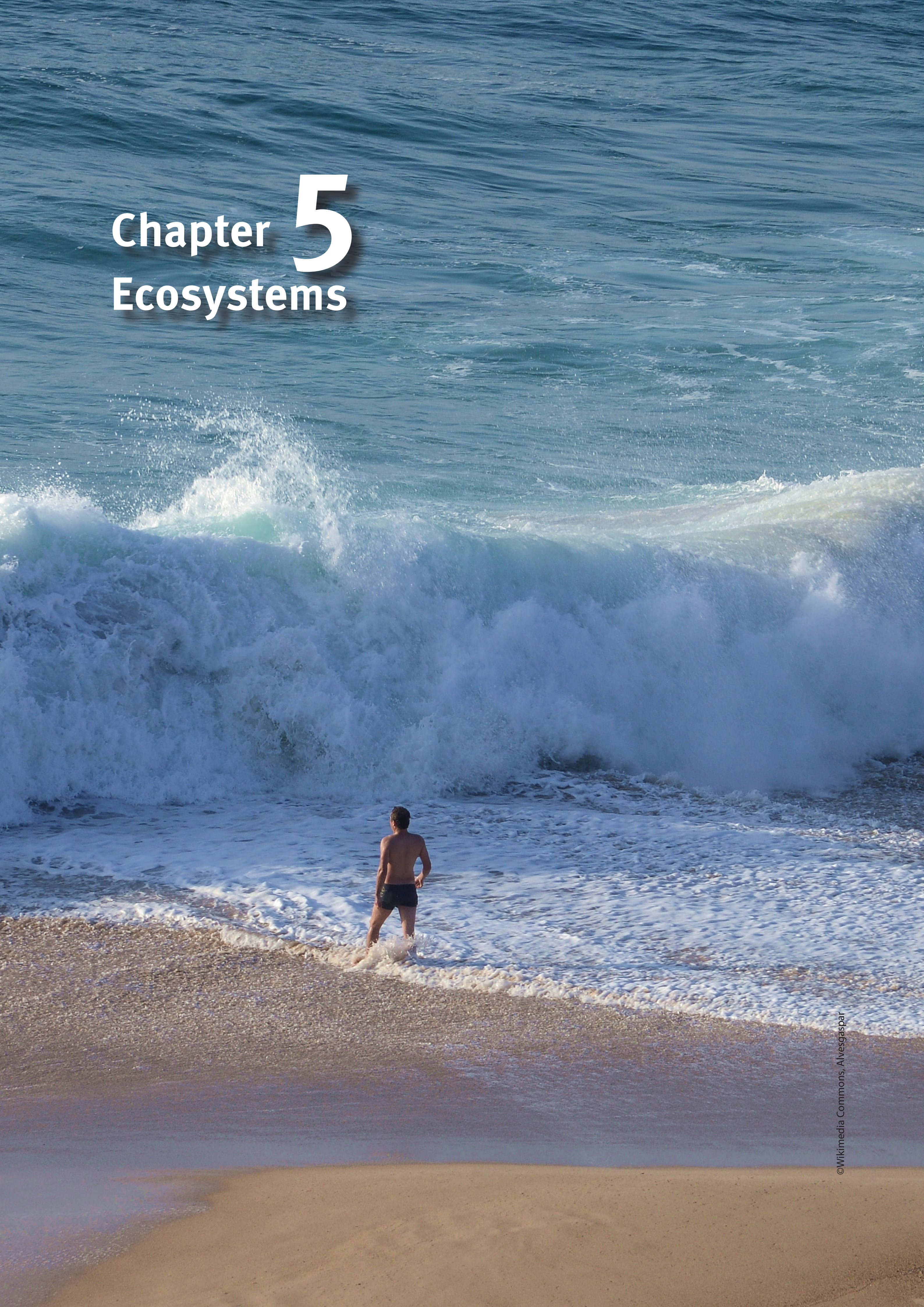
3. To determine freshwater systems within the 50 km coast:
   a. We extracted values from the Global Lakes and Wetlands Database GLWD3.0 Layer (Lehner and Doll 2004) (Table 4), assigning 100% of area for freshwater bodies.
   b. We extracted the values for the remaining areas for cropland, urban, pastureland, secondary land, and other land uses using **Equation 1,** replacing ice% with wetlands% in **Equation 1.**

Coral reef at palmyra atoll national wildlife refuge

Annex Table 4. Countries commonly populated with modelled data for the SSP scenarios reached 143 in number. Of these, countries surrounding the Black Sea, Bulgaria, Georgia, Romania and Ukraine, do not have IPCC projected data for sea level change, so that only 139 countries were assessed for sea level change associated risk.

SSP COUNTRY	Region	SSP COUNTRY	Region
Algeria	North Africa	Bahrain	Western Asia
Egypt	North Africa	Cyprus	Western Asia
Libyan Arab Jamahiriya	North Africa	Iran (Islamic Republic of)	Western Asia
Morocco	North Africa	Iraq	Western Asia
Sudan	North Africa	Israel	Western Asia
Tunisia	North Africa	Jordan	Western Asia
Benin	Western Africa	Kuwait	Western Asia
Cape Verde	Western Africa	Lebanon	Western Asia
Côte d`Ivoire	Western Africa	Occupied Palestinian Territory	Western Asia
Gambia	Western Africa	Oman	Western Asia
Ghana	Western Africa	Qatar	Western Asia
Guinea	Western Africa	Saudi Arabia	Western Asia
Guinea-Bissau	Western Africa	Syrian Arab Republic	Western Asia
Liberia	Western Africa	Turkey	Western Asia
Mauritania	Western Africa	United Arab Emirates	Western Asia
Nigeria	Western Africa	Yemen	Western Asia
Senegal	Western Africa	Bangladesh	Southern Asia
Sierra Leone	Western Africa	India	Southern Asia
Togo	Western Africa	Maldives	Southern Asia
Angola	Middle Africa	Pakistan	Southern Asia
Cameroon	Middle Africa	Sri Lanka	Southern Asia
Congo, Democratic Republic of	Middle Africa	Brunei Darussalam	Southeastern Asia
Congo, Republic of	Middle Africa	Cambodia	Southeastern Asia
Equatorial Guinea	Middle Africa	Indonesia	Southeastern Asia
Gabon	Middle Africa	Malaysia	Southeastern Asia
Sao Tome and Principe	Middle Africa	Myanmar	Southeastern Asia
Namibia	Eastern Africa	Philippines	Southeastern Asia
South Africa	Eastern Africa	Singapore	Southeastern Asia
Comoros	Eastern Africa	Thailand	Southeastern Asia
Djibouti	Eastern Africa	Timor-Leste	Southeastern Asia
Eritrea	Eastern Africa	Viet Nam	Southeastern Asia
Kenya	Eastern Africa	China	Eastern Asia
Madagascar	Eastern Africa	Hong Kong Special Administrative Region of China	Eastern Asia
Mauritius	Eastern Africa	Japan	Eastern Asia
Mozambique	Eastern Africa	Korea, Republic of	Eastern Asia
Somalia	Eastern Africa	Macao Special Administrative Region of China	Eastern Asia
Tanzania, United Republic of	Eastern Africa		
Australia	Oceania	Denmark	Northern Europe

SSP COUNTRY	Region	SSP COUNTRY	Region
New Zealand	Oceania	Estonia	Northern Europe
Fiji	Oceania	Finland	Northern Europe
New Caledonia	Oceania	Iceland	Northern Europe
Papua New Guinea	Oceania	Ireland	Northern Europe
Solomon Islands	Oceania	Latvia	Northern Europe
Vanuatu	Oceania	Lithuania	Northern Europe
Samoa	Oceania	Norway	Northern Europe
Tonga	Oceania	Sweden	Northern Europe
Canada	Northern America	United Kingdom of Great Britain and Northern Ireland	Northern Europe
United States of America	Northern America	Belgium	Western Europe
Belize	Central America	France	Western Europe
Costa Rica	Central America	Germany	Western Europe
El Salvador	Central America	Netherlands	Western Europe
Guatemala	Central America	Albania	Southern Europe
Honduras	Central America	Bosnia and Herzegovina	Southern Europe
Mexico	Central America	Croatia	Southern Europe
Nicaragua	Central America	Greece	Southern Europe
Panama	Central America	Italy	Southern Europe
Argentina	Southern America	Malta	Southern Europe
Brazil	Southern America	Montenegro	Southern Europe
Chile	Southern America	Portugal	Southern Europe
Colombia	Southern America	Slovenia	Southern Europe
Ecuador	Southern America	Spain	Southern Europe
Guyana	Southern America	Poland	Eastern Europe
Peru	Southern America	Russian Federation	Eastern Europe
Suriname	Southern America		
Uruguay	Southern America		
Venezuela (Bolivarian Republic of)	Southern America		
Aruba	Caribbean		
Bahamas	Caribbean		
Barbados	Caribbean		
Cuba	Caribbean		
Dominican Republic	Caribbean		
Haiti	Caribbean		
Jamaica	Caribbean		
Puerto Rico	Caribbean		
Saint Lucia	Caribbean		
Saint Vincent and the Grenadines	Caribbean		
Trinidad and Tobago	Caribbean		



Chapter 5
Ecosystems

Chapter 5.1 Overview

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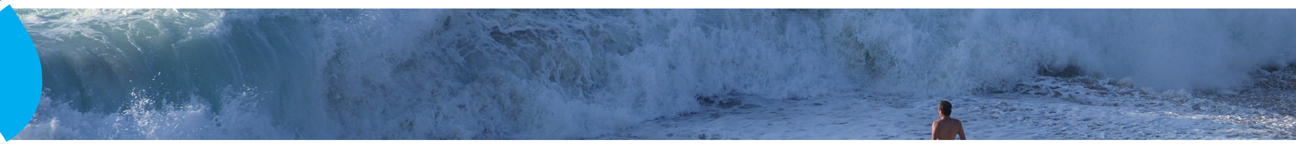
Ecosystems



5.1 Overview

5.1.1 Key Messages:

- Healthy ocean ecosystems are vital to the wellbeing of humans; and
- Human activities and associated global stressors such as ocean acidification can cause significant changes to the state of ocean ecosystems; and
- The vastness of the ocean provides a barrier to comprehensive monitoring of ocean ecosystem state, however, monitoring of key species or habitats can indicate potential changes to the wider marine ecosystem.

Open ocean ecosystems, habitats and biodiversity are all properties of the ecosystem state (shown in the Conceptual Framework as Box 3) which is central to the Open Ocean Assessment. Using the Conceptual Framework as a guide, human wellbeing is in part linked to sustained ecosystem services, which are in turn driven by the ecosystem state. Ideally a monitoring system feeding policy and governance would monitor the ecosystem state.

Ecosystem state changes include changes in primary productivity (which can be modelled based on chlorophyll data), the base of marine food webs, due to changes in ocean temperature, stratification and its interaction with the seasonal cycle, nutrients, and pollution from land-based nutrient input. These result in changes one step up in the trophic chain in zooplankton, and have repercussions further up in the ocean food web. These changes will have impacts on the rest of the pelagic ecosystem including commercially valuable species that are fished with consequences for people.

The remoteness and vastness of the oceans pose a serious barrier to a comprehensive open ocean ecosystem state monitoring system; it is simply impractical at present. Given scientific knowledge, educated guesses can be made about how ecosystem state, including biodiversity, is linked to stresses from human activities. In many cases these stresses are easier to measure comprehensively, at least for the few stressors that are thought to have global impact. Ocean ecosystem features that are particularly vulnerable were assessed too, as a complement to a mapping of where the stresses are strongest. The potential wide-ranging impacts of acidification on calcium carbonate species (for example: Pteropods) and ecosystems (for example: coral reefs) were selected for this reason. The results not only show current and projected future state responses to acidification; they also serve as an indication of potential impacts on the wider global marine ecosystem, services and subsequently human wellbeing. This provides guidance for improved monitoring at strategic locations in the open ocean where vulnerability and stress are highest, to ensure that these features are protected and can continue to provide ecosystem services.

The economic consequences of a change in governance designed to change stakeholder behaviour driving an associated stress on the open ocean can be significant. It can therefore be useful to attempt to link ecosystem state through the services it provides to human wellbeing with an economic valuation of the ecosystem service being examined.

Key indicators/metrics were identified by the sub-theme underlined above, and shown in the following chapters.

Chapter 5.2 Phytoplankton and Primary Productivity Baselines/IPCC Assessment Of Potential Future Impact

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5.2 Phytoplankton and Primary Productivity Baselines/IPCC Assessment Of Potential Future Impact

5.2.1 Summary and Key Messages

This Chapter covers the distribution of chlorophyll contained in phytoplankton in the surface waters of the world's ocean, quantified at high resolution in time and space using satellite observations. This product is derived from the Ocean-Colour Climate Change Initiative (OC-CCI) of the European Space Agency. Spanning some fifteen years (1998 – 2012), the fields provide the baseline for the current status and inter-annual variability in phytoplankton, which is at the base of the upper-ocean food chain and serves as food for other organisms in marine food webs. To illustrate some of the applications of the data, test products have been generated of marine primary production at the global scale and monthly resolution, for each of the years in the time-series. The dynamics of phytoplankton at the seasonal scale are also analysed, to extract indicators of phenology. The distribution of phytoplankton is strongly coupled to environmental variables, such that they can serve as sentinels of ecosystem response to environmental variability. This dataset is a rich resource for studying seasonal and inter-annual variations of phytoplankton in the open ocean and forms the foundation for a time-series that, if continued without interruption, should allow the identification of climate-change-related trends. The additional test products of primary production and phenological indicators demonstrate the usefulness of the chlorophyll-a dataset in understanding the marine carbon cycle and the timing of major biological oceanographic events, and which have profound impact on the health of marine ecosystems.

Key Messages

- Phytoplankton are critically important in the global carbon cycle and ocean ecosystems;
- Phytoplankton concentration can be assessed via satellite measurement of ocean colour that can be used to estimate chlorophyll concentration;
- Time-series of satellite-derived phytoplankton biomass is long enough to be used as a baseline for assessing phytoplankton status;
- Time-series information that are essential to see changes in phytoplankton activity in a changing climate are currently being developed;
- Phytoplankton biomass and primary production are sensitive indicators of environmental change at both regional and global levels;
- As phytoplankton is at the base of the marine food web, changes in phytoplankton and primary production have impacts on higher trophic levels; and
- Space-based ocean-colour radiometry is a cost-effective and reliable technique to monitor phytoplankton, a key element of the marine food web and carbon cycle.

5.2.2 Main Findings, Discussion and Conclusions

Chlorophyll-a is an important pigment contained in all plants. Measurements of chlorophyll-a concentration are key to understanding the distribution and abundance of phytoplankton in the global oceans. These microscopic organisms are responsible for half of the net photosynthetic primary production on the planet, supporting marine food-webs across the oceans and playing a key role in the global carbon cycle.

Primary production is the mass of carbon fixed into organic matter, through photosynthesis, per unit volume of seawater, over a given period of time. These values are typically integrated over the water column to obtain estimates of production per unit surface area. Units for the integrated product are mgC m^{-2} d^{-1}. It is an important quantity to measure, as phytoplankton are the foundation of the marine food web and changes in their distribution and abundance can have a dramatic influence on processes such as carbon export to the deep ocean and sediments, maintenance of fish stocks and marine ecosystem health.

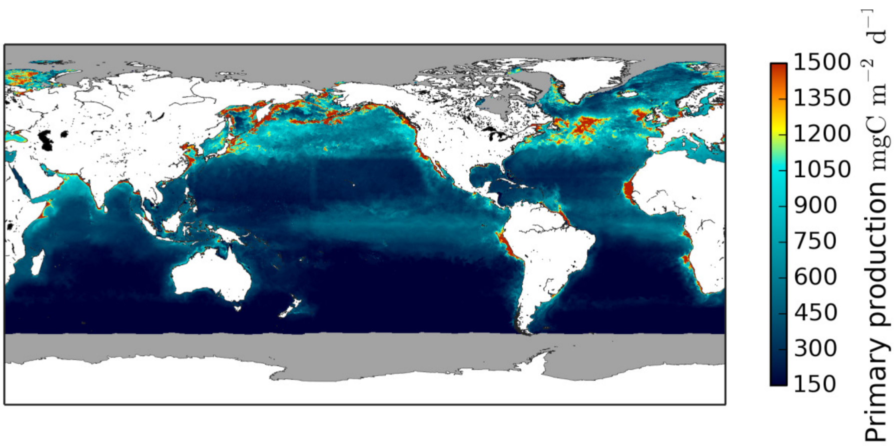
Phytoplankton respond to changes in a number of environmental conditions and so can act as sentinels of ecosystem change. To study changes in phytoplankton concentration on a global scale, remote-sensing platforms are ideal, due to their high temporal and spatial coverage. Such measurements allow us to quantify the phytoplankton phenology (seasonal dynamics, including timing and magnitude of growth) across the ocean.

The data presented here provides a global record of phytoplankton chlorophyll-a and the derived products of primary production and phytoplankton phenology. Together, these products allow an insight into the current variability in phytoplankton biomass across the globe and provide a time-series from 1998 to 2012 that will allow observations of the response of phytoplankton to climate variability on a global scale.

Findings

The results are a digital time series of chlorophyll fields at the global scale, with a spatial resolution of ~4x4 km and a temporal resolution of one day (available at www.esa-oceancolour-cci.org/). This dataset constitutes a rich data archive for studying seasonal and inter-annual variations in this biological field in the open ocean. The length of the time-series is insufficient for isolating potential trends related to climate change from climate variability. Because the ocean is subject to decadal-scale oscillations, the time series has to be extended to at least three or four decades, before climate-change-related trends can be identified, highlighting the importance of maintaining and building on this climate-quality dataset for many decades into the future.

Figure 5.1. An example of primary production (for May 2004) computed using the OC-CCI chlorophyll fields. The image shows high production in coastal and equatorial upwelling areas, and in the North Atlantic, associated with Spring bloom). These features vary seasonally and interannually.



The fields of chlorophyll concentration were combined with additional information to generate maps of primary production. The results are digital, monthly maps at ~ 9 x 9 km resolution. An example (May 2004) is shown in Figure 5.1. This is a test product, which has not been validated. It was generated to demonstrate one of the important applications of satellite-derived chlorophyll fields. An integrated annual production estimate was made for each complete year of data and the results, around 42Gt C yr$^{-1,}$ are comparable to previous estimates, as shown in Table 5.1.

The chlorophyll data have also been used to compute indicators of phytoplankton phenology for the years 1998 – 2011. The results are provided as digital fields at one-degree resolution. They are useful to study not only whether the chlorophyll concentrations in different parts of the world ocean are changing, but also to examine whether the timings of the major events in the phytoplankton calendar are changing.

The length of the time series of these products is not sufficient to detect changes that are significant in a climate-change context. The value of the results lies in providing a baseline, more than a decade long, of data, against

Table 5.1 Comparison of global annual marine primary production estimates

Source	Annual PP estimate for the global ocean
Longhurst et al. (1995)	44.7 – 50.2 Gt C yr^{-1}
Antoine et al. (1996)	36.5 – 45.6 GtC yr^{-1}
Field et al. (1998)	48.5 Gt C yr^{-1}
Geider et al. (2001)	48.3 Gt C yr^{-1}
Behrenfeld et al. (2005)	60 – 67 Gt C yr^{-1}
Westberry et al. (2008)	52 Gt C yr^{-1}
Moore et al. (2001)	45.2 Gt C yr^{-1}
Uitz et al. (2010)	45.6 Gt C yr^{-1}
TWAP test product	40.7 – 44.1 Gt C yr^{-1}

which future data can be compared for any potential evidence of change. Note that for this goal to be feasible, it is important to maintain the time-series without break and with consistent methods, for many decades into the future.

Discussion and Conclusions

Chlorophyll-a

By rigorously combining data from multiple sensors and providing uncertainty estimates on a pixel-by-pixel basis, the OC-CCI project has generated a climate-quality data record of phytoplankton chlorophyll-a. As the chlorophyll-a estimates are derived from remote-sensing measurements of ocean colour, most of the signal is from the first optical depth, with the consequence that they do not capture the full water-column chlorophyll in regions where the vertical structure in chlorophyll is pronounced, and where a deep chlorophyll maximum is present. The algorithm used in this work was designed for open ocean (Case 1) waters, and should be used in coastal (Case 2) waters only with caution. The product is *likely* to be less accurate in lakes and coastal regions. The OC-CCI product is still being developed and there are plans to update and refine the product over the next three years.

Primary Production

Small gaps in the primary-production estimates arise due to cloud cover, which introduced gaps in chlorophyll data, and larger gaps due to a number of months for which data on light at the sea surface was unavailable from NASA.

The method used here accounts for variability in primary production due to variations in chlorophyll concentration and available light. It does not account for year-to-year variations in the model parameters due to changes in environmental conditions. It would be desirable to develop validated methods for estimating photosynthesis parameters from space.

Phenological Indicators

The initial parameter estimation function used in this work did not perform very well in areas where the data values were low, and contained high relative variability. This is somewhat alleviated by the use of a smoothing function (Hann Window) on the data (only for the estimation of the initial parameters), with the main algorithm being run on the unsmoothed data. But the goodness-of-fit field provides a measure of how well the algorithm performed in reproducing the observed fields. Note that for the magnitudes of the peak values, the associated uncertainties are the same as the uncertainties in the chlorophyll fields themselves. For the timing of the events, the uncertainties are associated with gaps in the data; however these were minimised as much as possible by using OC-CCI data (through merging data from multiple sensors).

Coral spawning observations

Recommendations

Of the three satellite sensors used to generate the time series of products presented here, only MODIS-Aqua sensor of NASA is still operational (MODIS stands for Moderate Resolution Imaging Spectroradiometer). To identify long-term trends in the products presented here, which might be occurring in a changing climate, it is essential that the times series remain unbroken and continue into the future for many years. This would require that the MODIS-Aqua sensor continue to function at least until the launch of ESA's ocean-colour sensor OLCI (Ocean and Land Colour Instrument) on Sentinel-3. The longer the overlap between sensors, the better the cross-sensor calibration and bias correction that can be performed. Given that MODIS-Aqua sensor is now performing well past its design life span, the situation is precarious at present. It is recommended that at least two ocean-colour sensors are in orbit at any given time in the future, to avoid potential difficulties in achieving a seamless merging of the various missions. The possibility of incorporating data from other satellite sensors, such as VIIRS (Visible Infrared Imaging Radiometer Suite), into the time series should also be explored.

5.2.3 Notes on Methods

Chlorophyll-a

The chlorophyll-a product is Version-1 of the products generated by the OC-CCI. In the OC-CCI processing chain, water-leaving reflectances at multiple wavebands in the visible are derived from MERIS (Medium Resolution Imaging Spectrometer), MODIS and SeaWiFS (Sea-viewing Wide Field-of-view Sensor) sensors after atmospheric correction. The atmospheric correction algorithms that were used with each sensor were the ones that performed best in an inter-comparison that was undertaken as part of the OC-CCI Project. A band-shifting algorithm was then applied to the data, to bring the data from all sensors to a common set of wavebands, corresponding to SeaWiFS. The data from MERIS and MODIS were then compared with SeaWiFS data when overlapping data were available for each pair, to establish and correct for inter-sensor bias, if any, at each pixel. Water-leaving reflectances from the three sensors were then merged for each of the wavebands. The calculation of chlorophyll-a concentration was then performed using the empirical NASA OC4v6 algorithm, with the water-leaving reflectances at four wavelengths as input. This algorithm was also one of the best performing of in-water algorithms that were compared in the project. The units for the chlorophyll-a product are mg m^{-3} and it is provided at daily temporal resolution with a spatial resolution of ≈ 4 km/pixel. The coverage of the product is global and the data are currently available from September 1997 to December 2012. The chlorophyll products were validated by comparing the products against in situ observations, and the results of the validation were used to generate root-mean-square differences and bias in the product, for every pixel. For further details, please refer to the OC-CCI Product User Guide (http://www.esa-oceancolour-cci.org/?q=webfm_send/318).

Primary Production

Primary Production was estimated using a primary-production model (Platt and Sathyendranath 1988; Longhurst et al. 1995; Platt et al. 1995; Sathyendranath et al. 1995), a combination of remotely-sensed chlorophyll and light data, and information derived from ship-based in situ measurements on some model parameters. In validation exercises (comparison with field measurements of primary production), the model compared favourably with respect to other models (Friedrichs et al. 2009, Saba et al. 2010, 2011). For the computations, the model parameters, related to photosynthetic response to available light, and to vertical structure in chlorophyll concentration, were organised according to season into ecological provinces, as in Longhurst et al. (1995), with smoothing applied across boundaries of provinces. The product is provided at the global scale with a spatial resolution of 9 km and a temporal resolution of one month. The estimate of primary production given is the integral through the water column. Each biogeochemical province was assigned five parameters, which varied with the four seasons. Two of these were parameters defining the phytoplankton photophysiology: maximum photosynthetic rate per unit chlorophyll concentration at high light levels (P_m^B), and the rate of change of production with light availability, when light levels are low (α^B); three parameters were related to the vertical distribution of chlorophyll: the depth of maximum chlorophyll concentration (Z_m), the thickness of the subsurface peak in chlorophyll concentration (σ) and the ratio of the peak chlorophyll concentration to the background chlorophyll concentration (ρ). Parameters were smoothed across province boundaries to allow a transition zone between provinces.

The chlorophyll profile parameters were used in conjunction with the remotely-sensed chlorophyll data from the OC-CCI project, to create chlorophyll profiles for each 9 km pixel. Average sea-surface irradiance (Photosynthetically-Active Radiation) for each month and for each location was obtained from NASA and was used to scale the results of a spectral clear-sky model to allow input of spectrally-resolved irradiance into the primary-production model. The propagation of spectral light to various depths in the water column accounted for attenuation by water, phytoplankton and other coloured substances. The profile of light was then combined with the vertical profile of chlorophyll and photosynthetic parameters to obtain estimates of depth-resolved primary production. The calculations were repeated for hourly time steps during the day. The results were then integrated over time and depth to yield total primary production per unit area.

Phenology Indicators

Phytoplankton phenology describes the timings of major events in the annual cycle of phytoplankton. This builds on Platt and Sathyendranath (2008) and Racault et al. (2012). In this work, indicators associated with two major peaks of phytoplankton (nominally in Spring and Fall) were identified from the satellite data. The phenology indicators (timing and magnitude at peak of the two blooms and the duration of the blooms) were estimated through the fitting of an equation, constructed from two Gaussian peaks and a sloping baseline chlorophyll concentration, to the chlorophyll time-series for each year, resolved at five-day intervals. The time-series used is a five-day composite of the daily chlorophyll data that has been binned to a 1^o spatial resolution. The reason for the change in spatial resolution is the high processing time otherwise required, as well as the need to create time series with minimal gaps in the data.

To fit the double Gaussian equation, an initial guess of the parameters was provided to a sequential least squares minimisation function. The initial guesses for the chlorophyll-baseline parameters were calculated using the lowest 10% of data values. The mean of these points was used to set the initial guess for B_0 (background biomass) and the gradient initial guess was set as the gradient between the first ten and last ten points (from within the lowest 10% sub-set). To identify the two Gaussian peaks, the largest peaks in the data were identified by their area, where each peak is defined as a maximum with adjacent minimum. The initial guess for the peak width parameter (sigma) is then calculated for each of these two peaks, using the distance in time between the two neighbouring minima. The initial peak amplitudes are simply the chlorophyll values at each of the two peaks. To avoid the possibility that the minimisation function would merge multiple peaks into one broad peak, some bounds were introduced to limit the width of the fitted Gaussians.

This product also has a global coverage. The root mean square differences (RMSD) of the fit at each pixel alongside the phenology indicators as a metric of the quality of the fitting procedure was provided.

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Chapter 5.3 The Status of Zooplankton Populations

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5.3 The Status of Zooplankton Populations

5.3.1 Summary and Key Messages

Zooplankton are the link between primary productivity and the marine resources that society values, transferring energy from the base of the food chain to fish and marine birds and mammals. Changes in the abundance, timing or composition of zooplankton caused by environmental changes could have consequences for animals that rely on it as a food source. This chapter provides regional data and analyses of the status and trends in zooplankton abundance and composition from large scale surveys around the globe, to support the "Ecosystems" theme of this project. In some regions, the surveys extend for multiple decades.

Key Messages

There is a large amount of regional detail in these data, and different regions have different trends or patterns of variability but the main outcomes are:

- Zooplankton show species composition and abundance changes in response to ocean climate variability that are not always as expected, such as an increase in abundance of larger copepods under warmer conditions in parts of the North Atlantic and the Southern Ocean;
- Both the expected and unexplained changes have implications for higher trophic levels that depend on zooplankton for food. It is *virtually certain* (> 99% probability) that zooplankton assemblages will continue to change in density and/or species composition as climate changes;
- There are already documented distributional changes in zooplankton that are greater than those in terrestrial systems, and these will continue. Again, this is *likely* to impact fish and other zooplankton predators whether they can or cannot follow their prey;
- The methods of zooplankton surveying described here largely minimize transboundary water issues, since the transects mainly follow commercial shipping routes and some cross ocean basins; and
- A synoptic, consistent survey is essential to describe the magnitude of changes into the future. The Global Alliance of Continuous Plankton Recorder Surveys (GACS) is addressing this and new surveys are being initiated. Regions where we expect substantial impacts of climate change, particularly tropical and Arctic regions are largely unmonitored as yet, however, and remain a concern.

5.3.2 Main Findings, Discussion and Conclusions

Zooplankton support almost all marine ecosystems by supplying the energy derived from primary production to higher trophic levels such as squid, fish, marine birds and mammals. This can be either directly (many fish and baleen whales feed almost exclusively on zooplankton) or indirectly through intermediate trophic levels. Because they are not normally harvested, have limited control over their movements and have short generation times, zooplankton respond rapidly and directly to physical and biogeochemical changes in their environment, often integrating multiple signals. They are thus ideal indicators of ecosystem change.

There are numerous ways in which climate variability affects zooplankton. For example, as ectothermic organisms their metabolism is affected by temperature. Although in most of the world's oceans away from the equator, seasonal temperature changes are much greater than the relatively small annual deviations from the long-term mean, zooplankton populations are still very sensitive to interannual temperature variability. This is *likely* to be a consequence of the predictability of seasonal changes that has allowed many zooplankton to evolve finely-tuned life-history strategies that maximize the opportunities for growth at each life stage (Mackas et al. 2012). Trends in increasing upper ocean temperature can decrease the duration of life-cycle stages for some species, and delay them for others (Mackas et al. 2012) so altering the timing of seasonal abundance peaks from year-to-year. In turn then, predators may not have a food supply when expected.

Rather than gradual changes as a response to slowly changing sea surface temperatures (SST) marine ecosystems often show abrupt changes as critical thermal thresholds are reached. This can result in a series of step-like changes followed by more stable periods (Beaugrand et al. 2008). Different species of zooplankton have different optimal conditions for growth and reproduction and different tolerances. As local conditions change, so too will the success of each species, resulting in locally variable zooplankton communities and shifting distributions. Beaugrand et al. (2009) document northward shifts in calanoid copepods in North Atlantic waters of more than 23 $kmyr^{-1}$, exceeding migrations on land. Zooplankton predators may need to move to find their preferred food source, or if they are unable to move may need to switch to a less suitable prey.

Ocean chemistry also affects zooplankton, for example, shelled organisms such as pteropods may be adversely affected by ocean acidification. (See more details in Chs 4.5, 5.5 and 5.6) Their shells are made of aragonite and are thus very sensitive to thinning or dissolution due to increasing levels of partial pressure of CO_2. Work in the Southern Ocean by Bednaršek et al. (2012) has shown that there can be shell damage at aragonite saturation values less than 1. There is also evidence that pteropods in north Australian waters are also already experiencing shell thinning or increased porosity (Roger et al. 2012). Pteropods are a key prey item for some fishes (Armstrong et al. 2005) as well as providing an important link in the food web. If numbers of one or more zooplankton groups fluctuate significantly, this will change the interactions within and between the living ecosystem components. (See Chapter 5.5 for more details about pteropods)

Findings

Monthly averaged data from all the CPR (Continuous Plankton Recorder) sampled regions have been made available for this project. There is insufficient space to describe all of the results here so highlights, by region, are provided. Full sets of figures can be viewed on the project website[27].

The Northeast Atlantic

Over the last few decades the North Atlantic temperature has shown a strong increase (Ting et al. 2009) similar to the pattern found in Northern Hemisphere temperatures. The last few years, however, have seen a slight decline in temperature compared to the early and mid-2000s.

This region has the longest record of CPR data, with some regions consistently sampled for over 50 years. Many of the 41 sub-regions (particularly those labelled 1-5, see examples in Figure 5.2) show an increase over time in ACCS (Average Copepod Community Size, see Methods for derivation) for example: the copepod species have been getting larger, on average. This is somewhat unexpected given that for the region as a whole there has been a progressive increase over five decades in the presence of warm-water/sub-tropical species (which are typically smaller) into the more temperate areas of the Northeast Atlantic and a decline of colder-water species (typically larger) as shown by Beaugrand et al. (2002). This suggests that not all of the sub-regions are behaving similarly.

The Northwest Atlantic

Previous work has shown the Gulf of Maine region to have experienced significant changes in water properties and marine communities between the 1980s and 1990s, *likely* because of freshening conditions that resulted from high latitude warming and an increase in outflow of Arctic water (Greene and Pershing, 2007). Pershing et al. (2005) found an increase in small copepod abundances in the 1990s relative to the previous decade, particularly in winter, and suggested that the salinity changes increased stratification and increased winter primary production. At about the same time, Kane (2007) reported an increase in smaller copepod species on the adjacent George's Bank, by about an order of magnitude, altering the community composition there. The reduction in ACCS between the 1980s and 1990s is clearly evident in Figure 5.3 though more recent years have returned to near average.

27 www.onesharedocean.org/open_ocean/ecosystems/zooplankton

Figure 5.2. Average Copepod Community Size (mm) for 5 sub-regions of the NE Atlantic that are west of the European shelf waters (see map, top right). The trend lines (in red, moving average) indicate generally increasing size for regions C, D and E5.

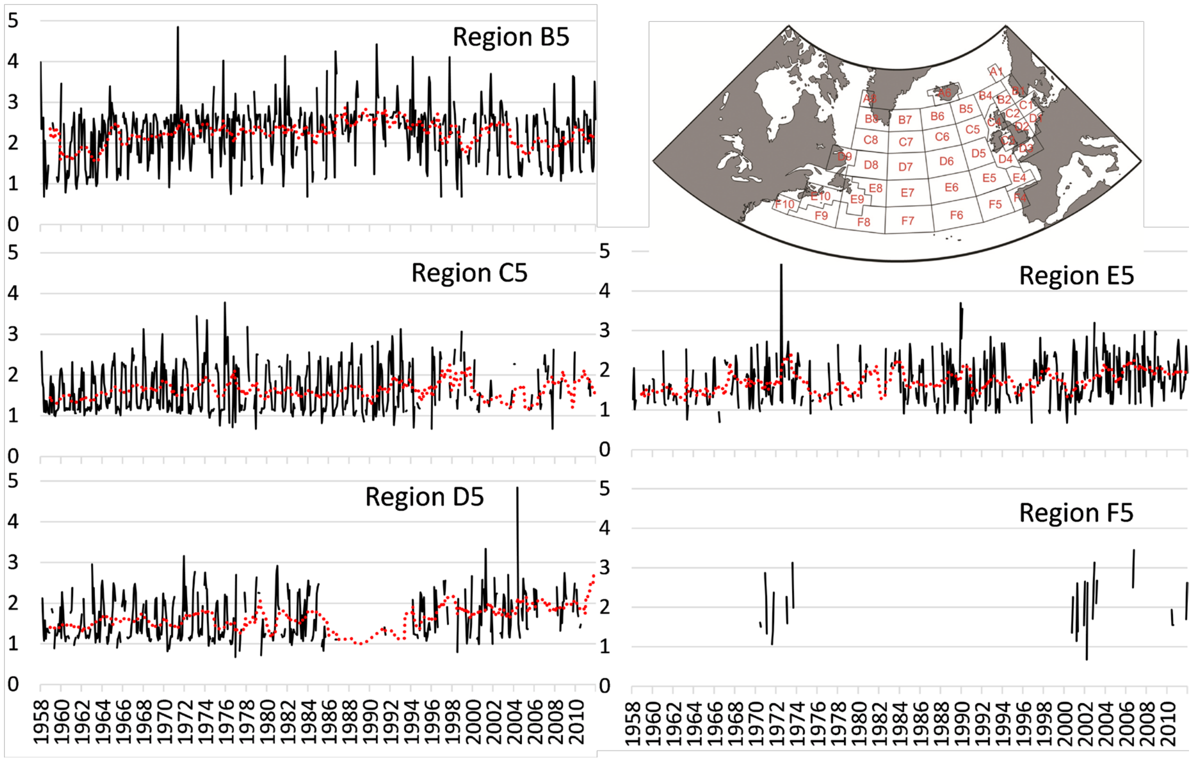
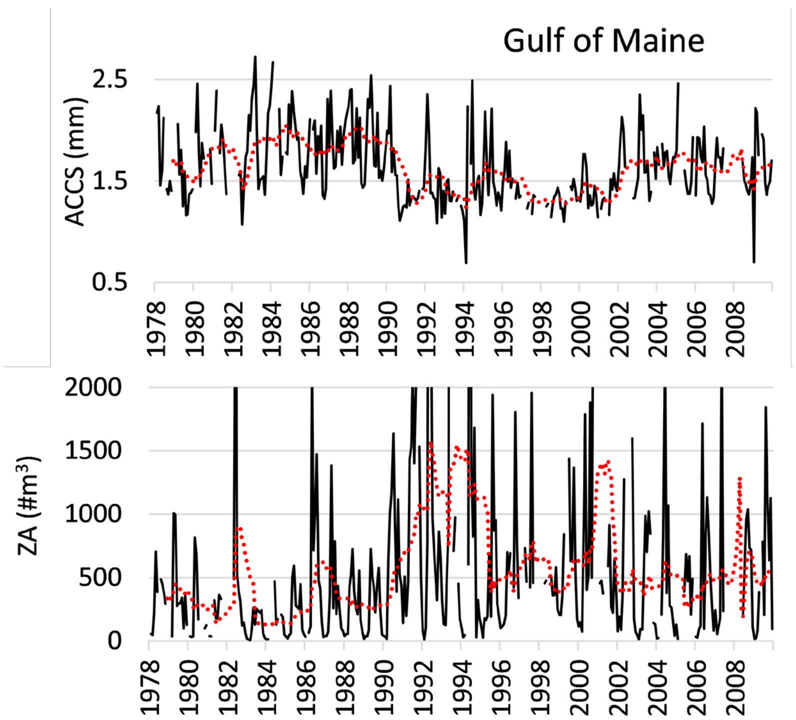


Figure 5.3. Average Copepod Community Size (upper) and Zooplankton Abundance (lower) for the Gulf of Maine region. The trend line (in red, moving average) shows the decrease in copepod size from the 1980s to 1990s coupled with the increase in abundance as small copepods became more prevalent.



The Northeast Pacific

Two of the dominant drivers of the North Pacific climate, the Pacific Decadal Oscillation (PDO, based on the analysis of Mantua et al. (1997)) and the El Niño-Southern Oscillation (ENSO) have shown increased variability in recent years. The PDO tended to remain in one phase or the other for 20-30 years during the last century but since 1998, phase changes have occurred roughly every five years.

There is a moderately short CPR time series in this region, beginning in 2000. All sub-regions show a decrease in the Zooplankton Abundance variable over the course of the time series, though this is only significant for the Aleutian shelf region. All sub-regions show an increase in ACCS over the time series, significant for the Northern Gulf of Alaska (N GoA), British Columbia (BC) shelf and Aleutian shelf regions.

The most likely explanation for these trends is that during the period of CPR sampling the North Pacific has been experiencing relatively high frequency shifts in sign of the PDO, such that the mid years of the 2000s experienced warm, PDO positive conditions but from 2008 to 2013 the northeast Pacific remained cooler than average and PDO negative. The larger subarctic species do better in cool conditions and so the last 5 years have seen a bias towards these forms, which dictates the direction of the linear trend in the time series, resulting in generally fewer, but larger organisms in cool conditions. The large-scale climate variability is apparently influencing the plankton over a similarly large spatial scale.

The Northwest Pacific

The time series of data is the same length as in the eastern North Pacific, but less seasonal coverage is available. The PDO influence is typically reversed in the western North Pacific with warmer conditions associated with a negative PDO and vice versa. However, ACCS in the summer increased in the second half of the time series in both sub-regions, as it did in the eastern North Pacific. The mechanism here remains unclear and further work is needed. Decadal-scale changes in copepod community structure and seasonal timing have been reported for this region based on a multi-decade net sampling program (Chiba et al. 2006) and suggest that from the 1950s until 2002 decadal variability was more prominent than a long-term trend, which is also supported by the CPR data. There is some evidence of bottom-up control occurring here with Sea Surface Temperature (SST) changes influencing primary productivity and this, in turn, the growth rates of key copepod species (Chiba et al. 2012).

The Benguela Current region

While we cannot compare Mesozooplankton Abundance directly with other CPR surveyed regions because of different sampling methodologies, changes in ACCS are less sensitive to the methods and so we have included these data in this assessment.

Zooplankton in this coastal-upwelling region show strong seasonality with a summer peak. Over the 60-year time-series however significant increases (more than two orders of magnitude) were documented in copepod densities between 1951 and 1995, followed by an order of magnitude decrease in the subsequent decade. This was believed to be partly because of changing pelagic fish stocks and the resulting changes in predation pressure (Verheye et al. 1998, Hutchings et al. 2009). At the same time we can see a decline in ACCS between the time periods of the 1950s and 60s and the decade of the 2000s. SST anomalies showed a large positive shift in 1994 through to at least 2007. The warming has modified the SST seasonality, shifting towards more equitable temperatures between summer and winter, and generally warmer SSTs during winter, off northern Angola. In southern Angola, warming occurred throughout the year with increased upwelling and seasonality (Jarre et al. in press). The sampling region falls at the boundary between the north and south and these differing regimes, but the reduction in ACCS during the same period is consistent with the theory that in warmer conditions smaller species should become more prevalent.

Australian Waters

The CPR survey around Australian waters is very recent, beginning in 2009, so no trends are able to be described as yet. However, there has been a substantial warming trend in all the sampled regions around Australia, with warming generally faster (about 0.07°C/decade) than the global average since the 1960s. As waters around Australia are generally warm, so many of the copepods are small – the mean copepod size across all samples is 1.15 mm, considerably smaller than in the neighbouring Southern Ocean for instance.

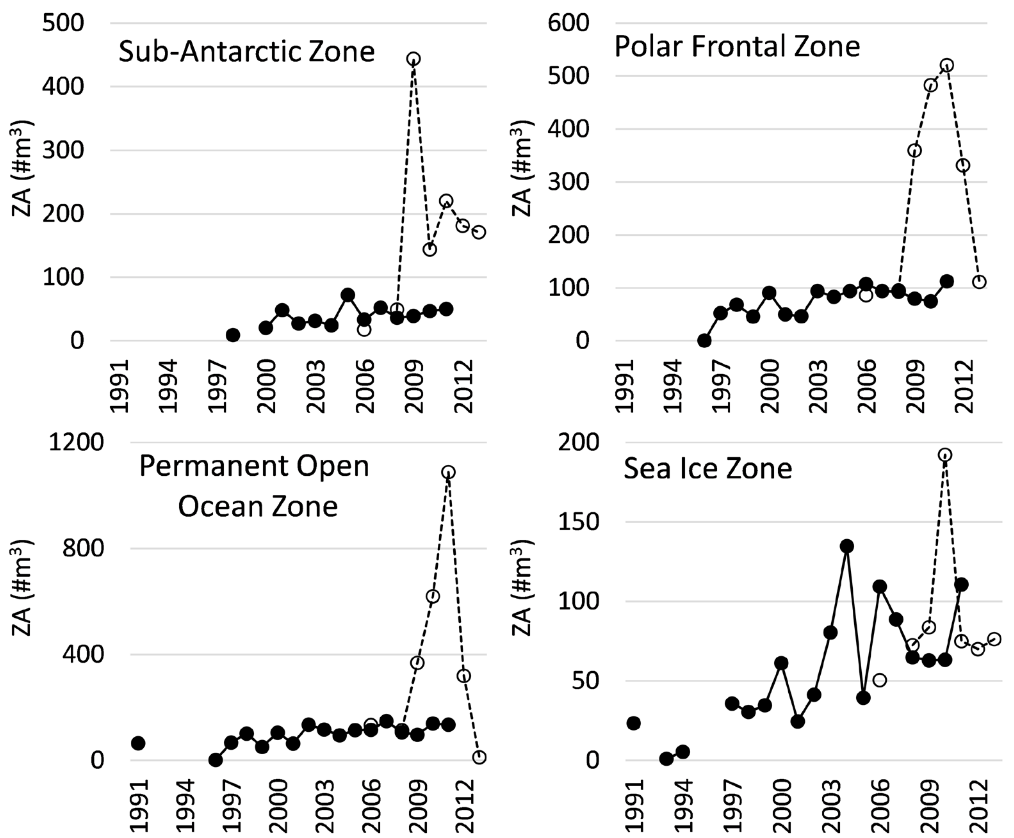
The Southern Ocean

Since the 1930s there has been a systematic and substantial warming of the Southern Ocean with much of this concentrated in the Antarctic Circumpolar Current (Aoki et al. 2003, Böning et al. 2008, Gille 2002, 2008). There has also been a freshening of the upper surface waters of the Southern Ocean (Boyer et al. 2005, Böning et al. 2008, Rintoul et al. 2012), which will lead to increased stratification and potentially a reduction in the input of nutrients into the euphotic zone (Rintoul et al. 2012).

Global warming will affect the extent and volume of sea ice, which in turn will affect the sea ice organisms such as Antarctic krill. There has been an approximate 25% loss of sea ice between the 1950s and 1970s (de la Mare 1997, 2009). The warming of the Southern Ocean, with its effects in terms of loss of sea ice, is not uniform across the region. Ducklow et al. (2007) described the western Antarctic Peninsula as “experiencing the most rapid warming of any marine ecosystem on the planet”.

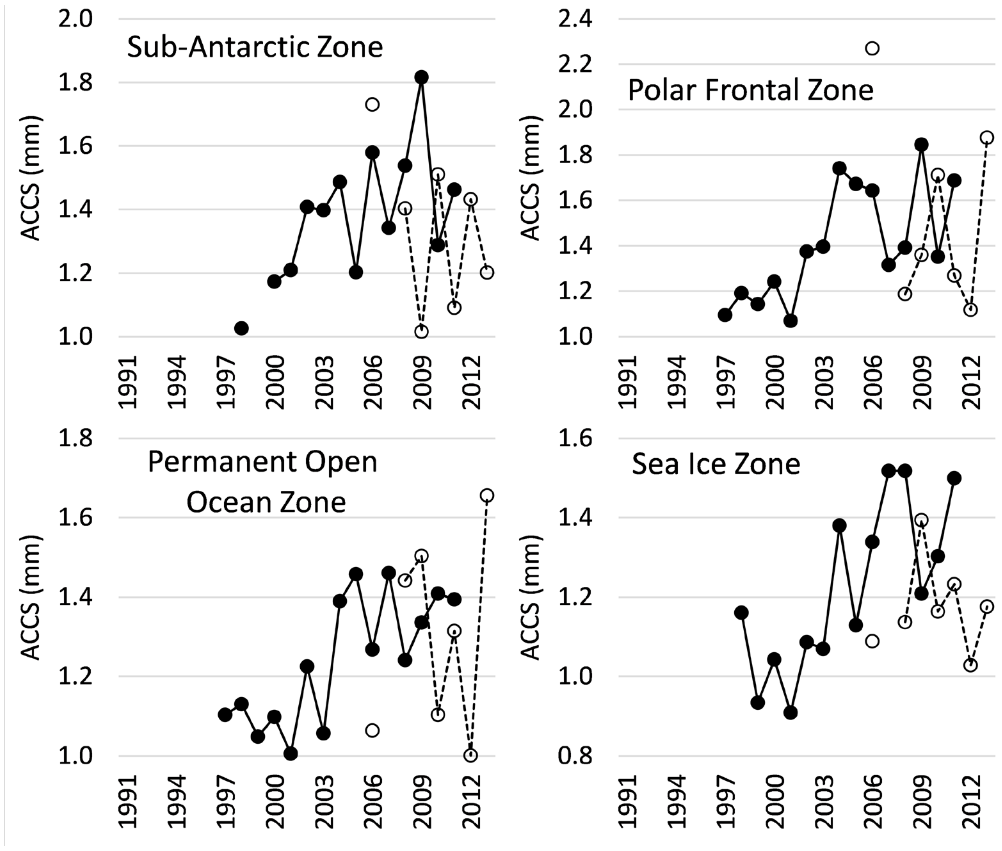
CPR sampling of some parts of the Southern Ocean extends over several decades (Robinson et al. 2014). The ZA variable shows a steady increase in abundance over time in all four zones of the East Antarctic region (Figure 5-4). All increases were statistically significant, although the specific causes of these increases still need to be identified. By contrast the Ross Sea region showed no trend in any of the four zones over the shorter period of CPR tows in that region. However, the total abundances of zooplankton in the Ross Sea region were generally higher than the abundances in the East Antarctic region.

Figure 5.4. Annual Zooplankton Abundance for the East Antarctic (black lines and filled circles) and Ross Sea (dashed lines, open circles) regions. Increasing abundance with time in all four East Antarctic regions is evident.



The ACCS variable also increased significantly over time in all four zones of the East Antarctic region (Figure 5-5). The increase in ACCS values indicates a shift in the abundance and dominance of copepod species to larger species which is contrary to the hypothesis that warming waters, as is occurring in the region, would favour smaller copepods. Other factors are thus driving the shift in species dominance and need to be determined. This could be related to mixed layer depth changes resulting from the warming, which in turn influences primary productivity. For example, increased wind forcing, presumably from climate change, is increasing the speed of the Antarctic Circum-polar Current and may, therefore, increase mixing and the depth of the Mixed Surface Layer. In turn this would increase nutrients available and phytoplankton concentrations, potentially more diatoms which are favoured by the bigger copepods. The CPR operations in the Ross Sea region have not been operating long enough yet to identify any trend within the ACCS.

Figure 5.5. Annual Average Copepod Community Size for the East Antarctic (black lines and filled circles) and Ross Sea (dashed lines, open circles) regions. Increasing size with time in all four East Antarctic regions is evident.



Discussion and Conclusions

It is clear that zooplankton abundance and community structure are highly variable and strongly influenced by the physical environment. Some regions are exhibiting long term trends (for example: the east Antarctic sector of the Southern Ocean), while others show decadal to sub-decadal variability. Most of the examples described here relate to temperature and salinity changes and the ways in which these attributes affect the water column structure and lower trophic level ecosystem functioning. Not all the results are as expected, in several regions we report an increase in ACCS under warming conditions (for example regions of the North Atlantic, Southern Ocean and western North Pacific) though other regions do show the expected pattern with warm conditions leading to smaller species (for example the Benguela, northeast Pacific and northwest Atlantic).

A long standing hypothesis related to global warming is that increased surface temperatures will result in increased water-column stratification that in turn will reduce mixing and decrease nutrient supply to the euphotic zone (McGowan et al. 2003; Roemmich and McGowan, 1995; King et al. 2011) with negative impacts on fisheries. Other work suggests a different outcome, at least in regions with nutrients supplied by upwelling. Rykaczewski and Dunne (2010) showed that increases in nitrate supply and productivity occurred despite increases in stratification and limited changes in wind-driven upwelling. The increases were attributed to enrichment of deep source waters resulting from decreased ventilation of the North Pacific. East Antarctic regions of the Southern Ocean have shown significant increases in zooplankton abundance over 20 years, despite warming and presumably increased stratification, though an increase in the strength of the ACC could in fact increase mixing. Clearly, further work to understand the mechanisms operating on lower trophic levels at the regional scale is required.

Currently CPR data do not show evidence of impacts of increasing ocean acidification on zooplankton abundance or community structure but it is *likely* that some vulnerable groups of organisms will be affected in the future. Continued monitoring should enable such changes to be detected.

Recommendations

It is *virtually certain* that the global ocean has warmed and that such warming will continue and cause timing, abundance and community composition changes in the zooplankton. It is clear from these results that there is a need to continue to monitor the world's zooplankton, as well as work to understand the regional outcomes of climate change. Changes in zooplankton biogeography, such as that documented by Beaugrand et al. (2009) in the northeast Atlantic can only be measured and tracked with large-scale transboundary sampling. New regional CPR surveys are planned from Brazil to the Antarctic, and in the eastern Mediterranean, with an Indian Ocean survey at the concept stage which are steps in the right direction. The Global Alliance of CPR Surveys (GACS) works to facilitate new surveys and collaboration between surveys but significant coverage gaps, such as the Arctic and tropical regions, need to be addressed. The key challenge to expanding the global CPR survey is to secure new and continuing funding sources, either in the particular countries/regions or at the international level.

5.3.3 Notes on Methods

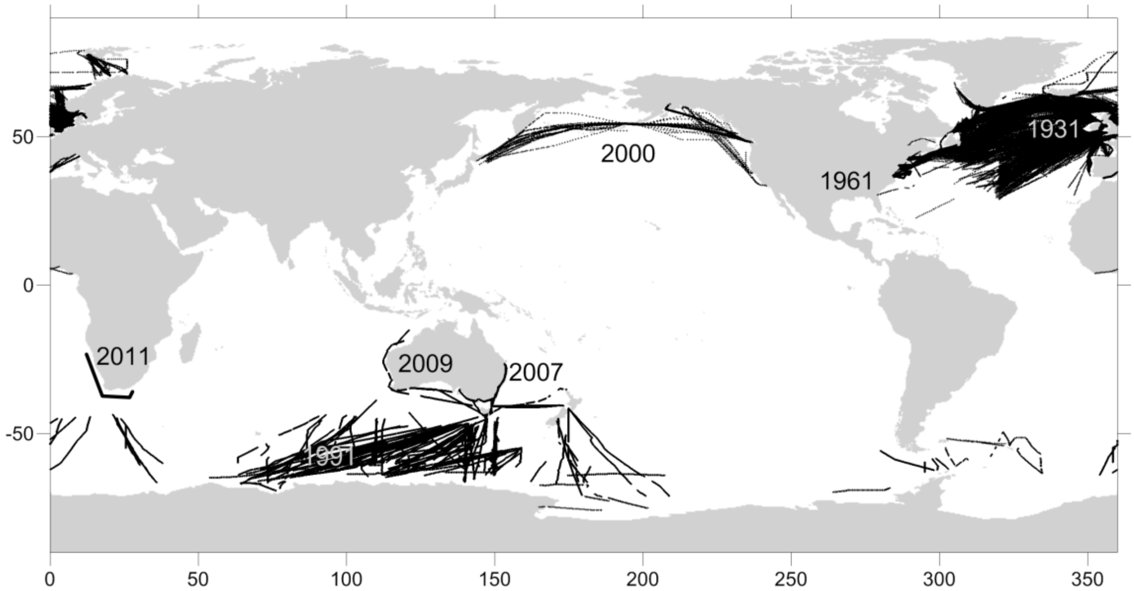
Data sources for this report

Zooplankton as a group includes many different types and sizes of organism from single-celled protozoa to larger crustacea such as krill. The data in this report are derived from zooplankton sampled by Continuous Plankton Recorders (CPRs). CPRs are typically deployed from commercial ships on their normal routes of passage, and have been used since the early 1930s. Surveys cover large spatial scales and several cross entire ocean basins. This approach provides seamless information between ocean and continental shelves, thus reducing transboundary sampling issues, though there are limitations stemming from the funding available, shipping routes, and the interests or focus of the funding agencies. As zooplankton cannot be observed from satellites as phytoplankton can, the CPR provides our best approach to observe how zooplankton changes through time in our oceans.

Here the focus is on the groups best sampled by the CPR with the aim of understanding the quantity and composition of zooplankton, two aspects important to the ecosystem services that zooplankton support. A change in abundance will affect the availability of zooplankton as prey, and a change in species composition could affect the nutritional quality to their predators. The variable "Mesozooplankton Abundance" (ZA) covers the size range most quantitatively sampled by the CPR and includes those organisms about 200 µm to a few mm in length, but excludes gelatinous plankton as those are not well preserved by the sampler. The variable "Average Copepod Community Size" (ACCS) covers arguably the most important and numerous group of crustacean zooplankton, the copepods. The species composition of copepod communities can be robustly determined, since copepods have definite growth and adults of a species have a narrow size range. This makes the average size of the copepod community an ideal indicator of species composition. Size also influences many processes affecting organisms (for example: physiology such as metabolism), populations (for example: population growth rates) and communities (for example: energy transfer through the food web; carbon flux to deeper waters).

The CPR is a robust mechanical device towed behind ships in the near-surface waters (usually commercial ships but also research, military and fishing vessels) that filters plankton from the water along the ship's path onto a length of 270 µm mesh. The mesh is divided into separate 18.5 km samples after the sampling (9.25 km in the Southern Ocean Survey), with time, date and position of each sample calculated from ship's log information or recorded underway GPS/environmental data. The plankton are identified with a microscope and counted. Full details of the methodology can be found in Batten et al. (2003) and Hosie et al. (2003), and details on data analysis and utility in Richardson et al. (2006). There are several CPR surveys around the globe (for more details see www.globalcpr.org), each using a consistent methodology, but varying in duration from multiple decades to just a few years for the most recent. Although there are still many places not sampled (tropical regions being the most obvious gap) this approach affords the greatest consistent synoptic open ocean coverage of the status and trends of zooplankton (Figure 5.6).

Figure 5.6. Map showing the historic Continuous Plankton Recorder sampling lines and the start year of each regional survey.



The data are subdivided in each region into sub-regions according to hydro-meteorological factors such as shelf versus deep ocean, prominent fronts or gyres, although coverage is limited in each case to where the ships have travelled and data may not be available for the whole of that sub-region.

Regions Sampled

Figure 5.7 shows the regional subdivisions which are described here:

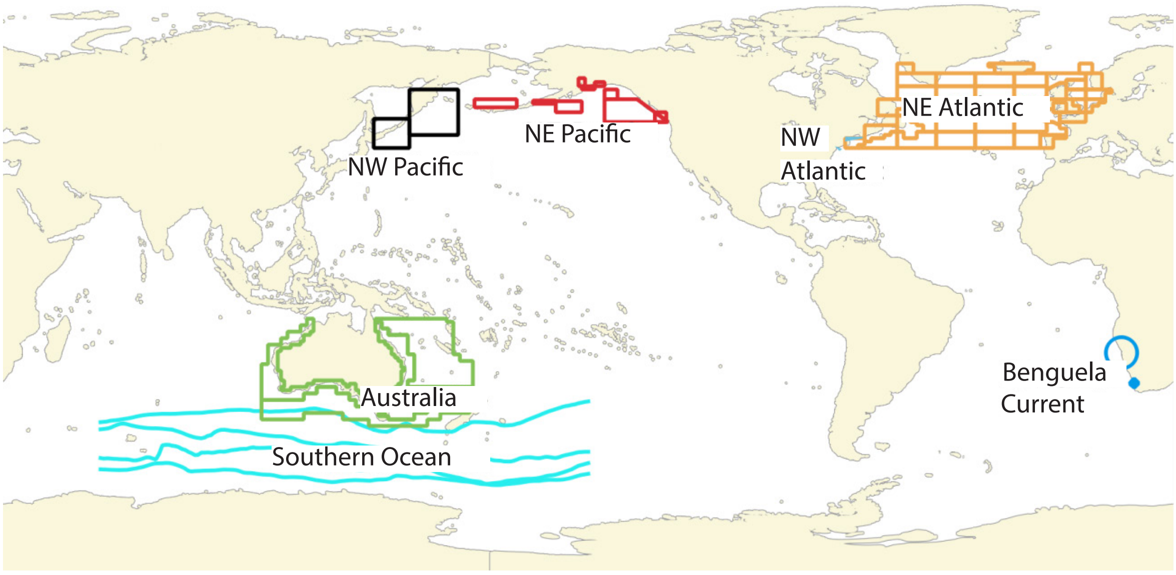
- *Northeast Atlantic*: The region with the greatest temporal (generally over 60 years, beginning in 1931) and spatial coverage. Because of the large amount of data it has been subdivided into 41 "Standard Areas", usually along major lines of latitude and longitude (see www.sahfos.org for further details on these standard areas, or the map in Figure 5.2 above).
- *Northwest Atlantic*: Subdivided into the Gulf of Maine and mid-Atlantic Bight regions, sampling started in 1961.
- *Northeast Pacific*: Subdivided into the coastal regions of the British Columbian shelf, the shelf south of Prince William Sound, Cook Inlet, the shelf Southeast of Cook Inlet, and the shelf around Unimak Pass in

the Aleutian Islands. Open ocean regions include the Northeast Pacific, the northern Gulf of Alaska, the western Gulf of Alaska, and the southern oceanic Bering Sea. Sampling started in 2000.

- *Northwest Pacific*: Subdivided into the Northwest Pacific Oceanic Gyre and the Oyashio current region (typically richer in nutrients). Sampling started in 2000.
- *Benguela Current*: CPR surveys off the west coast of South Africa, Namibia and Angola are the most recent routine survey to get underway, with samples first collected in 2011. Data have not been included in this assessment, though it is expected that future assessments will contain CPR data, but there is a lengthy time series of zooplankton net sampling from the region dating back to 1951. Sampling took place in St Helena Bay, South Africa (latitude 32-33°S) and more recently also off Walvis Bay in Namibia, 23°S, 4°E, during austral autumn, at the peak of pelagic fish recruitment.
- *Australia*: Australia is unique globally in being bounded by two poleward-flowing warm-water currents and the CPR survey samples the east, west and south coasts of Australia. Sampling started in 2009. Longhurst provinces were used to divide up the Australian marine domain into ecoregions viz. AUSE (Eastern Australia Coastal), ARCH (Western Pacific Archipelagic Deep Basins), TASM (Tasman Sea), AUSW (Australia-Indonesia Coastal), MONS (Indian Ocean Monsoon Gyres), SSTC (South Subtropical Convergence).
- *Southern Ocean*: With no land masses except Antarctica as the southern boundary, the Southern Ocean is characterised by latitudinal fronts. Sampling began in 1991. Four frontal zones are recognised:
    - the Sea Ice Zone (SIZ) with the northern limit being defined as the maximum northern winter extent based on the 15% ice cover threshold,
    - the Permanent Open Ocean Zone (POOZ) between the SIZ and the Polar Front, which lies within the ACC but displays a marked change in temperature and salinity,
    - the Polar Frontal Zone (PFZ), between the Polar Front and the Sub-Antarctic Front, which is the northern boundary of the Antarctic Circum-polar Current (ACC),
    - and the Sub-Antarctic Zone (SAZ), north of the Sub-Antarctic Front, which is a noted biogeographic boundary for zooplankton.

Data within each frontal zone have also been subdivided into the eastern Antarctic Sector and the Ross Sea sector.

Figure 5.7. Regions and their subdivisions used in this report



Definition of Variables

The two variables selected to represent the zooplankton community as captured by the CPR and provide evidence of either density or composition changes were:

1. Mesozooplankton abundance

The total abundance of zooplankton organisms retained in each CPR sample, excluding microplankton and eggs.

2. Average Copepod Community Size

This is an index of species composition since each taxon recorded is assigned a length value (based on information from the literature). Note that change in size within the taxon is not measured. Average size will increase (decrease) if the relative number of individuals of larger species increases (decreases).

$$\overline{S} = \frac{\sum_{i=1}^{N}(L_i \times X_i)}{\sum_{i=1}^{N} X_i}$$

For each sample, the length *L* (in mm) of each copepod species *i* (adult female length), is multiplied by its abundance X_i, summed over all species (*N*) and divided by the total abundance, according to Richardson et al. (2006).

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Chapter 5.4 Combined Threats to Warm Water Coral Reefs from Warming Seas, Ocean Acidification and Local Threats

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5.4 Combined Threats to Warm Water Coral Reefs from Warming Seas, Ocean Acidification and Local Threats

5.4.1 Summary and Key Messages

This work builds on the global spatial analysis of threats to coral reefs, *Reefs at Risk Revisited* (Burke et al. 2011) by updating projections of future global threats to coral reefs driven by increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere, and the resulting warming and acidification of the oceans. This chapter investigates the present and future ocean warming and acidification (in the decades beginning 2010, 2030 and 2050) and how these 'global threats' compound more local threats to coral reefs - overfishing, direct physical damage, sedimentation and pollution, from both land and sea. The data on local threats come directly from *Reefs at Risk Revisited* (Burke et al. 2011). Data on current and future warming (for the 2010s, 2030s and 2050s) were developed by the UNESCO-IOC from an ensemble of fully coupled Global Circulation Models (GCMs), for two scenarios - the Representative Concentration Pathway (RCP) 8.5 ('Business As Usual' scenario) and RCP 4.5 (the two degree stabilization scenario). Data on ocean acidification for the same time periods and scenarios were developed by National Oceanic and Atmospheric Administration (NOAA).

Despite their value to humans for food, livelihood, recreation and coastal protection, coral reefs are severely threatened by both local and global threats. At present, over 60 per cent of the world's coral reefs are threatened by local activities such as overfishing, destructive fishing, coastal development and pollution from both land and sea, with over one quarter at *high* or *very high* threat. When the influence of warming seas and ocean acidification for the current decade are considered, the percentage of reefs rated as threatened increases slightly, but the proportion of reefs at *high*, *very high* or *critical* threat levels increases to 37 percent.

Threats to coral reefs will increase in the coming decades due to continued greenhouse gas emissions driving ocean warming and acidification. Using projections of ocean warming and acidification from an ensemble of global climate models, it is estimated that in the 2030s about 90 per cent of the world's coral reefs will be threatened and by the 2050s virtually all reefs will be threatened by the combined (integrated) pressures from local and global threats. It is also estimated that the proportion of integrated threat coming from global sources (warming and acidification) to be 20 per cent in the current decade, 40-45 per cent in the 2030s and between 55 and 65 per cent in the 2030s. However, future emissions of greenhouse gases will greatly influence the severity of that threat. Under the RCP 8.5 ('Business As Usual') scenario, 95 per cent of reefs are projected to be in areas rated as under at least *high* threat (with 55 per cent in the *very high*, *critical* or *extreme* categories). If greenhouse gas emissions are reduced to keep the world under 2.0 C degrees of warming (RCP 4.5) it is projected that 55 per cent of reefs to be under at least *high* threat (with 35 per cent in the *very high*, *critical* or *extreme* categories). Although the latter is not a rosy picture, it represents a starkly better future for many of the world's coral reefs.

Key Messages

- Over 60 per cent of the world's coral reefs are currently threatened by local activities such as overfishing, destructive fishing, coastal development and pollution from both land and sea;
- By the 2030s, it is estimated that about 90 per cent of the world's coral reefs will be threatened and by the 2050s virtually all reefs will be under threat from combined local and global pressures;
- It is estimated that the proportion of threat to reefs coming from global sources (warming and acidification) to be 20 per cent in the current decade, 40-45 per cent in the 2030s and between 55 and 65 per cent in the 2050s;
- Future emissions of greenhouse gases will greatly influence the severity of the threat to coral reefs; and
- Despite their value to humans for food, livelihood, recreation and coastal protection, coral reefs are severely threatened by both local and global pressures.

5.4.2 Main Findings, Discussion and Conclusions

Coral reefs are vital, valuable, highly productive ecosystems, providing benefits (goods and services) to millions of people around the world. They are important sources of food and livelihoods; are a magnet for divers and snorkelers; generate the white sand which attracts coastal tourists from around the world; protect shorelines from erosion and inundation; and harbor enormous biological diversity.

Despite their importance, coral reefs face a wide and intensifying array of threats — from both local and global sources. Local threats to coral reefs include overfishing, destructive fishing, coastal development, runoff of sediment and pollution from the land, and impacts from shipping. Overfishing can alter the ecological balance on the reef, particularly by reducing herbivorous fish, which help to control algae (Mumby, P. J. et al. 2006). Increased nutrients in coastal waters (from runoff of fertilizers or sewage discharge) promote the growth of algae, impeding the settlement of coral larvae and growth of coral. Compounding these local threats are two global threats stemming from increasing concentrations of greenhouse gases in the atmosphere – warming seas and ocean acidification.

Warming seas have already caused widespread damage to reefs, with high temperatures driving a stress response called coral bleaching, where corals lose their colorful symbiotic algae (known as zooxanthellae), exposing their white skeletons (Eakin, C. M. et al. 2009). Corals filter food from the water using their tentacles, but they also rely heavily on their zooxanthellae, which use the sun's energy to synthesize sugars. The algae provide a critical source of food to the corals, enabling them to grow where nutrients are scarce, but restricting them to shallow waters (50 meters or less in depth). As such, temperature-induced coral bleaching leaves coral with less food, and therefore weakened. Many corals recover after bleaching, but recovery is less likely if bleaching is frequent (recurring), or if the coral is subject to other stresses – sedimentation, pollution, uncontrolled algae, or high acidity in surrounding waters (Wilkinson, C., and D. Souter, 2008). Wilkinson (2000) estimated that 16 per cent of the world's reefs were effectively destroyed during the major El Nino / La Nina climate event in 1998. Many of the reefs in the Indian and Western Pacific Ocean have since recovered; however many have not effectively recovered, especially those under anthropogenic pressures (Wilkinson 2000). A recent study by the Global Coral Reef Monitoring Network (GCRMN) suggests that the area of live coral in the Caribbean has declined by more than 50% since 1970. (Jackson, J.B.C, et al. 2014).

As increasing atmospheric CO_2 is absorbed into the ocean, ocean water increases in acidity and decreases the availability of concentrations of minerals like calcite and aragonite that corals need to build their skeletons (See detailed explanation in Chapter 4.4 of this Report). Ocean acidification reduces coral growth rates and, if unchecked, could reduce their ability to maintain their physical structure (Anthony et al. 2008; Cao et al. 2007) (See Chapter 5.6 of this Report). With this combination of local threats plus global threats from warming and acidification, reefs are increasingly susceptible to disturbance or damage from storms, infestations, and diseases. Such degradation is typified by reduced areas of living coral, increased algal cover, reduced species diversity, and lower fish abundance (Hughes, T. P. et al. 2007).

This study provides an examination of these combined pressures on coral reefs through the development of indicators of relative pressure on coral reefs. It looks at the combined influence of local threats, warming and acidifying water for the decades beginning with 2010, 2030 and 2050. For the 2010s, only the RCP 8.5 ('Business As Usual' scenario) is examined, as this best reflects greenhouse gas emissions to date. For the future time periods, two trajectories of greenhouse gas emissions are examined - RCP 8.5 and RCP 4.5 (emissions which stabilize warming at two degrees above preindustrial levels). Threats from warming and acidifying seas are evaluated using a methodology developed for the Reefs at Risk Revisited project (WRI, 2011).

Findings

Indicators presented reflect relative pressure on coral reefs from a) local pressures and b) integrated local and global threats. Any coral reefs in areas with a threat rating of *medium* or higher are referred to as a threat rating of coral reefs from a) local pressures and b) integrated loc*high, very high, critical* and *extreme.*

Local threats

Reefs at Risk Revisted (WRI, 2011) identified 60 per cent of the world' (WRI, 2011) identified 60 per cent of the world coral reefs as threatened by local human activity, with over 27 percent at high or very high threat. These areas are experiencing pressure from one or more local pressure – overfishing, destructive fishing, coastal development, watershed-based sediment and pollution, or marine-based threat. Threat is particularly high in Southeast Asia, where more than 90 per cent of reefs are threated – with nearly half at *high* or *very high* threat (See Figures 5.8 and 5.9).

This study developed a threat index which combines the percentage in different threat categories into a single index. (Local threat index = % under *Medium* threat + 2 x % *High* threat + 3x % *Very high* threat). The threat index ranges from 1.6 in Southeast Asia, to a *low* of 0.2 in Australia. The index for the world's reefs is 1.0. (See Table 5.2)

Table 5.2 Coral reefs by integrated local threat

Region	Low	Medium	High	Very High	% of world's reef area	Threat Index
Atlantic	25%	44%	18%	13%	10.6%	1.2
Australia	86%	13%	1%	0%	17.1%	0.2
Indian Ocean	34%	32%	21%	13%	12.4%	1.1
Middle East	35%	44%	13%	8%	6.0%	1.0
Pacific	52%	28%	15%	5%	26.4%	0.7
Southeast Asia	6%	47%	28%	20%	27.4%	1.6
World Total	**39%**	**33%**	**17%**	**10%**	**100%**	**1.0**

Figure 5.8. Reefs classified by local threat.

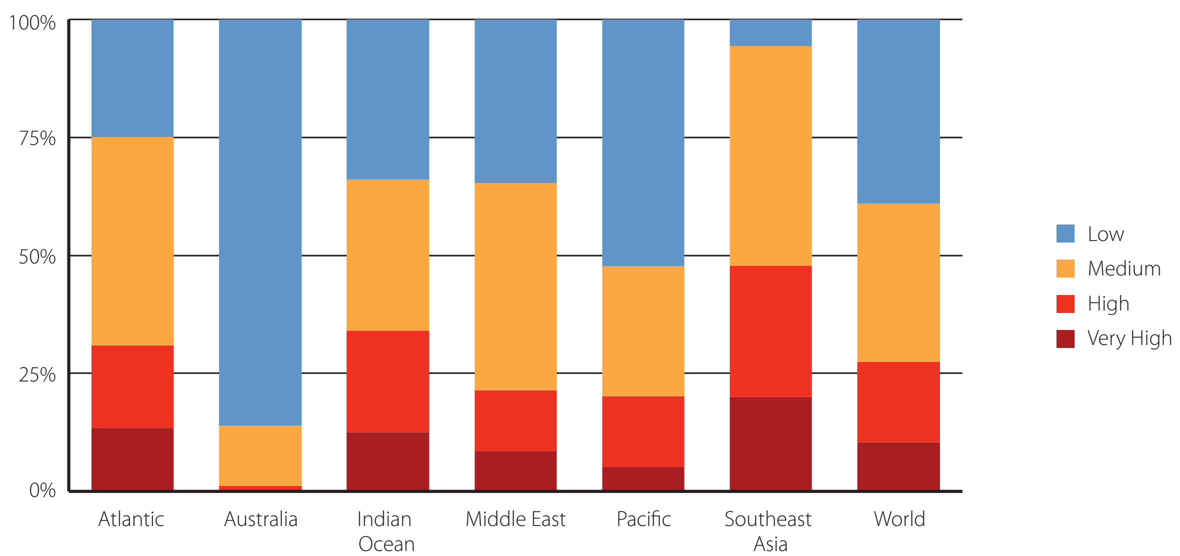
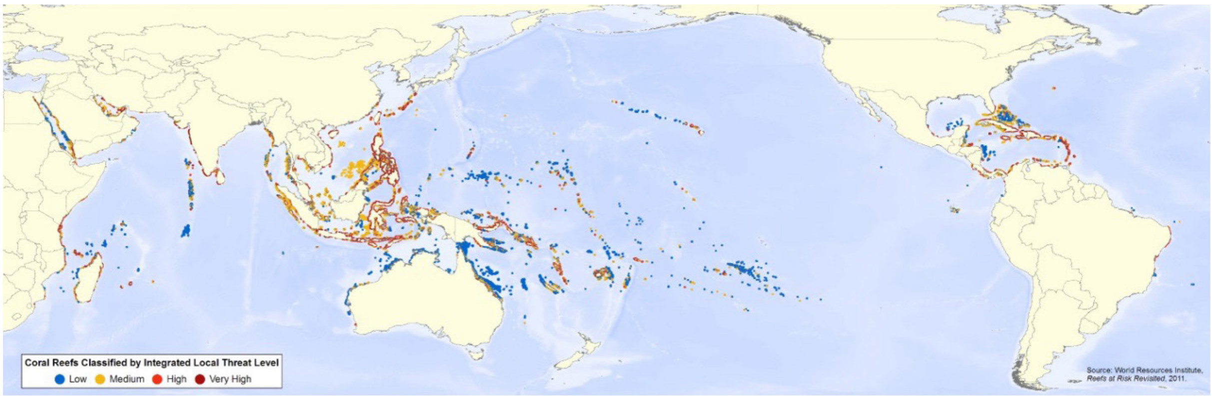


Figure 5.9. Coral reefs classified by threat from local activities.



Threat from Warming Seas

The influence of thermal stress on coral reefs was evaluated in terms of projections of the number of years within a decade that the accumulated degree heating months (DHM) exceeds a Bleaching Alert Level 2. Locations where this occurs two or fewer times during the decade were rated as being under *low* threat from thermal stress, areas where it occurs 3-5 times were rated as being under *medium* stress, and areas where Bleaching Alert Level 2 occurs most years (6 or more) within the decade are rated as being *high* threat areas, as the associated frequency of coral bleaching would *likely* exceed the ability of the coral to recover.

The warming data from the ensemble of climate models suggest relatively *low* thermal stress on coral reefs during the current decade, increasing in the 2030s (more significantly in the RCP 8.5 scenario, with about 10 per cent of reefs in *medium* and *high* threat areas), with very significant increases by 2050. Depending on the emissions scenario, between 40 per cent (RCP 4.5) and 99 per cent (RCP 8.5) per cent of reefs will be in areas at *medium* or *high* threat from thermal stress. (See Figure 5.10 and Table 5.3)

Threat to world's coral reefs from warming seas - by decade and scenario

Figure 5.10. Threat to world's corals reefs from warming seas – by decade and scenario.

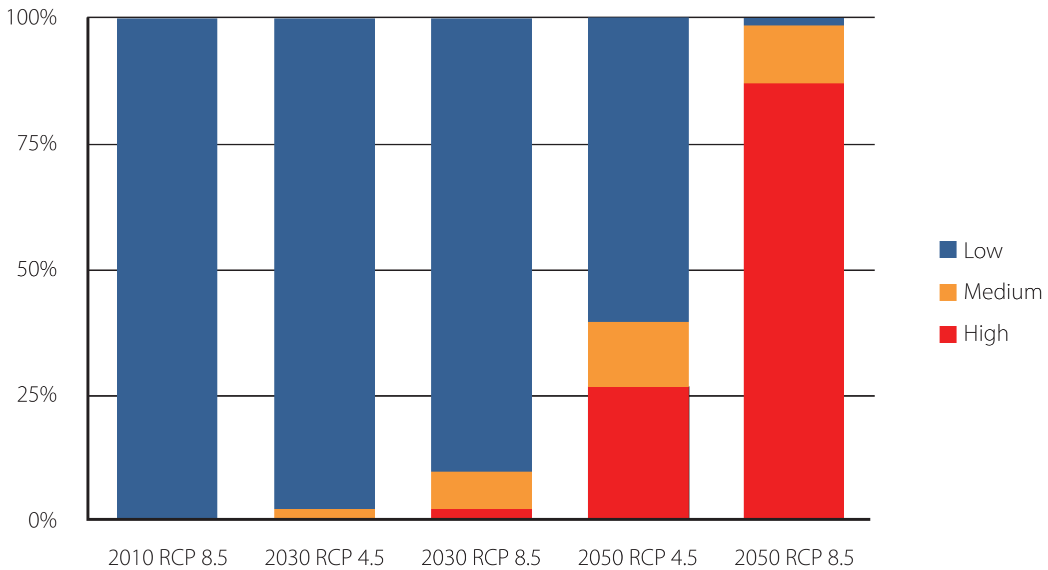


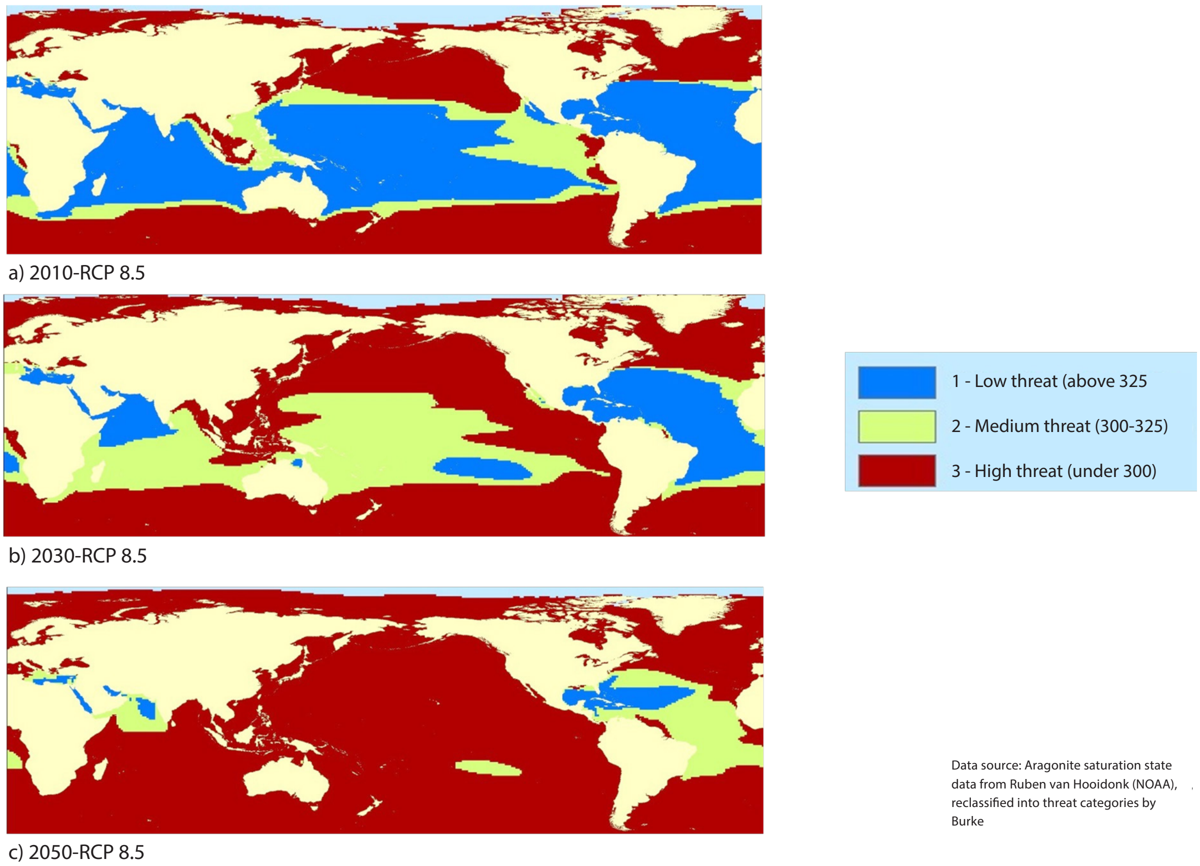
Table 5.3 Threat to coral reefs from ocean warming - by decade and scenario

Warming	Warming 2010 RCP 8.5			Warming 2030 RCP 4.5			Warming 2030 RCP 8.5			Warming 2050 RCP 4.5			Warming 2050 RCP 8.5		
REGION	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Atlantic	99%	1%	0%	98%	2%	0.0	68%	22%	10%	32%	14%	54%	1%	7%	92%
Australia	100%	0%	0%	100%	0%	0.0	98%	2%	0%	94%	1%	5%	4%	27%	70%
Indian Ocean	100%	0%	0%	92%	7%	0.0	74%	20%	6%	29%	21%	50%	1%	6%	93%
Middle East	100%	0%	0%	91%	9%	0.0	98%	2%	0%	58%	28%	14%	2%	17%	81%
Pacific	100%	0%	0%	100%	0%	0.0	95%	4%	1%	66%	9%	25%	1%	6%	93%
Southeast Asia	100%	0%	0%	99%	1%	0.0	95%	5%	0%	60%	16%	24%	1%	10%	90%
Global	100%	0%	0%	98%	2%	0.0	90%	8%	2%	60%	13%	27%	1%	11%	87%

Threat from Acidification

Threat to coral reefs from acidifying seas was evaluated based on the average aragonite saturation state from an ensemble of climate models (detailed in Chapter 4.4 of this Report, van Hooidonk 2015). Areas with aragonite saturation levels of > 3.25 were classified as low threat (adequate for coral growth); between 3.0 and 3.25 medium threat (due to low saturation levels); and below 3.0 high threat (due to extremely marginal levels for coral growth). (See Figure 5.11.)

Figure 5.11. Ocean acidification threat levels by decade for RCP 8.5.



Data source: Aragonite saturation state data from Ruben van Hooidonk (NOAA), reclassified into threat categories by Burke

Data on aragonite saturation state from an ensemble of climate models suggest that about one-quarter of the world's reefs are at medium or high threat from acidification during the current decade (under the RCP 8.5 scenario). By the 2030s, between 65 per cent (RCP 4.5) and nearly 80 per cent (RCP 8.5) of reefs will be threatened by acidification. By the 2050s, the overall percentage of reefs threatened by acidification will have risen to over 80 per cent in both scenarios, with a large percentage of coral reefs at high threat. In the RCP 8.5 scenario, 80 per cent of reefs are in high acidification threat areas, where coral growth would be severely hampered (See Figure 5.12 and Table 5.4).

Figure 5.12. Threat to world's coral reefs from ocean acidification - by decade and scenario.

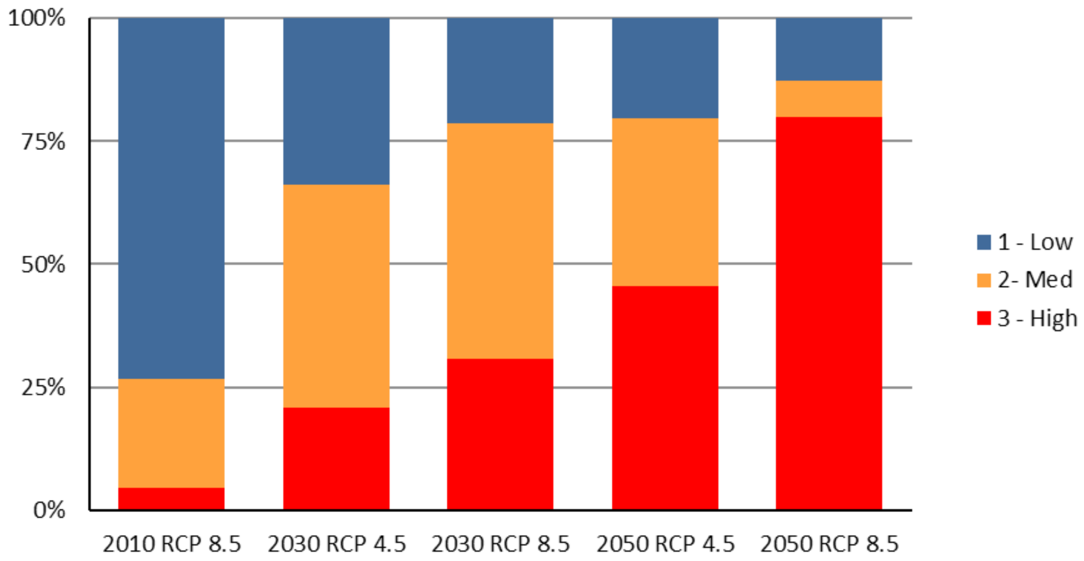


Table 5.4 Threat to coral reefs from Ocean Acidification - by decade and scenario

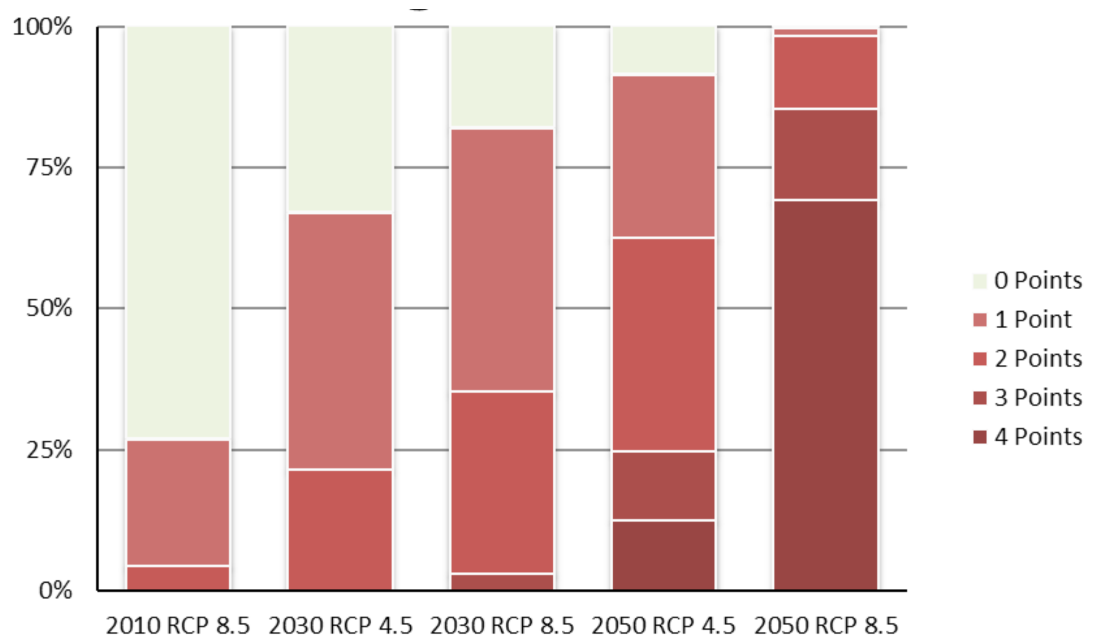
Acidification	Acid 2010 RCP 8.5			Acid 2030 RCP 4.5			Acid 2030 RCP 8.5			Acid 2050 RCP 4.5			Acid 2050 RCP 8.5		
REGION	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Atlantic	100%	0%	0%	100%	0%	0%	99%	1%	0%	99%	1%	0%	67%	32%	1%
Australia	100%	0%	0%	12%	88%	0%	0%	97%	3%	0%	87%	13%	0%	0%	100%
Indian Ocean	87%	8%	5%	52%	41%	7%	22%	63%	16%	17%	57%	26%	2%	15%	83%
Middle East	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	90%	10%	0%
Pacific	98%	2%	0%	32%	66%	1%	8%	87%	5%	7%	46%	48%	0%	6%	94%
Southeast Asia	10%	76%	14%	0%	29%	71%	0%	2%	98%	0%	0%	100%	0%	0%	100%
Global	73%	22%	4%	34%	46%	21%	21%	48%	31%	20%	34%	45%	13%	7%	80%

Combined Warming and Acidification Threat

Ocean warming and acidification are compounding threats to coral reefs. Prior to looking at these global threats coupled with local threats, this study looked at these two global threats combined. The combined threat was examined through simple addition of point scores. Areas with medium threat from warming or acidification receive one point, while areas at high threat receive two points. These two threats are added (for each time period and scenario), resulting in a grade ranging from 0 (low for both threats) to 4 (high for both threats).

Figure 5.13 reflects the growing pressure on coral reefs from these global threats from the current decade through the 2050s. The difference in threat between the RCP 4.5 and 8.5 scenarios is very apparent in the 2050s, where about 25 per cent of reefs are in areas with 3 or 4 threat points under RCP 4.5, while under RCP 8.5, 85 per cent of reefs are these categories.

Figure 5.13. Combined threat to coral reefs from warming and acidification.



Note: For the subsequent calculation of integrated threat (local and global threat) areas with one or two points from warming and acidification are increased by one threat grade (above their local threat grade) in the integrated threat index. Areas with three of four points are increased by two threat grades.

Integrated local, warming and acidification threat

The means of integrating threat was conservative – striving to achieve a nuanced ranking of future threat, and one that does not overstate the combined pressures. The threat integration included up to three threat points from current local threat to reefs – (1) *medium* (2) *high* (3) *very high* – and up to two additional points due to warming or acidification.[28]

Integration of local and global threats to coral reefs allows comparison of the change in projected threat to coral reefs over time; differences in projected threat depending on greenhouse gas emissions; and the proportion of threat in a given decade/scenario attributed to global versus local sources.

- **Current threat/2010s.** Over 60 per cent of the world's coral reefs are threatened by local activities such as overfishing, destructive fishing, coastal development and pollution from land or sea, with 27 per cent at *high* or *very high* threat. When the influence of warming seas and ocean acidification for the current decade are considered, the per cent of reefs threatened increases slightly, but the proportion of reefs at *high*, *very high* or *critical* categories shifts to 37 per cent (see Figure 5.14.) The threat index at the bottom of Table 5.5 provides a simple means of comparison of the intensity of threat to coral reefs for a given decade and scenario. This index increases by 25 per cent between local only threats and local and climate threat in the 2010s.

28 Reefs are assigned to their threat category from the integrated local threat index as a starting point. Threat is raised one level if reefs are at medium or high threat from either thermal stress or ocean acidification, or if they are at medium threat for both. If

- **2030s.** Threat to coral reefs will increase in the coming decades due to continued greenhouse gas emissions driving ocean warming and acidification. Using projections of ocean warming and acidification from an ensemble of global climate models, we estimate that in the 2030s about 90 per cent of the world's coral reefs will be threatened, with slightly higher percentages and threat levels under the RCP 8.5 scenario (threat index of 1.85) as compared with RCP 4.5 (threat index 1.65). (See Figure 5.14 and Table 5.5)
- **2050s.** During the 2050s, virtually all coral reefs are rated as threatened. Under the RCP 8.5 ('Business As Usual') scenario, 95 per cent of reefs are projected to be in areas rated as at least *high* threat (with 55 per cent in the *very high*, *critical* or *extreme* categories). If greenhouse gas emissions are reduced to keep the world under 2.0 C degrees of warming (RCP 4.5) it is projected that 55 per cent of reefs will be under at least *high* threat (with 35 per cent in the *very high*, *critical* or *extreme* categories). (See Figure 5.14.) The threat index for the 2050s is 2.15 (RCP 4.5) and 2.85 (RCP 8.5), reflecting the very influential role that future greenhouse gas emissions play in pressures on coral reefs.
- **Distinction by region.** Figure 5.15 reflects the increase in threat over time by region for the RCP 8.5 scenario. This presentation highlights the shift in both Australia and the Pacific from a majority of coral reefs at *low* risk in the 2010s to predominance at *medium* threat in the 2030s to predominance at *high* threat in the 2050s. By contrast, *high* threat dominates the reefs in Southeast Asia in 2010s, but by the 2050s, *very high* and *critical* grades dominate. Figure 5.16 reflects this progression for the world's reefs – also for RCP 8.5.
- **Contribution of global vs local sources.** It is estimated that the proportion of integrated threat coming from global sources (warming and acidification) to be 20 per cent in the current decade, 40-45 per cent in the 2030s and between 55 and 65 per cent in the 2030s. (See Table 5.6.) These proportions are derived by comparing the 'local only' threat index to the integrated index for each decade/scenario.

Figure 5.14. Integrated threat to coral reefs from local threats, warming and acidification.

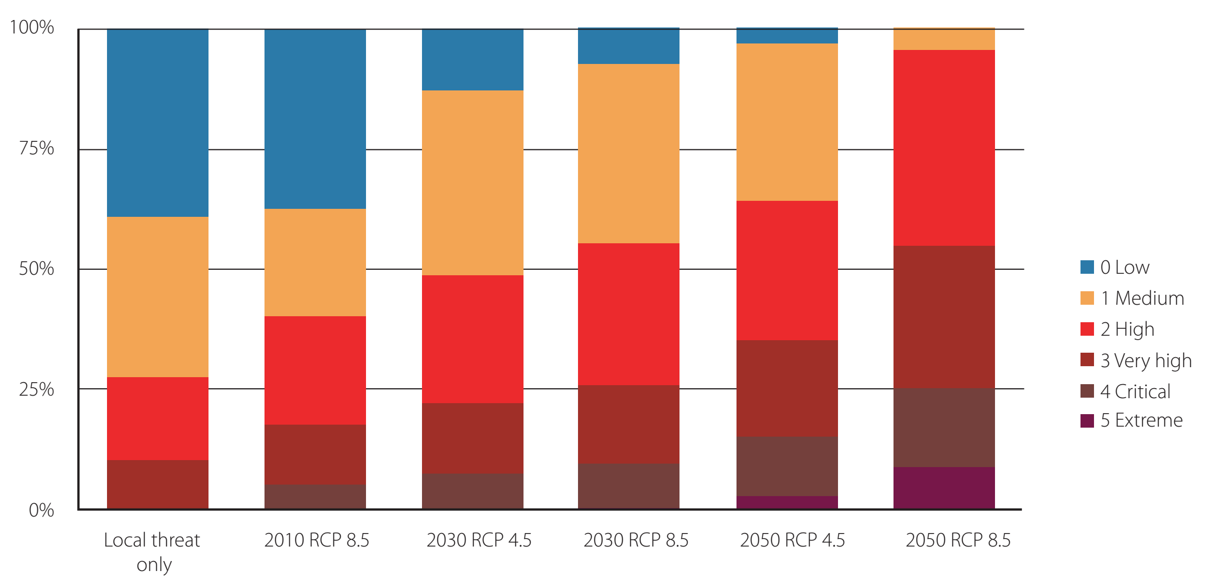


Table 5.5 Integrated threat from local threats and warming and acidifying seas. (Percent of reefs threatened by year and scenario)

Integrated threat	2010	2030		2050	
	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
	2010_85	2030_45	2030_85	2050_45	2050_85
0_Low	37%	13%	7%	3%	0%
1 Medium	23%	38%	37%	33%	5%
2 High	22%	27%	29%	29%	41%
3 Very High	12%	15%	16%	20%	30%
4 Critical	5%	8%	9%	12%	16%
5 Extreme	0%	0%	0%	3%	9%

Table 5.6 Contribution of global threats (warming and acidification) to the integrated threat index.

Decade and scenario	Percent
2010 RCP 8.5	20%
2030 RCP 4.5	40%
2030 RCP 8.5	46%
2050 RCP 4.5	53%
2050 RCP 8.5	65%

Discussion

This analysis method reflects a simplification of human activities and complex natural processes. The model relies on available data and predicted relationships, but cannot capture all aspects of the dynamic interactions between people, climate, and coral reefs.

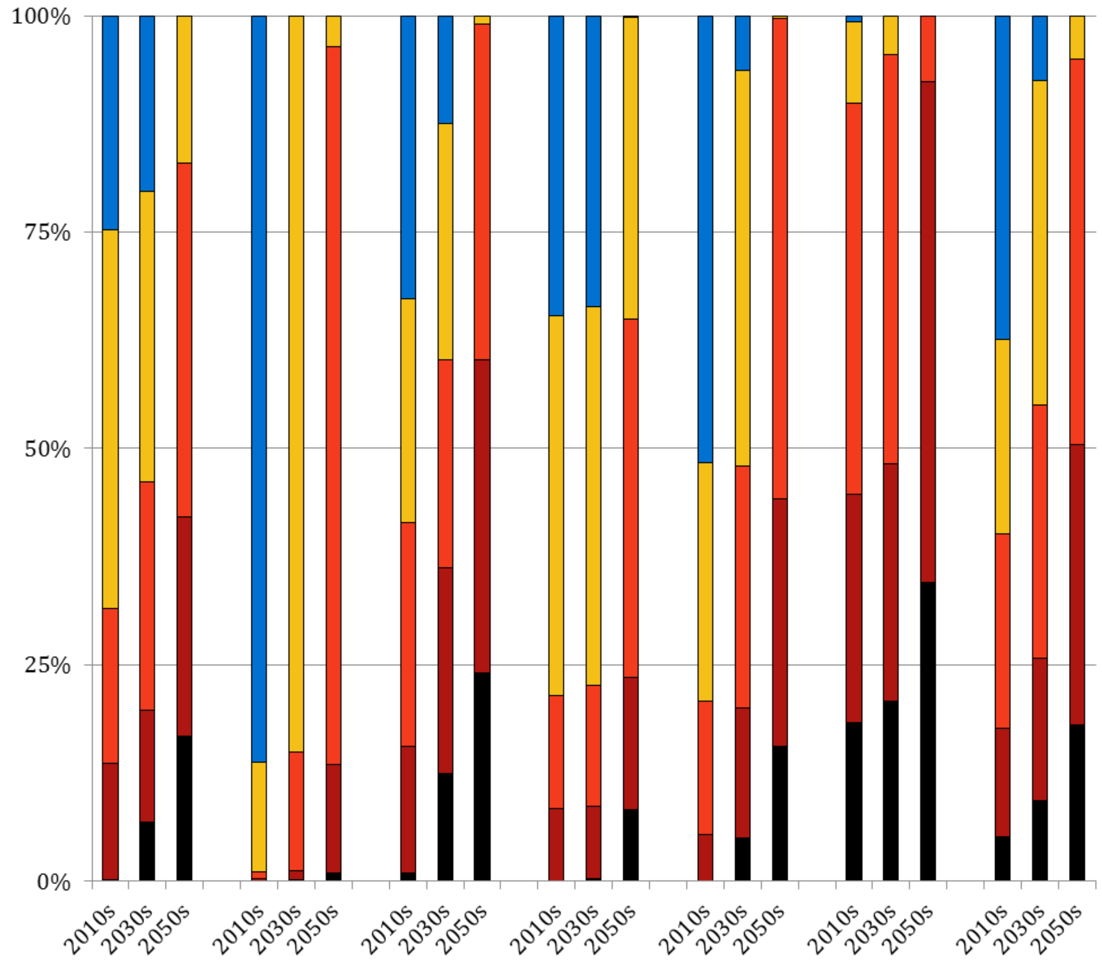
The threat indicators gauge current and potential risks associated with human activities, warming seas and ocean acidification. A strength of the analysis lies in its use of globally consistent data sets to develop globally consistent indicators of human pressure on coral reefs. A purposefully conservative approach to the modeling was used, where thresholds for threat grades are set at reasonably *high* levels to both counter any data limitations and avoid exaggerating the estimated threats.

The global approach provides a broad view of threats to coral reef health, but is not comprehensive. For example, the modeling did not include the potentially compounding threats of coral disease or increased storm intensity because of too many uncertainties in their causes, distribution, and relationships.

For the local threats, monitoring data and expert observations were used, where available, to calibrate the individual threat layers and validate the overall model results. The thresholds chosen to distinguish *low*, *medium*, and *high* threat rely heavily on the knowledge of project collaborators - from both this study as well as the Reefs at Risk Revisited project (Burke et al. 2011) - with expertise across different geography and aspects of reefs and reef management.

Reliance on an ensemble of climate models has both strength and limitations. The approach avoids relying too much on the biases of individual models, but averaging across models can omit some of the nuances of local climate, which could influence whether warming thresholds are crossed, such as a Bleaching Alert Level 2.

Figure 5.15. Integrated local and global threats to coral reefs by region for RCP 8.5.



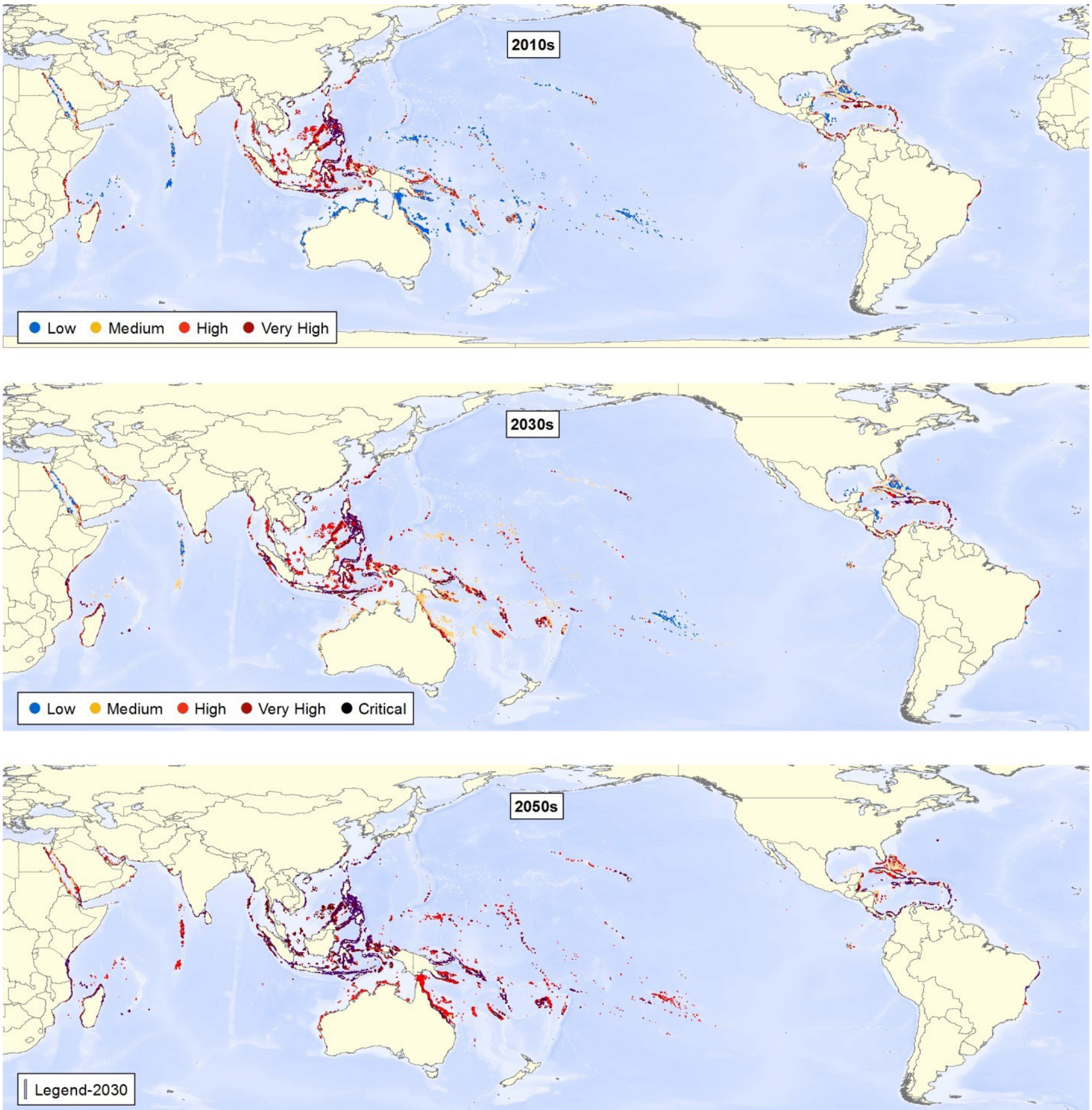
Projections of the threat of warming to coral reefs are relatively *low* for the current decade and only begin to exceed 10 per cent of the global coral reef area after the 2030s. This is *likely* an underestimate of threat to coral reefs from warming seas over the next 25 years, in light of the extent of mass coral bleaching already observed (Sheppard, C. R. C. et al. 2002; Eakin, C. M. et al. 2009; Berkelmans, R. G. et al. 2004; Wilkinson, 2008.).

Projections of ocean acidification suggest that about one-quarter of coral reefs are threatened in the current decade, with an increase to between 65 and 80 per cent of coral reefs during the 2030s. In light of the scarceness of observations of ocean acidification impacts on coral reefs to date, it is difficult to evaluate the estimates for the current decade, but the estimates are not implausible (Veron, J. E. et al. 2009).

This approach of integrating projected warming and ocean acidification prior to combining it with the local threat estimates, coupled with using a conservative approach to increasing the local threat estimates, serves to dampen the uncertainty associated with the projections of global threats.

Hence, despite the uncertainties inherent in future projections, the analysis does serve to highlight that the trajectory of our future greenhouse gas emissions will have significant influence on threats to and the *likely* health of the world's coral reefs.

Figure 5.16. Integrated local and global threats to the world's coral reefs under the RCP 8.5 scenario.



Recommendations

Despite their value to humans for food, livelihood, recreation and coastal protection, coral reefs are severely threatened by both local and global threats. Over 60 per cent of the world's coral reefs are threatened by local activities such as overfishing, destructive fishing, coastal development and pollution from land and sea. Threat to coral reefs will increase in the coming decades due to continued greenhouse gas emissions driving ocean warming and acidification, but the degree of threat will be greatly influenced by our greenhouse gas emission trajectories. Shifting from the emissions trajectory of 'Business As Usual' (RCP 8.5) to a two degree increase stabilization level (RCP 4.5) would make a tremendous difference in the intensity of threats to coral reefs by the 2050s. Such a shift reduces the percentage of coral reefs in the highest three threat categories (*very high*, *critical* and *extreme*) by one third, significantly improving the chance of those reefs surviving through the 2050s. Urgent and deep reductions of CO_2 emissions to the atmosphere is therefore essential for the continued health and survival of the majority of coral reefs by reducing impacts from ocean warming and acidification. Reducing local stressors will however buy time and ensure that more will survive for longer.

Coral reefs are sensitive, yet resilient ecosystems. They are a virtual 'canary in the coal mine,' serving as an indicator of the pressures we are placing on global ecosystems. They provide a key example of the effect of increasing greenhouse gas concentrations in the atmosphere (and the ocean) and provide additional incentives for far-reaching action to reduce our emissions.

Coral reefs are resilient and can often recover if threats are reduced. A growing body of evidence has shown that by reducing local threats (including overfishing and nutrient and sediment pollution), reefs may recover more quickly from coral bleaching (West and Salm, 2003). Resilience can be enhanced in critical areas – such as coral reefs that contain important sources of larvae – by reducing local threats. In addition, active management to reduce local threats in areas which have recently bleached can aid in coral recovery (Marshall and Schuttenberg, 2006).

5.4.3 Notes on Methods

Local threat to coral reefs

The most recent detailed global assessment of local threat to coral reefs comes from *Reefs at Risk Revisited* (WRI, 2011). Under the *Reefs at Risk Revisited* analysis, a WRI-led partnership developed global-extent estimates of threat to coral reefs from **four distinct categories of local threat:**

- overfishing (including destructive fishing);
- coastal development;
- watershed-based sediment and pollution; and
- marine based threats (physical damage and pollution).

The **Integrated local threat index** combines these four local threat indicators into one global index of local human pressure on coral reefs that reflects their cumulative impact on reef ecosystems. The integrated local threat index was developed by summing the four individual local threats, where reefs were categorized into *low* (0), *medium* (1), or *high* (2) in each case (See http://www.wri.org/sites/default/files/technical_notes.pdf for details of development of each individual threat indicator. WRI, 2011.) The summed threats were then categorized into the index as follows:

- ***Low:*** 0 points (scored *low* for all local threats);
- ***Medium:*** 1–2 points (scored *medium* on one or two local threats or *high* on a single threat);
- ***High:*** 3–4 points (scored *medium* on at least three threats, or *medium* on one threat and *high* on another threat, or *high* on two threats); and
- ***Very high:*** 5 points or higher (scored *medium* or higher on at least three threats, and scored *high* on at least one).

The resulting integrated local threat index is the base for the cumulative threat assessment conducted for the Open Ocean Assessment.[29] (*Maps of individual threats are available online at* www.wri.org/reefs.*)* This global, spatial,

29 The global indicators developed by the Reefs at Risk Revisited project enable comparative analyses of threats to coral reefs on many scales, and support conservation priority-setting. The Reefs at Risk indicators are a simplification of human activities and complex natural processes, but provide globally-consistent indicators of relative human pressure on coral reefs. Reef grid cells have been classified by present integrated local threats to coral reefs (combined threat from coastal development, marine-based pollution and damage, watershed-based pollution, and overfishing/destructive fishing). Values of 0 indicate low threat, 1 indicates medium threat, 2 indicates high threat, and 3 indicates very high threat. Citation: World Resources Institute. Reefs at Risk Revisited. 2011. (see http://www.wri.org/publication/reefs-risk-revisited for the full report and downloadable data.)

local threat index was overlaid with a map of the world's coral reefs[30] to develop an estimate threat at each coral reef location (at 0.0056356564 decimal degree resolution). Areas are referred to as threatened if they are rated as *medium* threat or higher. In these areas, one would expect to see coral degradation such as reduced live coral cover, reduced rugosity and diversity, increased algal cover, and reduced fish abundance.

Warming Seas - Thermal Stress to Coral Reefs

Thermal stress was evaluated for the decades beginning 2010, 2030 and 2050 based on data from an ensemble of GCM models integrated at the UNESCO-IOC (for the RCP 8.5 'Business As Usual' scenario, where the rate of emissions does not decrease in the future, and for the RCP 4.5 scenario, where emissions are stabilized to limit average global warming to two degrees above preindustrial levels. Data are at 0.017453 decimal degree resolution. Data from the ensemble of models were averaged on a monthly time-step, which might serve to dampen variability in results. The indicator of future thermal stress is accumulated degree heating months (DHM), as represented by the frequency (per cent of years) that the DHM exceeds the bleaching threshold in each decade. The bleaching threshold used is a NOAA Bleaching Alert Level 2 (for example: a DHM ≥ 2, which is the same as a degree heat weeks (DHW) ≥ 8), which represents conditions that can cause severe coral bleaching and/or mortality (Donner et al. 2008). These thresholds were adjusted on a cell-by-cell basis against baseline climatology. SST projections are corrected, then compared to an actual climatology for each date (see Chapter 4.2 of details on computing the frequency of DHM >2.)

The final data layers representing the frequency of severe thermal stress for decades 2010, 2030 and 2050 were reclassified into three threat categories. '*Low*' threat areas are projected to experience Bleaching Alert Level 2 conditions 0, 1 or 2 times during the decade; '*medium*' threat areas projected to experience Bleaching Alert Level 2 conditions 3, 4 or 5 times during the decade; and '*high*' threat areas, projected to experience Bleaching Alert Level 2 conditions most years in the decade (6-10 times).

Acidifying Seas – Ocean Acidification threat to Coral Reefs

The indicator of ocean acidification used in this analysis is aragonite saturation state. As dissolved CO_2 in the ocean increases, pH decreases and the aragonite saturation level decreases. The aragonite saturation state data used in this analysis were provided by of NOAA (see Chapter 4.4 of this report for details, van Hooidonk 2015). The data are estimates of average near-surface aragonite saturation state for the periods 2010-2019, 2030-2039 and 2050-2059, under the RCP 8.5 and RCP 4.5 scenarios.

The variables Sea Surface Temperature (SST), surface salinity and others were obtained from fully coupled models in the Coupled Model Intercomparison Project 5 (CMIP5; http://pcmdi9.llnl.gov/ esgf-web-fe/). All model outputs were regridded to the same one degree resolution grid using bilinear interpolation (roughly 90 km resolution). If multiple runs were available for a model, these runs were averaged first. Then a multi model ensemble was created. Monthly values were averaged to get yearly or decadal averages. Aragonite saturation state was calculated from SST, surface pressure of CO_2, pH, and salinity (Hooidonk, R. J. et al. 2014).

30 Coral reef data - A global map of shallow, tropical coral reefs, gridded at 500-m resolution was developed for use in the *Reefs at Risk Revisited* project. The map was developed by a collaboration of the Institute for Marine Remote Sensing, University of South Florida (IMaRS/USF), Institut de Recherche pour le Développement (IRD), UNEP-WCMC, The World Fish Center, and WRI (2011)
The composite data set was compiled from multiple sources, incorporating products from the Millennium Coral Reef Mapping Project prepared by IMaRS/USF and IRD. This Gridded 500m data were reprojected to WGS84 ('Geographic'), with 0.0056356564 decimal degree resolution.

Thresholds for aragonite saturation that indicate suitability for coral growth were taken from Reefs at Risk Revisited, based on Guinotte et al. (2003), with minor adjustments. Areas with an aragonite saturation state of 3.25 or greater were classified as under *low* threat (which is slightly more conservative than a threshold of 3.5, considered "adequate" saturation in Guinotte, et al.); areas between 3.0 and 3.25 were classified as *medium* threat (considered "*low* saturation" in Guinotte, et al.), and areas of less than 3.0 were classified as *high* threat (considered "extremely marginal" in Guinotte et al. 2003)

Integrating local and global threats to coral reefs

The integrated local threat index was combined with modeled projections of ocean acidification and thermal stress for three time periods; the decades beginning: 2010, 2030 and 2050 to estimate the influence of these combined pressures on coral reefs. The weighting for integration used in *Reefs at Risk Revisited* was used, which weights local threats more heavily, in light of the greater uncertainty associated with future threats, and the finer resolution of local threat estimates. Reefs are assigned to their threat category from the integrated local threat index as a starting point. Threat is raised one level if reefs are at *medium* or *high* threat from either thermal stress or ocean acidification, or if they are at *medium* threat for both. If reefs are at *high* threat for thermal stress or acidification, and at least *medium* threat for the other threat, the threat classification is increased by two levels. In order to portray some nuance in the degree of threat, the rating scale has been extended to include two additional threat categories above *very high* called '*critical*' and '*extreme*'. The analysis assumes no change in current local threat levels, either due to increased human pressure on reefs or changes in reef-related policies and management.

Hence:

- 0 points – both warming and acidification are at *low* threat - no adjustment;
- 1 – 2 points – 1 or 2 *mediums* or 1 *high*– increase 'integrated threat' by one level; and
- 3 - 4 points – 1 *high* and a *medium* or two *highs* – increase 'integrated threat' by two levels;

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Chapter 5.5 Pteropods at Risk

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5.5 Pteropods at Risk

5.5.1 Summary and Key Messages

Pteropods, also called sea butterflies, are tiny snails living in the water column that play a critical role in various ecosystems as prey for a variety of predators. There is a great concern about the potential impact of global change – and particularly ocean acidification – on these organisms as they exhibit an external shell, which is sensitive to changes in ocean chemistry. To represent the impact of both ocean acidification and global warming on pteropods, risk indicators have been calculated for three widely spread taxa that are dominant in high latitudes (Limacina helicina), temperate (Limacina retroversa), and warm waters (Creseis spp.). To create the indicators, experimental and observational data on pteropods' response to global change were coupled with models describing chemical (aragonite saturation state) and physical (temperature) conditions of the ocean at present, in 2030 and 2050, under the "business as usual" carbon dioxide (CO_2) emission scenario (RCP 8.5) and the "two degree stabilization" CO_2 emission scenario (RCP 4.5). The present results confirm that global change is a very serious threat for high latitude pteropods: by 2050 under the CO_2 emissions scenario RCP 8.5, they *likely* will not be able to thrive in most of the Arctic Ocean and some regions of the Southern Ocean. Aside from polar species, the temperate species (Limacina retroversa) are also *very likely* to be affected by global change, with only 20 per cent of their current area of distribution remaining classified as *low* risk by 2050. Warm water species *likely* will not be as strongly affected by ocean acidification by 2050, but excessive temperatures will represent a threat, particularly in the equatorial Pacific. These results highlight that only a strong reduction in anthropogenic CO_2 emissions will limit the effects of both ocean acidification and global warming on these organisms. The impact of disappearing pteropods is hard to quantify at present, but it is *likely* that several key ecosystems will be affected with potential economic impacts.

Key messages

- Pteropods play critical roles in ocean ecosystems, and are threatened by twin pressures: ocean acidification and ocean warming; and
- High latitude pteropods are of particular concern, as ocean acidification and global warming are pushing in opposite directions to reduce the area of optimal environmental conditions.

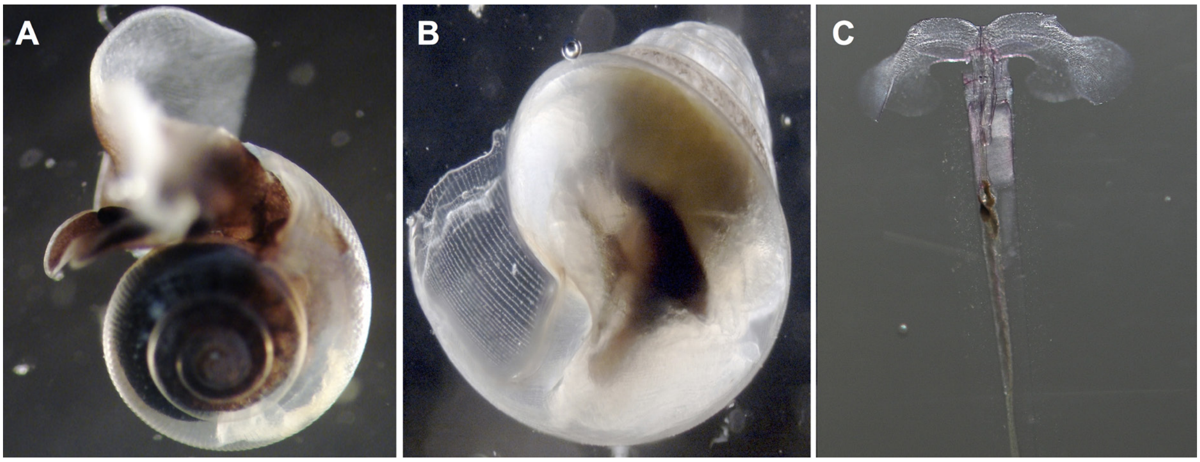
5.5.2 Main Findings, Discussion and Conclusions

Introduction

Shelled pteropods (order Thecosomata) are zooplanktonic molluscs that spend their entire life in the water column and are widely distributed across the ocean. Pteropods can be found in very large abundances (for example: Pane et al. 2004), particularly in high latitude areas where they can represent as much as 93 per cent of the total zooplankton biomass (Hunt et al. 2008). Due to their high abundance and nutritional value, pteropods are keystone species in various pelagic ecosystems and a food source for many predators such as herring, salmon, whales and seabirds (Karnovsky et al. 2008; Hunt et al. 2008; Armstrong et al. 2005; Weslawski et al. 2000). For example, Armstrong et al. (2005) have shown that, in the years of high abundance, the pteropod Limacina helicina can represent as much as 60 per cent of the prey of juvenile pink salmon in the Gulf of Alaska.

Concern about the future of pteropods in an acidified ocean has risen in the scientific community, because their shells are made of aragonite, a metastable form of calcium carbonate that is 50 per cent more soluble than calcite in seawater (Mucci 1983). Pteropod shells, which are external and grow throughout their entire life, play a critical ecological and biogeochemical role. From an ecological point of view, pteropod shells are a protection against small predators and play a role in buoyancy control and vertical diel migrations (Lalli and Gilmer 1989). They also help maintain the structural integrity of organisms by playing the role of external skeleton (Comeau et al. 2010a). Biogeochemically, shells are also important since they are a key component of the calcium carbonate cycle (Berner and Honjo 1981), and they facilitate the storage of organic carbon (Collier et al. 2000) to the deep ocean by the so-

Figure 5.17. Photographs of the three pteropod species for which indicators of global change were developed. The selected species were: A) Limacina helicina, the dominant species in high latitudes, B) Limacina retroversa, the dominant species in sub-polar and temperate waters, and C) Creseis spp. a widely distributed taxon in temperate and tropical waters.



called ballast effect. Because of their sensitivity to ocean chemistry, shells can also be used as important indicators of the intensity and duration of ocean acidification conditions faced by pteropods during their life (Bednaršek 2014a).

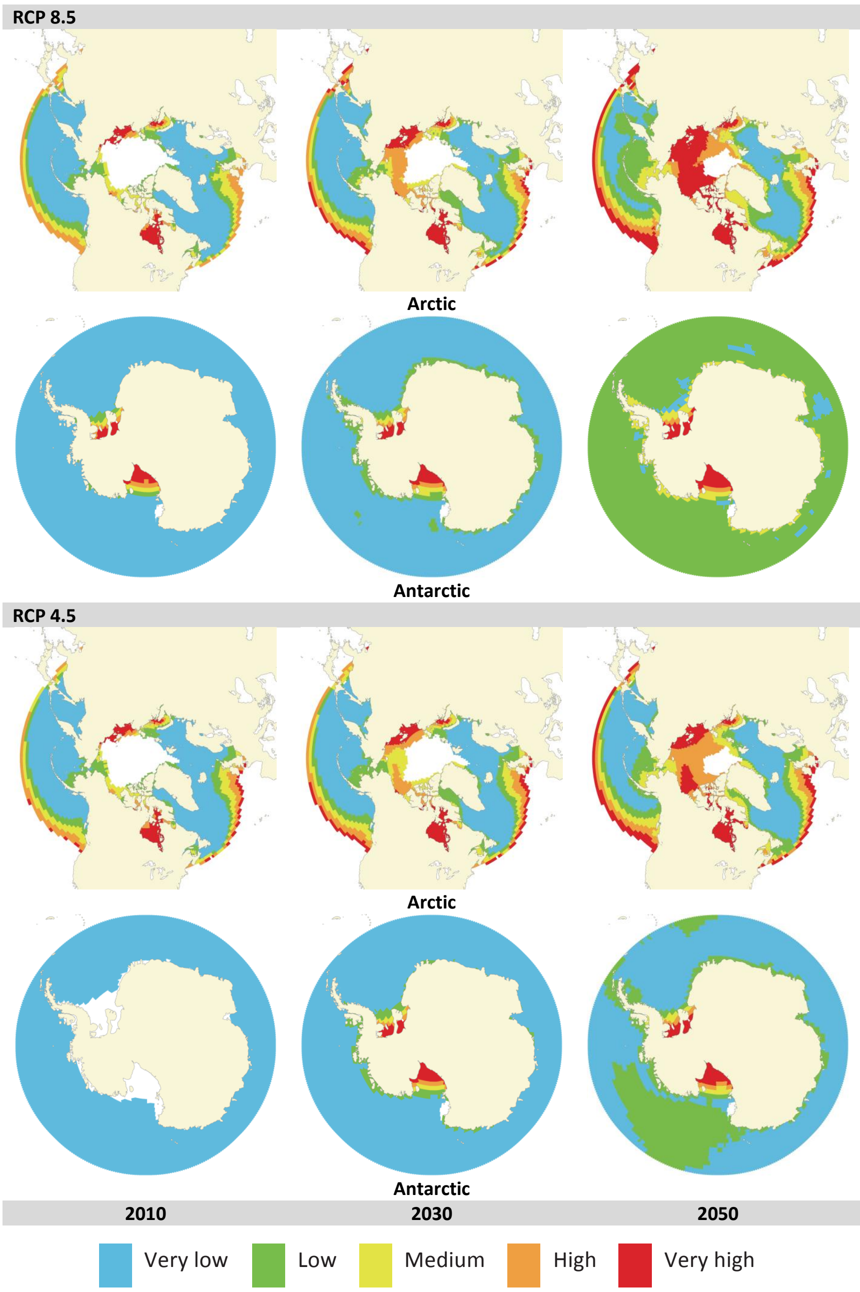
Studies on the effects of ocean acidification on pteropods are relatively recent with the first observations of the effects of low pH done in 2005 on the pteropod Clio pyramidata (Orr et al. 2005). Over the past five years, several studies on the effect of ocean acidification have been performed on pteropods, with a particular focus on the polar species Limacina helicina. Studies on this species have shown that ocean acidification leads to a decrease in shell production (Lischka et al. 2011; Comeau et al. 2010b; Comeau et al. 2009), an increase in shell degradation (Busch et al. 2014; Lishka and Riebesell 2012; Comeau et al. 2012a) and an increase in mortality that is enhanced at elevated temperatures (Lishka and Riebesell 2012; Lischka et al. 2011). The effects of ocean acidification have also been investigated on the subpolar species Limacina retroversa for which decreasing pH has been shown to cause an increase in shell degradation (Lishka and Riebesell 2012; Manno et al. 2012) and a decrease in swimming activity when combined with freshening (Manno et al. 2012). Temperate and tropical species have received less attention, with only few experiments performed on the physiological response to ocean acidification (Mass et al. 2012). Very low pH has also been shown to inhibit the formation of shell in juvenile of Cavolinia inflexa (Comeau et al. 2010a). Beyond experimental evidence, the sensitivity of pteropods to ocean acidification has also been confirmed by in situ observations of dissolution marks on pteropods exposed to naturally low pH conditions (Bednaršek et al. 2014b; Bednaršek et al. 2012a and b; Roger et al. 2012).

Decreasing pteropod abundances could lead to profound modifications of food web and biogeochemical cycles that could have important repercussions. Of particular concern is the impact for fisheries of a decline in pteropod populations caused by ocean acidification and global warming because they play key role as a prey in various ecosystems. To assess the risk represented by ocean acidification and global warming on this key organism, a set of global scale risk indicators, based on present knowledge of pteropods, were developed. These indicators were developed to provide information on the potential exposure of pteropods to future environmental conditions impairing their capacity to produce their crucial external shell in a more acidic ocean and to survive in a warmer ocean. Experimental data available, current knowledge on pteropods species distribution and optimal temperature, and biogeochemical model projections (see Chapters 4.2 and 4.4), were used to develop the indicators. The indicators were developed for three taxa that, combined, have a distribution covering the whole ocean: a polar species (Limacina helicina), a subpolar species (Limacina retroversa), and a temperate taxon (Creseis spp.).

Findings

The distribution of the three pteropod taxa covered the whole ocean, with L. helicina principally located at latitude below 60° South and above 40° North, L. retroversa found at latitude of 45°-65° South and 40°-65° North, and Creseis spp. distributed between 40° South and 45° North. Based on data from the Ocean Biogeographic Information System (OBIS) database, L. helicina was found 95 per cent of the time in temperatures that were below 10°C, L. retroversa was found in waters below 16°C, and Creseis spp. was found in waters below 28°C.Indicators for L. helicina

Figure 5.18. Maps showing the risk indicators for the combined effects of ocean acidification (decreasing aragonite saturation state) and global warming on the pteropod Limacina helicina. Indicators were created for the area of distribution of L. helicina using model projections for aragonite saturation state and temperature of the oceans at present, in 2030 and 2050, under the "business as usual" carbon dioxide emission scenario (RCP 8.5) and the "two degree stabilization" carbon dioxide emission scenario (RCP 4.5).



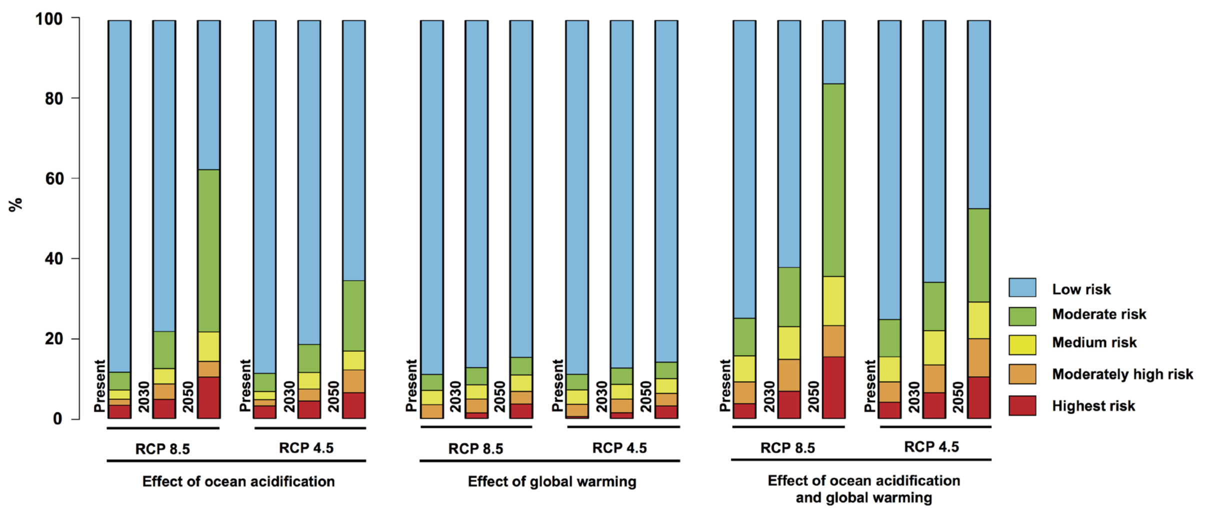
For the polar pteropod L. helicina, the effect of ocean acidification and temperature will be decoupled in space. Decreasing aragonite saturation state (Ωarag) *likely* will have a strong impact on the population living in the coldest temperature, whereas global warming will limit the distribution of L. helicina towards temperate waters.

At present L. helicina is already at risk in some areas of the ocean such as the North of Russia or Hudson Bay where distribution of L. helicina towards temperate waters found at latitudes in the North East Pacific and Atlantic Oceans also limit the temperate distribution of L. helicina.

Model projections for indicators for aragonite saturation state show that, under the RCP 8.5 scenario, most of the Arctic Ocean will be considered as high or very high risk by 2030 and by 2050 (Figure 5.18b and 5.18c), because of increasing difficulties in producing shells. In the Southern Ocean, by 2050 and in RCP 8.5, most of the water will be considered as medium risk with some areas at the highest latitudes, classified as very high and critical risks (Figure 5.18c). In RCP 4.5, the deleterious effects of decreasing aragonite saturation state will be less pronounced in the Arctic region, very high and critical risks will be less extended in 2030 and 2050 (Figure 5.18e and 5.18f). Under the influence of ocean acidification, low risk areas for calcification are expected to drop from ~87 per cent at present to 76 per cent in 2030, and 30 per cent in 2050 in RCP 8.5, and 79 per cent by 2030 and 61 per cent by 2050 in RCP 4.5 (Figure 5.19).

The impact of global warming will be less pronounced at latitudes at which L. helicina is found. At present 89 per cent of these latitudes are classified as *low* risk, a percentage that will drop by 4 per cent by 2050 under both CO_2 emission scenarios (Figure 5.19).

Figure 5.19. Stacked plot showing the percentage of the area of distribution of the Arctic pteropod Limacina helicina exposed to the different risk indicators. Risk indicators were created for the effect of ocean acidification alone (decreasing u_{arag}), the effect of global warming alone (temperature) and the effects of global change (combination of ocean acidification and global warming).

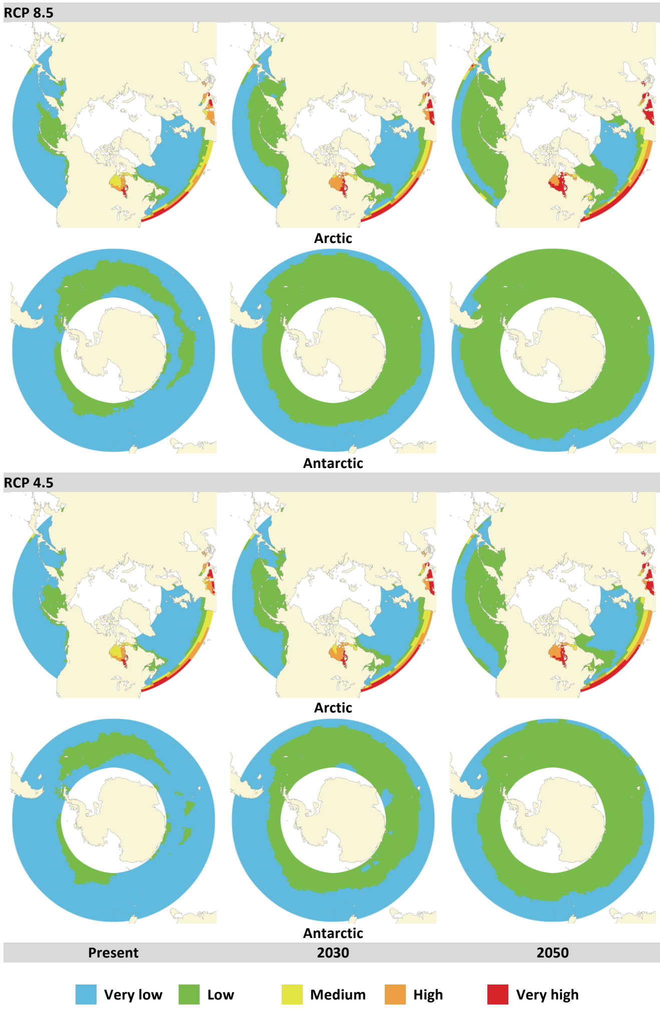


When temperature and the aragonite saturation state are combined, 75 percent of the latitudes where L. helicina is found are low risk at present. When temperature and hat will drop by 4 per cent by 2050 under both emission scenarios (Figure 5.low risk at present. In RCP 8.5, the low risk areas represent 62 per cent of the ocean by 2030, and only 16 per cent by 2050, while the medium, high, very high, and critical risk regions increase in size. This reduction is more limited in RCP 4.5 s for which the low risk areas represent 66 per cent by 2030 and 47 per cent by 2050.

Indicators for L. retroversa

For the sub-polar and temperate pteropod L. retroversa, ocean acidification and warming will probably impact the population in both hemispheres (Figure 5.20). At present, at latitudes where L. retroversa is found, 76 percent of the

Figure 5.20. Maps showing the risk indicators for the combined effects of ocean acidification (decreasing aragonite saturation state) and global warming on the pteropod Limacina retroversa. Indicators were created for the area of distribution of L. retroversa using model projections for aragonite saturation state and temperature of the oceans at present, in 2030 and 2050, under the "business as usual" carbon dioxide emission scenario (RCP 8.5) and the "two degree stabilization" carbon dioxide emission scenario (RCP 4.5).

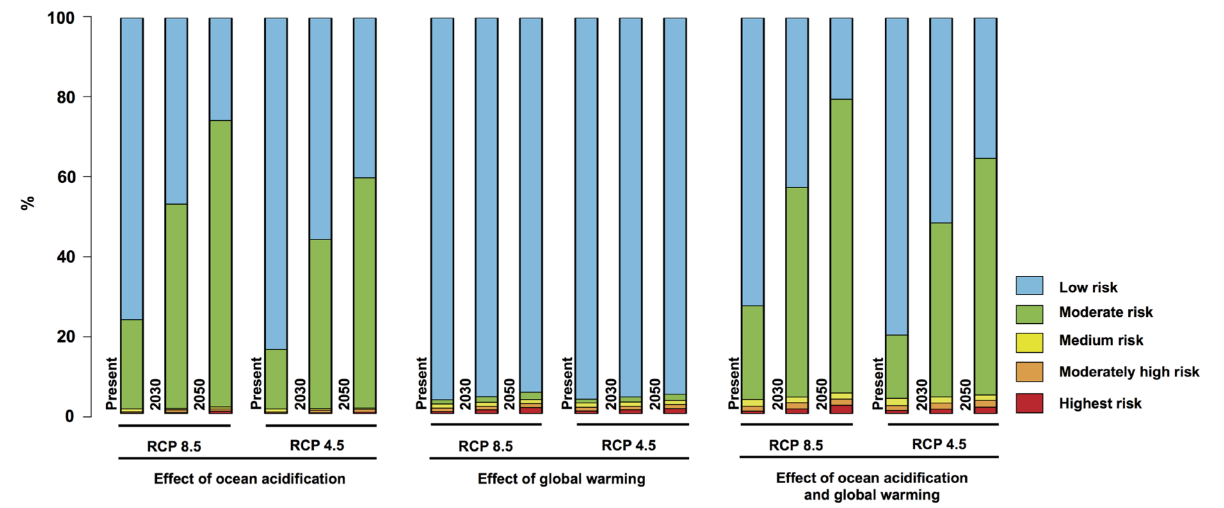


ocean has aragonite saturation state that represent a low risk for pteropod shell degradation (Figure 5.21). Due to decreasing aragonite saturation state, low risk areas are expected to fall to 47 per cent by 2030 and 26 per cent by 2050 in RCP 8.5, with most of the Southern Ocean and North Pacific Ocean having medium risks for L. retroversa. In RCP 4.5, the effects of decreasing aragonite saturation state by 2050 will be less pronounced with low risk areas down to 56 per cent by 2030 and 40 per cent by 2050.

Temperature at present limits the distribution of L. retroversa in its equatorial latitudes particularly in the North Hemisphere, where this species is found at lower latitudes (Figure 5.20a). The direct effect of global warming on L. retroversa will likely be limited as areas where temperature represents low risk will decrease by 1-2 per cent in 2050 under RCP 8.5 and RCP 4.5 (Figure 5.21).

When the impact of decreasing Ωarag and global warming are combined, the low risk area for L. retroversa is reduced by 2030 to 43 and 52 per cent (RCP 8.5 and 4.5, respectively). By 2050, the low risk area likely will be reduced to 20 and 35 per cent (RCP 8.5 and 4.5, respectively; Figure 5.21) and most of the areas will fall into the medium risk category.
Indicators for Creseis spp.

Figure 5.21. Stacked plot showing the percentage of the area of distribution of the sub-polar and temperate pteropod Limacina retroversa exposed to the different risk indicators. Risk indicators were created for the effect of ocean acidification alone (decreasing u_{arag}), the effect of global warming alone (temperature) and the effects of global change (combination of ocean acidification and global warming).



For Creseis spp., populations living in equatorial waters likely will be the most affected by global change (Figure 5.22), which is due to warming Under the influence of decreasing Ωarag alone, ~98 per cent of the area of distribution of Creseis spp. will still be classified as low risk, calcification will not be expected to decrease by more than 20 per cent by 2050 in this area (Figure 5.23, which will probably have limited biological impacts.

Temperature is *likely* to affect Creseis spp. as some regions of the ocean at latitudes where this species is found are

Figure 5.22. Maps showing the risk indicators for the combined effects of ocean acidification (decreasing aragonite saturation state) and global warming on the pteropod taxon Creseis spp.. Indicators were created for the area of distribution of Creseis spp. using model projections for aragonite saturation state and temperature of the oceans at present, in 2030 and 2050, under the “business as usual” carbon dioxide emission scenario (RCP 8.5) and the “two degree stabilization” carbon dioxide emission scenario (RCP 4.5).

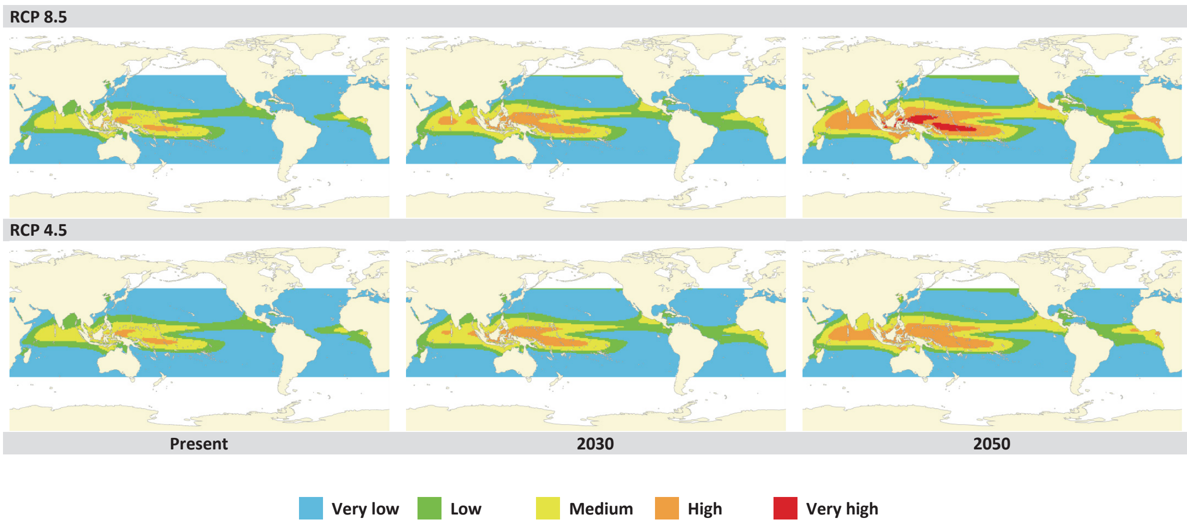
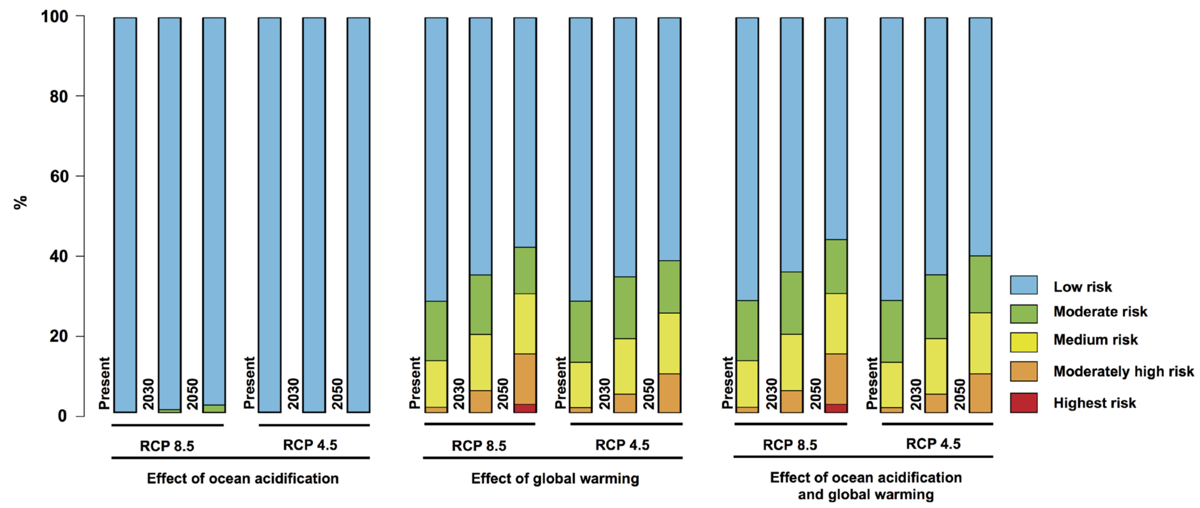


Figure 5.23. Stacked plot showing the percentage of the area of distribution of the warm water pteropod taxon Creseis spp. exposed to the different risk indicators. Risk indicators were created for the effect of ocean acidification alone (decreasing u_{arag}), the effect of global warming alone (temperature) and the effects of global change (combination of ocean acidification and global warming).



already above the maximal optimal temperature (Figures 5.22a and 5.22d). Global warming will reduce the *low* risk area from 72 per cent at present to 65 per cent and then 58 per cent under RCP 8.5 in 2030 and 2050, respectively (Figure 5.23). The decrease will be less important with model RCP 4.5 for which *low* risk area will be down to 66 per cent and 62 per cent in 2030 and 2050, respectively.

The combined effects of ocean acidification and warming are mostly driven by increasing temperature and will result in a *low* risk area of 56 per cent and 60 per cent by 2050 (RCP 8.5 and RCP 4.5; Figures 5.22 and 5.23) followed by a gradual increase in *high* and *very high* risk areas.

Discussion and conclusions

The development of these indicators confirms the threat both global warming and ocean acidification for pteropods. The indicators show that the two scenarios of global change will affect pteropods differently as a function of their distribution and their species. The high latitudes species (L. helicina) will be more affected by ocean acidification, while the low latitudes taxon (Creseis spp.) will mostly be impacted by warming, at least in the next few decades. Because of its intermediate distribution, L. retroversa *likely* will be less exposed to the effects of ocean acidification and global warming in the near future. However, further studies are necessary on this very abundant and widely distributed species, notably to quantify the response of its calcification as a function of Ωarag. The future of Creseis spp. appears to be highly threatened by global warming, with most of the tropical region becoming too warm for this species. However, it is important to note that the effects of temperature on this organism have never been laboratory tested and that the temperature effects were estimated as a deviation from the maximum temperature at which this species is now found.

While pteropods could adapt to warmer temperatures, physiological repercussions such as increasing physiological activity *likely* could lead to negative feedback such as a reduction in organism size (Yvon-Durocher et al. 2011). Behaviour might also be affected, with potential seasonal migration to colder water or changes in vertical distribution to avoid warm waters. In any case, physiological or behavioural alterations *likely* would modify the role of pteropods in marine ecosystems, which could have cascading effects on marine food webs if pteropods are not replaced by organisms with similar function. Aside from their role in the food chain decreasing, pteropod populations or modification in their migration could have large impacts on the carbon and carbonate cycles. This is because pteropods are significant contributors of carbon export to the deep ocean (Noji et al. 1997, Manno et al. 2010) and can represent up to 12 per cent of the global carbonate fluxes (Berner and Honjo 1981).

As previously suggested (Orr et al. 2005), the high latitude pteropod L. helicina is the species that is the most exposed to global change. In the highest latitudes, decreasing Ωarag will limit the possibility for L. helicina to build its protective shell, which will be in addition accompanied by very fast dissolution process (Bednaršek et al. 2014b). Furthermore, populations will not be able to migrate to lower latitudes to avoid the corrosive waters as low latitude water will warm to levels at which this species is currently not found or physiologically acclimated (Lalli and Gilmer 1989). Nevertheless, the impact of global change will not be uniform across the Arctic Ocean and the Southern Ocean due to localized differences. This is explained by different physical and chemical properties, such as higher total alkalinity and temperature in some regions that directly impact Ωarag and thus, pteropod calcification. Generally though, the Arctic Ocean appears to be particularly vulnerable to low Ωarag, which is confirmed by present observations of aragonite undersaturation in the North of Canada (Yamamoto-Kawai et al. 2009).

The impact of decreasing shell formation for pteropod survival and growth is still unknown. As an example, a study has reported that larvae of the Arctic pteropods L. helicina are viable after 29 days of laboratory incubation in waters that are undersaturated with respect to aragonite, although their shells exhibit extensive degradation (Lischka et al. 2012). Growth of shell-less pteropod larvae has also been reported in organisms exposed to low Ωarag, although the body shape was not maintained (Comeau et al. 2010b). In nature, it is doubtful that pteropods with weaker or no shell would survive because shells act as defenses against small predators and infections, and also offer their hosts a means to regulate their buoyancy and thus their diurnal migrations (Wormuth 1981). Another critical role for shells is to function as a skeleton and help maintain the structural integrity of soft body parts.

The potential impact of decreasing pteropod populations and particularly L. helicina, is still unknown. The loss of Arctic pteropods could have major biogeochemical, ecological and economic impacts. One region of particular concern is the Gulf of Alaska (Mathis et al. 2014), where L. helicina represents 45 per cent of the diet of pink salmon (Aydin et al. 2005) and up to 60 per cent of the diet of juveniles (Armstrong et al. 2005). The potential impacts of their disappearance on fish populations and other predators will depend on the capacity of these predators to switch to another food source of equivalent energetic value (Gannefors et al. 2005).

Recommendations

The present indicators confirm that a reduction in CO_2 emissions will limit the impacts of global change for pteropods. For the three species, *high* risk areas in 2050 were much more extended under the business as usual scenario (RCP 8.5) than under the low CO_2 emissions scenario (RCP 4.5). This study also highlights the necessity to collect more data on the response of pteropods to both ocean acidification and warming as empirical studies with long-term studies are particularly limited in numbers. While, there is little doubt that pteropod populations will be highly affected by global change, particularly in the high latitudes, it is critical to work on developing tools and models to anticipate the potential repercussions of decreasing pteropod abundances at the ecosystem (for example: impact for fisheries) and biogeochemical (for example: impact for the carbonate cycle) levels. Only such studies will lead to estimating the potential economic repercussions of vanishing pteropods.

5.5.3 Notes on Methods

Data acquisition

Distributions of the three targeted species were obtained from the OBIS database (see Chapter 5.7 for details) that contains over 7800 entry for L. helicina, 48 000 for L. retroversa and 300 for Creseis spp. Distribution of pteropods was also verified by comparing collected data to data available in the literature (Lalli and Gilmer 1989; Bednaršek et al. 2012b). Since highly accurate species-specific distribution is hard to establish and can vary with season, areas of distribution were *likely* overestimated and therefore were determined as the latitudes where 95 per cent of the individuals were reported in the aforementioned sources.

Model projections for the surface waters aragonite saturation state (Ωarag), which is an indicator of ocean acidification, and the temperatures infor the business as usual scenario RCP 8.5 (Moss et al. 2010) and the stabilization scenario optimistic RCP 4.5, were provided by Ruben vVan Hooidonk (2015) - see Chapter 4.4. While pteropods do migrate vertically, this parameter was not taken into account in this study due to the difficulty of obtaining models projections for water Ωarag aragonite saturation state and temperature at depth. However, the use of surface estimations has probably resulted in a slight underestimate of the effect of ocean acidification, as aragonite saturation state Ωarag is known to be lower at depth. Indicators were created for the decade 2010, 2030, and 2050 under the two emission scenarios for the effect of ocean acidification alone (decreasing aragonite saturation stateΩarag), the effects of global warming (temperature), and the effects of global change (combination of ocean acidification and warming). For each species, data for the model covering the range of distribution of a given species (latitudes where 95 per cent of the individuals were reported, see above) were selected to create species-specific indicators on the selected range of distribution. For L. helicina, low-latitudes regions in the North East Pacific and Atlantic were excluded because this species is not found all year round in these regions because of high temperature.

Data on the response of pteropods to ocean acidification are limited due to the difficulty associated with maintaining pteropods in culture (Howes et al. 2013). For the polar species L. helicina, data on the response of gross calcification (production of new shell, GCaCO3) to aragonite saturation state Ωarag were collected from Comeau et al. (2010b) and was GCaCO3 = 0.57 logn (aragonite saturation stateΩarag) + 0.25. The use of this relationship was strengthened by observations of similar increase in shell degradation with decreasing aragonite saturation state Ωarag (Lischka et al. 2012, Berdnarsek et al. 2012). As an example, aragonite saturation state Ωarag ~ 1.2 corresponded to a decrease in gross calcification of ~30 per cent compared to the reference and an increase in shell dissolution of ~ 20 per cent (based on Lischka et al. 2012). Known genetic differences between the Arctic pteropod L. helicina helicina, and the Antarctic pteropod Limacina helicina antarctica (Hunt et al. 2010), were not considered for this analysis as there are no data indicating a different response to ocean acidification for the two homonym species. No data on the quantification of gross calcification or dissolution (Bednaršek et al. 2014b) as a function of aragonite saturation state Ωarag were available for the sub-polar L. retroversa, but shell degradation as a function of aragonite saturation state Ωarag has been qualitatively estimated (Lishcka et al. 2012; Manno et al. 2012). These results were pooled and used in the current study to create an equation connecting aragonite saturation state Ωarag and shell dissolution. For Creseis spp., data on the quantitative response of gross calcification to aragonite saturation state Ωarag of Creseis virgula were used (Comeau et al. 2012b). Since there are no data available for other species of this taxon, the response of gross calcification to ocean acidification was assumed to be similar for all Creseis species. Data on the response of pteropods to warming are very limited and cover a limited range of temperatures and species (Lishcka and Riebesell 2012; Lishcka et al. 2011; Comeau et al. 2010). For this reason, the maximal optimal temperatures at which organisms are currently found were used to estimate the threshold at which warm temperatures will affect pteropods. Maximal optimal temperatures were determined as temperatures below which 95 per cent of the organisms from a given species are found currently at global scale (OBIS database) (Crimmins et al. 2011). Uncertainties about the risk indicators come from two sources: uncertainties in the projections of future aragonite saturation state and temperature (see details in Chapter 4.4), and uncertainties in the response of pteropods to aragonite saturation state and temperature.

While uncertainties in aragonite saturation state and temperature projections were beyond the scope of this study, it is reasonable to assume that the presentation of two scenarios (RCP 4.5 and RCP 8.5) covers the future range of climate change and associated impacts. Regarding uncertainties in the response of pteropods to aragonite saturation state and temperature, the current state of knowledge does not allow estimating the range of biological responses expected including a potential acclimation to these conditions. Models were therefore constructed using the current state of knowledge and designed to limit overestimation of the risk indicators by not considering, for example, net calcification, which is potentially more susceptible than gross calcification.

Indicator conception

To create the indicators, data on distribution, experimental data on shell production or degradation, maximal optimal temperature, and biogeochemical model projections were combined for each pteropod species. Indicators were created following Burke et al. (2011) (see also Chapter 5.4) and consisted of five risk levels (from 1 to 5): low, medium, high, very high, and critical. As aragonite saturation state is expected to affect mainly calcification, these indicators were designed to represent changes in water chemistry that would lead to a decrease in gross calcification (for L. helicina and Creseis spp.) or increase in dissolution (for L. retroversa). In contrast, empirical data on temperature effects are very scarce and indicators were designed to represent a potential avoidance of the area by pteropods, as a function of deviation from the maximum temperature where organisms are currently found. For the impact of ocean acidification alone, species-specific locations of sampling from the OBIS database were coupled with the current aragonite saturation state model to estimate the current mean aragonite saturation state at which each species is found. Deviations from the specific means were used to calculate the percentage decreases in shell production or increases in shell degradation (for L. retroversa). The five indicators, low, medium, high, very high, and critical, corresponded to regional changes in water chemistry potentially leading to changes in pteropod calcification (shell growth and shell degradation), for a given species of: less than 20 per cent, 20-40 per cent, 40-60 per cent, 60-80 per cent, and more than 80 per cent. Note that changes in pteropod's distribution as a function of aragonite saturation state have not so far been clearly established.

For temperature, since data on the effect of warming are highly limited, it was assumed that each increase by 1°C above the specific maximal optimal temperature yielded a one level increase in risk indicator. This assumption was based on three main reasons. First, previous observations showed that STT drives the distribution of zooplankton, including pteropods (for example: Rutherford et al. 1999, Beaugrand et al. 2013). Second, high temperature (within the range of the current indicators) was shown to increase mortality of the larvae L. helicina (Lischka et al. 2011). Third, while 95 per cent of the pteropods for a given species are currently found under their specific maximal optimal temperature, none are found at the maximal optimal temperature + 4°C, so the risk is critical. The risk indicators were therefore designed to cover five levels between maximal optimal temperature for a given species and optimal temperature + 4°C, where they are not found. Integrated indicators were developed to create a simple risk indicator taking into account the combined effects of decreasing aragonite saturation state and increasing temperature (derived from Burke et al. 2011). To calculate the integrated indicators, individual indicators for aragonite saturation state and temperature were assigned number from 1 to 5 (low, medium, high, very high, and critical), they were added together, and 1 was subtracted to avoid overestimation of the indicator. This subtraction was motivated by the fact that there is at present no strong evidence of fully-additive effects of temperature and ocean acidification on pteropods. With this method, an area classified as medium risk (2) for aragonite saturation state and medium risk (2) for temperature was classified as high risk (3) for the combination of ocean acidification and warming, while an area classified as low risk (1) for aragonite saturation state and medium risk (2) for temperature was classified as medium risk (2).

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Chapter 5.6 The Risk Of Ocean Acidification To Ocean Ecosystems

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5.6 The Risk of Ocean Acidification to Ocean Ecosystems

5.6.1 Summary and Key Messages

Ocean acidification is a process that refers to major changes to the ocean's carbonate chemistry, mainly caused by ocean uptake of anthropogenic emissions of carbon dioxide. This process involves a decrease in ocean pH (important for regulation of the internal acid balance and physiological health of many organisms) carbonate ions and calcim carbonate minerals such as aragonite and calcite (important for shell and skeleton builders) and an increase in bicarbonate ions (important for algal photosynthesis).

To understand what marine ecosystems may look like in the future if carbon emissions continue unabated, it is necessary to know the severity of the perturbation that different ecosystems will be exposed to and their ability to adapt within the time-scales of change. The severity and speed of ocean acidification, the exposure and vulnerability of the component organisms of an ecosystem to ocean acidification and their role in an ecosystem contribute to the risk of impacts to ecosystem structure and function. Although there are great uncertainties moving from impacts on individual organisms to impacts on complex marine ecosystems, these basic changes to marine chemistry pose a substantial risk to marine ecosystem structure and function through the impacts on the growth, physiology, behaviour, predator-prey interactions, competitiveness and population dynamics of individual species and how these may cascade through the rest of the ecosystem. Some organisms are able to adapt to ocean acidification, especially if food resources are high, by trading-off energy from one physiological function to another, although this may impact their long-term survival and ecosystem function.

Foodwebs where vulnerable organisms provide key trophic links, especially those exposed to undersaturated waters in polar, sub-polar and upwelling regions where severity will be greatest, will be at *high* risk of impact from ocean acidification. However, ecosystems formed by the aragonitic skeletons of deep-sea or tropical corals are also at *high* risk of impact from ocean acidification, either due to *high* severity, exposure or vulnerability or a combination of all three. Risk increases further when ocean acidification acts in concert with other global and/or local ocean stressors.

Predicting impacts of changing biodiversity or community dynamics on ecosystem structure and function also requires expanding the scope of current experimental research to examine multi-stress impacts in multi-level foodwebs and complex ecosystems.

Key Messages

- Basic changes to marine chemistry pose a substantial risk to marine ecosystem structure and function through the impacts on the growth, physiology, behaviour, predator-prey interactions, competitiveness and population dynamics of individual species and how these cascade through the rest of the ecosystem;
- Though some organisms may be able to adapt to ocean acidification by trading-off energy from one physiological function to another, this may impact their long-term survival and ecosystem function;
- *Risk* of impacts will depend on the *severity* (of which strength and speed are components) of ocean acidification, and the *exposure* and *vulnerability* of organisms to ocean acidification especially those playing key roles in ecosystems. The higher the *severity*, *exposure* and *vulnerability* the greater the *risk* of impact to numbers of organisms and therefore to foodwebs and ecosystems; and
- Foodwebs where *vulnerable* organisms provide key trophic links, especially those *exposed* to undersaturated waters in polar, sub-polar, deep sea and upwelling regions where *severity* will be greatest, will be at *high risk* of impact from ocean acidification. However, as ocean acidification progresses with increasing anthropogenic CO_2 emissions, ecosystems across the whole ocean will be at *risk*.

5.6.2 Main Findings, Discussion and Conclusions

The stressor – ocean acidification

The ocean absorbs 24 million tonnes of CO_2 every day, around 27 per cent of that emitted to the atmosphere mainly through burning of fossil fuels (Le Quéré et al 2013). When CO_2 enters the surface ocean it rapidly undergoes a series of chemical reactions, which produce hydrogen ions [H+] resulting in an increase in the acidity (lowered pH), a decrease in the concentration of calcium carbonate ions and an increase in the concentration of bicarbonate ions.

Three oceanic sites have monitored ocean carbonate chemistry over 20 years and show decreasing seawater pH and carbonate ion concentration concurrent with rising atmospheric CO_2 (IPCC 2013). Mean ocean pH has decreased by 0.1 since the start of the 'Industrial Revolution', a decline of around 30 per cent.

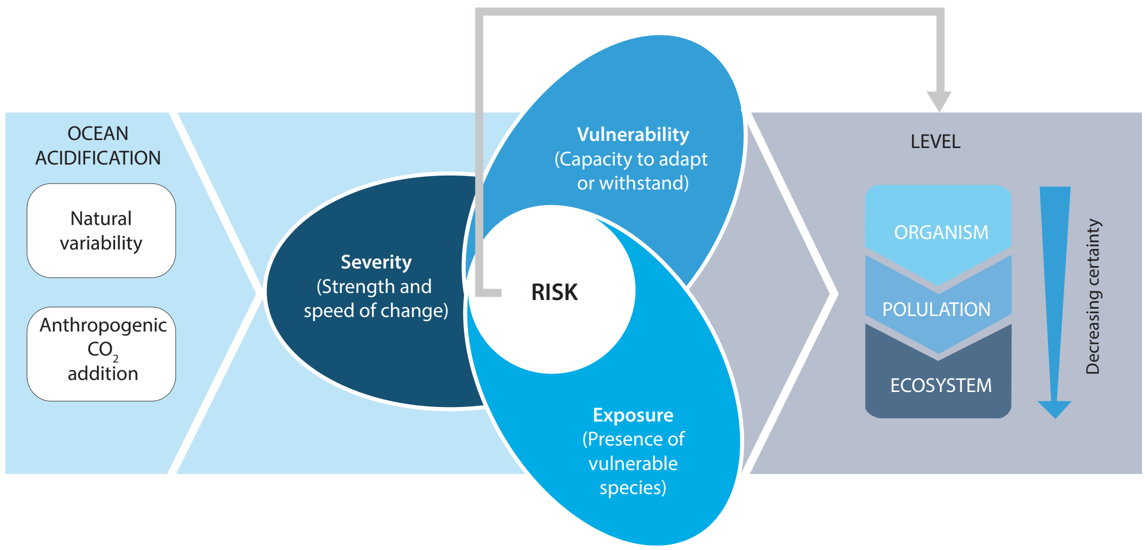
IPCC (2013) projects a global increase in ocean acidification for all "Representative Concentration Pathways" (RCP) scenarios, with decreases in mean surface ocean pH by the end of the 21st century in the range of 0.06 - 0.07 (RCP 2.6), 0.14 - 0.15 (RCP 4.5), 0.20 - 0.21 (RCP 6.0) and 0.30 - 0.32 (RCP 8.5). The RCP 8.5 outcome represents an increase in acidity of >150 per cent compared with pre-industrial values (IPCC 2013; Bopp et al. 2013, Joos et al. 2011; van Hooidonk 2015) (See Glossary Box 2).

Risk to ecosystems from ocean acidification

Such fundamental and rapid changes to basic ocean chemistry represent a great challenge for many marine organisms and complex marine foodwebs and ecosystems. Over the last decade there has been a dramatic increase in research on impacts of ocean acidification, initially involving simple short-term experiments on single processes in single species. However, experiments have become increasingly more complex; carried out over a long-term, looking at multiple processes, different life stages, multiple species or communities and the combined effect of other stressors.

There have been recent reviews, meta-analysis and assessments of the impacts of ocean acidification mostly on individual isolated species under laboratory conditions which are drawn upon here (Wicks and Roberts 2012; Williamson and Turley 2012; Kroeker et al. 2013; Whittmann and Portner 2013; Gattuso et al. 2014; IPCC 2014; CBD 2014). However, how impacts at the organism level are reflected in the real world, at the population and ecosystem level, is far from clear and more challenging to determine due to the complex nature of marine ecosystems. This Chapter will explore the ways in which ocean acidification might pose a risk to the structure and function of marine ecosystems.

Figure 5.24. The relationship between severity and speed, and the exposure and vulnerability of organisms in the risk of impact from ocean acidification to ecosystems. Adapted from the concept of risk developed for extreme climate hazards by IPCC (2012).

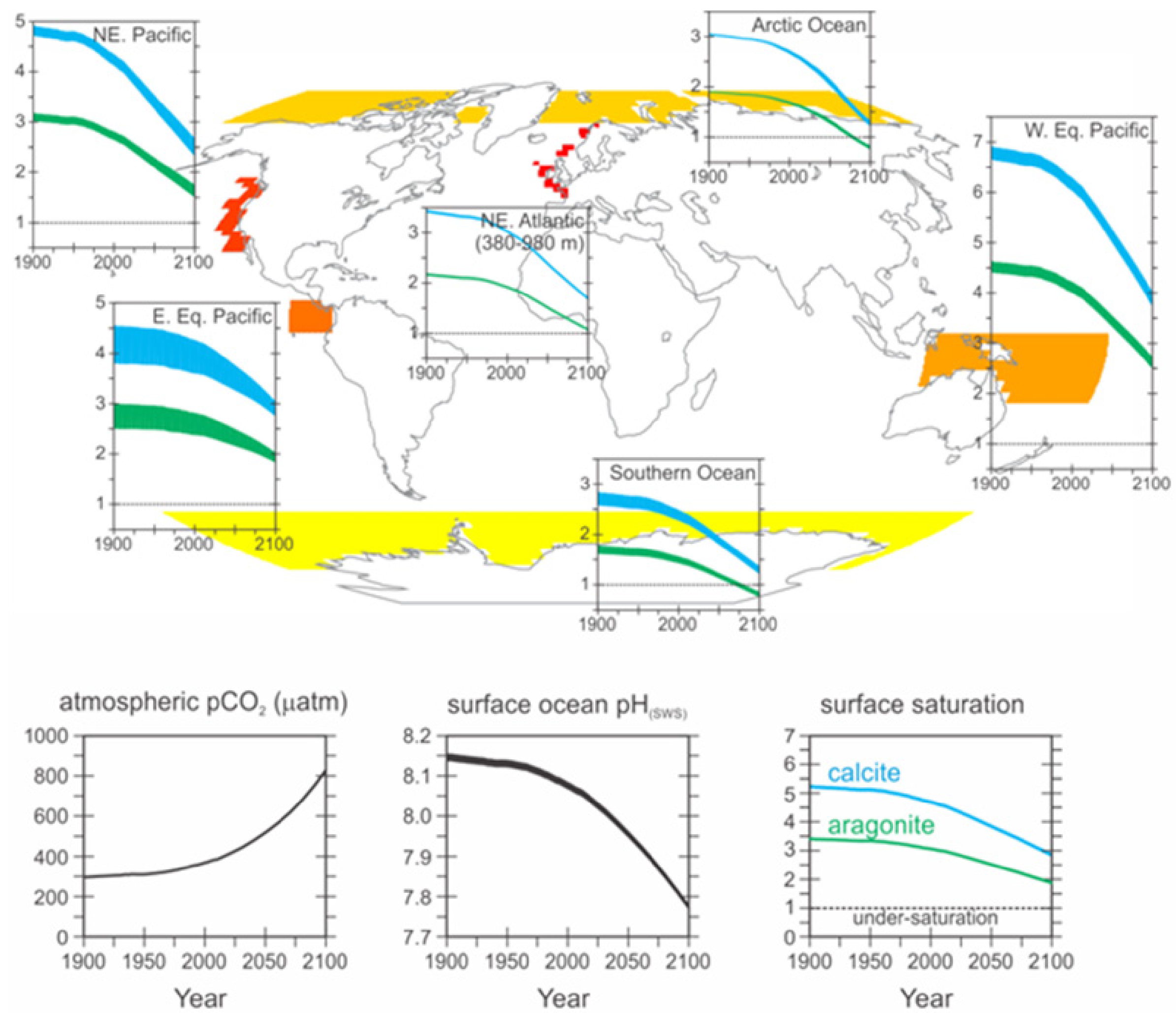


Here *risk* from ocean acidification is defined as the likelihood of severe alterations in the normal functioning of an ecosystem and will depend on the *severity* (of which strength and speed are components) of ocean acidification, and the *exposure* and *vulnerability* of organisms to ocean acidification especially those playing key roles in ecosystems (for example: ecosystem engineers, key trophic links) (Figure 5.24). The higher the *severity*, *exposure* and *vulnerability* the greater the *risk* of impact at organism to ecosystem levels. The arrow on the right shows the decreasing certainty of impacts on an organism through to complex ecosystems.

Severity and timescale

The strong coupling between atmospheric CO_2 and surface ocean acidification means that further and rapid emission of CO_2 to the atmosphere will inevitably increase the *severity* of ocean acidification (with >150 per cent increase in ocean acidification projected with RCP 8.5 by 2100 (IPCC 2013)). It is not just the magnitude of the carbon input that is important: the timescale over which this carbon perturbation occurs is also critical to the ocean's carbonate

Figure 5.25. Projected regional changes in ocean chemistry (top map and graphs), likely to be experienced by particularly vulnerable ecosystems and global-scale surface ocean changes (bottom three graphs) using SRES A2 scenario. For each of the six illustrative high risk marine ecosystems (Arctic Ocean, Southern Ocean, Northeast Pacific margin, intermediate depth Northeast Atlantic (500–1500 m), western equatorial Pacific, eastern equatorial Pacific) the blue shaded band indicates the annual range in ocean saturation state with respect to aragonite, while the green shaded band indicates the range for calcite saturation. Area average surface ocean conditions are calculated for all regions with the exception of the NE Atlantic where area average benthic conditions between 380 and 980 m have been used. The thickness of the line indicates the projected seasonal range, with the threshold of undersaturated environmental conditions marked as a horizontal dash line.



Source: Turley et al. (2010).

chemistry. The time-scale for the current perturbation is just a few hundred years and too short for the natural capacity of the ocean to buffer it. If this anthropogenic carbon input was spread over a timescale of thousands of years, the ocean's buffering system would decrease the *severity* of change to the ocean's carbonate chemistry (Zeebe and Ridgwell 2011). The current speed of ocean acidification is unprecedented within the last 65 million years (IPCC 2013; Ridgwell and Schmidt 2010), possibly the last 300 million years (IPCC 2013; Hönisch et al. 2012) and it will take tens of thousands of years for future ocean pH to return to near pre-industrial conditions (Archer 2005). Such *severity* and speed of change increases *risk* to marine foodwebs and ecosystems.

Although ocean acidification is happening across the whole global ocean, the *severity* of ocean acidification will be highest in cold waters because they absorb more CO_2 than warmer waters (Figure 5.25. Polar and sub-polar waters will therefore experience the lowest pH and carbonate ion concentrations (Figure 5.25, with aragonite reaching undersaturation in about 50 per cent of the Arctic Ocean around 2050, although large areas will achieve undersaturation within the next two decades (Steinacher et al. 2009, Turley et al. 2010). Undersaturation in the Southern Ocean and sub-polar waters will follow shortly after this (Orr et al. 2005). Upwelling waters already rich in CO_2 will also be affected early, with some already experiencing periods of undersaturation (Feely et al. 2008; Hauri et al. 2013). The deep-sea is not immune to anthropogenic ocean acidification with the aragonite saturation horizon moving towards the sea surface at a pronounced rate of 1-2 myr^{-1} (Feely et al. 2004; Orr et al. 2005). On the Icelandic Sea it is shoaling at a faster rate of about 4 myr^{-1} so that each year another 800 km^2 of seafloor becomes exposed to waters that have become undersaturated with respect to aragonite (Olafsson et al. 2009). Earth system models project for three out of four RCPs, that by 2100 over 17 per cent of the seafloor area below 500m depth in the North Atlantic sector will experience pH reductions exceeding −0.2 units by 2100 (Gehlan et al. 2014). Tropical waters will never experience undersaturation, however they will experience a rapid fall in saturation state (Figure 5.25).

Exposure

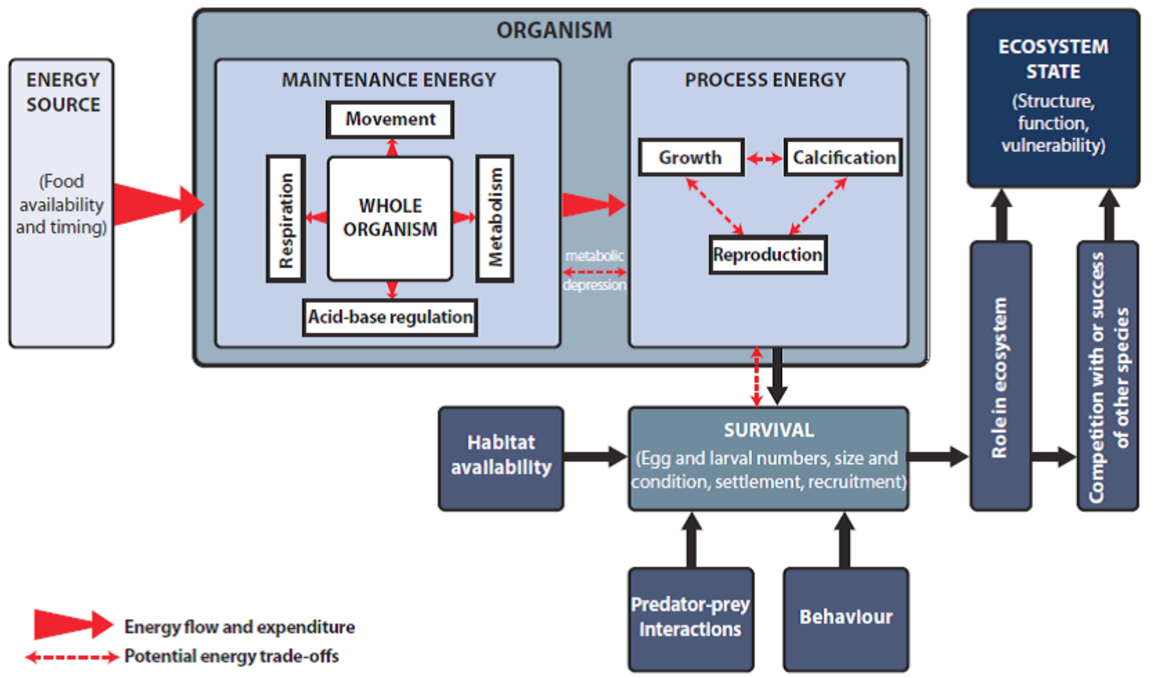
Exposure is the presence of organisms, communities or ecosystems to ocean acidification (Figure 5.24). As ocean acidification is a global phenomenon and all marine systems contain large biodiverse and often complex ecosystems, *exposure* will be omnipresent as CO_2 emissions increase through this century. Ecosystems present in areas of current low pH or calcium carbonate undersaturation, or those where low pH or undersaturation is projected to occur relatively rapidly such as polar, upwelling and deep-sea waters, will have increased *exposure* to ocean acidification and hence increased *risk*. The presence of ecosystems dependent on high concentrations of calcium carbonate to build reef like structures, such as those produced by calcifying cold water and tropical corals also increases risk.

Vulnerability

Vulnerability is the propensity or predisposition of a species, population or ecosystem to be adversely affected by ocean acidification (Figure 5.24. *Vulnerability* encompasses a variety of concepts and elements including sensitivity or susceptibility and the ability of an ecosystem and its component parts to withstand or adapt to the effects ensuring the preservation of its essential basic structures and functions. Adaptation to ocean acidification could influence the degree to which ocean acidification translates into impacts but is also influenced by the *severity* of change. Adaptation ability is *likely* to be higher in some species than others. For example, trans-generational or evolutionary adaptation has been shown in some rapidly-reproducing species (Sunday et al. 2014), reducing impacts of projected CO_2 emission scenarios. However, the speed of current change is unlikely to allow widespread adaptation, especially in slower growing species (IPCC 2014).

Some organisms can withstand periods of acidification if food availability is high or they can trade-off energy flow to different physiological or metabolic processes in the organism (Figure 5.26. An organism requires energy gained from the food it ingests to maintain itself (for example: for metabolism, respiration, acid-based regulation and movement). It must also expend energy in processes such as calcification, growth and reproduction and ensure eggs and larvae are produced in sufficient size, numbers and condition for species recruitment and survival (Figure 5.26). Trade-offs between different energy requirements have been observed in organisms when placed in low pH conditions in order to withstand ocean acidification but this can impact their survival (reviewed by Wicks and Roberts 2012). How the impact of ocean acidification scales up from impact on the individual organism level to the ecosystem level depends

Figure 5.26. Energy flow and energy requirement of different processes within an organism and potential energy trade-offs that can occur in order to withstand ocean acidification. Potential ecosystem level impact depends on the role of the organism in the ecosystem, its food availability and whether it can manage its energy flow and expenditure to ensure its survival to propagate successfully and maintain its competitive advantage over other species.



on the role of the organism in the ecosystem, and whether changes to its energy flow (caused by, for example, changes to food availability and/or increased energy requirements for a physiological process) will ensure its survival and long-term fitness and competitiveness within an ecosystem framework (Figure 5.26. However, there is currently no understanding of how food availability in different levels of a foodweb will change in a future ocean.

It is therefore important during the assessment of possible impacts to study the weakest link in an organism's physiology and life cycle. A *vulnerability* to lower pH and carbonate saturation state in any of these functions at any life stage could result in loss of competitive fitness, narrowing of a species ecological niche or its demise (Wicks and Roberts 2012).

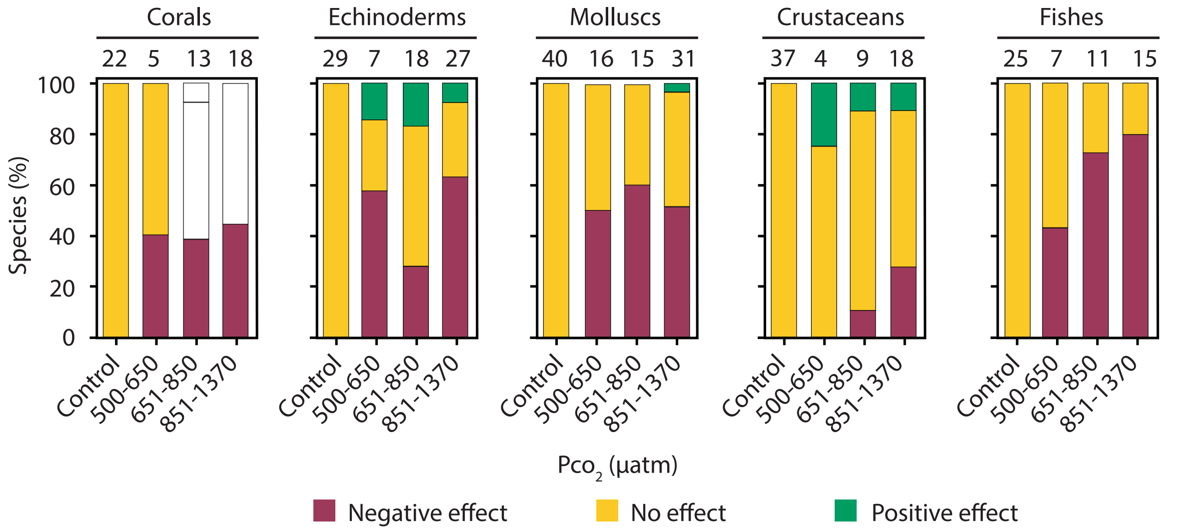
Risk to organisms

Vulnerability to ocean acidification has been mainly tested on single species, often in short-term experiments but increasingly in longer-term experiments. A synthesis of the results of 228 studies examining biological responses to ocean acidification reveal decreased survival, calcification, growth, development and abundance in response to acidification when the broad range of marine organisms is pooled together (Kroeker et al. 2013). This meta-analysis showed that early life history stages were particularly vulnerable in some but not all taxa. The magnitude of responses varies among taxonomic groups, for example crustaceans seem less vulnerable than echinoderms, molluscs, corals and fish (Wittmann and Pörtner 2013; Figure 5.27.

Risk to communities, foodwebs and trophic interactions

Experiments using multi-species assemblages revealed enhanced variability in species' responses suggesting that it is important to consider indirect effects and exercise caution when forecasting abundance patterns from single species laboratory experiments (Kroeker et al. 2013). Furthermore, the results suggest other factors, such as nutritional status or source population, could cause substantial variation in organisms' responses and enhanced vulnerability to acidification to occur when taxa are concurrently exposed to elevated seawater temperature. For example, the blue

Figure 5.27. Synthesis of experimental results on impacts of ocean acidification taxa



Source: Nature Climate Change Journal; Wittmann and Pörtner (2013)

mussel (*Mytilus edulis*) tolerates low pH when food supply is abundant (Thomsen et al. 2013). However, low food concentrations and low pH each significantly decreased shell length growth and the magnitude of inner shell surface dissolution (Melzner et al. 2011). This illustrates that under food limited conditions, this species allocates energy to more vital maintenance processes rather than to shell conservation. High food availability was also found to offset the negative consequences of elevated CO_2 on larval shell growth and total dry weight in the larvae of the Olympia oyster (*Ostrea lurida*) (Hettinger et al. 2013).

Some organisms prosper in more acidic waters. With the exception of those that calcify, most sea grass, macroalgae and microalgae respond positively to elevated bicarbonate ion concentrations by increasing photosynthesis and growth (Raven et al. 2005). Observations of natural CO_2 vents in coral reef systems off Papua New Guinea show increased algal growth but declining coral reef biodiversity and loss of reef structure that provides homes to many reef dependent species as pH decreases close to the vents (Fabricius et al. 2011). Other vents in the Mediterranean Sea also show declining biodiversity and loss of shelled organisms but increases in sea grass meadows and alien species as pH declines closer to the vents (Hall-Spencer et al. 2008).

Some non-calcifying algae may do better than others and thereby change the structure and functioning of an ecosystem. For example, profound effects of ocean acidification were found at the productive base of the pelagic foodweb in the Arctic using mesocosm CO_2-enrichment experiments, which enclose large volumes of seawater containing the whole plankton community (Brussaard et al. 2013). The composition and growth of the two smallest (picophytoplankton and nanophytoplankton) components of the phytoplankton community increased at the expense of the growth and biomass of the larger diatoms but were also found to be prone to viral lysis. A shift towards the smallest primary producers and increased viral lysis as a result of acidification would have direct consequences for the structure and functioning of pelagic ecosystems by shunting more carbon through the microbial loop rather than to grazing zooplankton and on higher trophic levels. This is an example of how responses (even positive ones) to ocean acidification could have a bottom-up impact on ecosystem dynamics and how it is important to consider multiple organisms or levels. For instance, isolated research on diatom species in the laboratory would not have revealed that they could be out-competed by the smaller members of the phytoplankton community with a conclusion that diatoms may do well in a high CO_2 ocean.

Organisms higher up the foodweb are not just at risk from "bottom-up" impacts. Evidence is accumulating that CO_2 projected to occur by 2100 impairs sensory performance and alters the behaviour of larval teleost fishes (Munday et al. 2009; Dixson et al. 2010), impairing decision-making (Domenici et al. 2012) and the response to auditory (Simpson et al. 2011) and olfactory cues (Munday et al. 2009; Dixson et al. 2010). Trans-generation acclimation does not seem to reduce such impacts, implying that genetic adaptation will be necessary to overcome the effects of ocean acidification on behaviour (Welch et al. 2014). Projected future CO_2 levels impair odour tracking behaviour of the smooth dogfish (*Mustelus canis*) an Elasmobranch fish (Dixson et al. 2014). A highly sensitive sense of smell is considered particularly important for these apex predators to detect chemical cues emanating from distant prey. If other sharks are affected similarly to the smooth dogfish, the consequences of a decrease in their effectiveness as apex predators could have cascading effects throughout ocean ecosystems (Myers et al. 2007). Elimination or decreased effectiveness of top predators can be far-reaching and include release of intermediate predator prey populations from predatory control and induction of subsequent cascades of indirect trophic interactions (Pace et al. 1999). Changes to apex predators by ocean acidification may result in top-down impact on ecosystems dynamics.

Risk to key links in foodwebs

Some species represent key links in foodwebs. For example, sea butterflies (Pteropoda) contribute on average 25 per cent to total phytoplankton grazing and consume up to 19 per cent of daily primary production in the Southern Ocean. In addition they are also an important prey item for many predators, such as larger zooplankton as well as herring and salmon (Hunt *et al.* 2008). Laboratory experiments show great sensitivity of Arctic pteropods to ocean acidification (Comeau et al. 2009 and 2010a; Lischka et al. 2011; Comeau 2015, see Chapter 5.5 of this Report). Natural populations of the shelled pteropod *Limacina sp.* are already showing shell thinning in the Southern Ocean and the California Current Ecosystem where pH and carbonate levels are lowest (Bednaršek et al. 2012; 2014). These shelled molluscs seem at *high risk* from ocean acidification due to their high levels of *exposure*, *vulnerability* and the *severity* and early onset of acidification in their habitat (Bednaršek et al. 2012 and 2014; Comeau 2015, See Chapter 5.5 of this Report). Some pteropod species that naturally migrate for short periods into oxygen minimum zones, where pH is low, are not affected but it is unlikely that they will be able to withstand the longer time-scales associated with ocean acidification (Maas et al. 2012). Juveniles of the species *Cavolinia inflexa* held in low pH seawater for 5–13 days were viable but completely shell-less (Comeau et al. 2010b). If this were to happen in their natural habitat it is *likely* that there would be long-term effects on population fitness through loss of swimming efficiency and defensive capacity. As important links in the foodweb, a reduction in pteropod survival in polar, sub-polar and upwelling waters could have implications to ecosystem structure and function through changes in predator-prey interactions.

To maintain a shell when exposed to more acidic conditions an organism may have to divert energy from other metabolic processes to up regulate calcification in order to compensate for dissolution of this calcified structure (Findlay et al. 2009). Other metabolic processes may also be impacted by the higher CO_2 so this compensation may be a useful adaptive response for only short periods of time and may not be helpful over the timescale associated with ocean acidification. The physiological adaptations to combat the effects of decreasing pH may themselves reduce survival and fitness as much as acidification itself. An extreme example of this is the brittlestar (*Amphiura filiformis*), a key link in benthic foodwebs, which exhibited a trade-off between maintaining skeletal integrity and arm function by using the muscle as an energy source (Wood et al. 2008). Such adaptive responses may be helpful to cope with the natural daily or even seasonal variability of ocean pH but may be less effective on the timescale of ocean acidification resulting in reduced long-term fitness and survival. This highlights the need to place short-term acclimation responses, sometimes seen in short-term experiments, in perspective when interpreting them in the long-term timescale of ocean acidification.

In the Southern Ocean extensive krill (*Euphausia superba*) populations support many predators and it is therefore a keystone species for this ecosystem. Shifts in krill metabolism have been observed when exposed to low pH and are consistent with increased physiological or energy costs associated with internal acid-base regulation (Saba et al. 2012). Such trade-offs may hamper growth and reproduction, which could negatively impact the krill population and cascade through the ecosystem (Figure 5.26).

Risk to ecosystem builders

Organisms forming three dimensional structures on a sufficient scale create some of the most diverse ecosystems on the planet and can occur in the warm sunlit upper or deeper darker waters of the ocean.

Scleractinian cold-water corals, also known as deep-sea corals, may form one of the most vulnerable ecosystems to ocean acidification (Guinotte et al. 2006). They are found at depths from 200–>1,000 m throughout the ocean and are several 100s of years old. Their reef-like structures can be sizable, extending 10s of kilometres and reach heights of 10s of metres and may cover a similar proportion of the ocean as tropical coral reefs (Freiwald and Roberts 2005; Guinotte et al. 2006). These *Lophelia* reefs and giant carbonate mounds are biodiversity hotspots acting as a refuge, feeding ground and nursery for deep-sea organisms (CBD 2014, Roberts et al. 2006). It has been estimated that about 70 per cent of known cold-water coral ecosystems will experience under-saturated conditions with respect to aragonite, the form of calcium carbonate used to form their skeletons, within this century (Orr et al. 2005; Guinotte et al. 2006; Turley et al. 2007). Locally, down-welling of food rich, high pH water from the upper ocean may facilitate the short-term survival of some communities (Findlay et al. 2013) but with increased warming of surface waters the down-welling would be bringing warm waters that may elicit a negative response.

While short-term experiments assessing the effects of ocean acidification on cold-water coral species showed the vulnerability of their growth and metabolism to low pH (Maier et al. 2009; Hennige et al. 2014), relatively long-term laboratory experiments of 6-9 months duration found no apparent impacts (Form and Riebesell, 2012; Maier et al. 2013; Movilla et al. 2014). This implies their resilience to acidification, at least for the time-scales of these experiments, possibly through energy intensive up-regulation of their internal pH at the sites of calcification (McCulloch et al. 2012) or through reallocation of energy from other processes (CBD 2014). This underlines the need to carry out energy budgets to determine whether this apparent acclimation comes at a cost to long-term fitness. However, the carbonate mounds, which create the three dimensional habitat of these reef-like ecosystems, are comprised of dead skeletons unprotected by living tissue and these will be susceptible to dissolution as the waters around them become undersaturated with respect to aragonite (CBD 2014). It is noteworthy that few cold water framework forming corals currently exist below the saturation horizon or in the North Pacific where this horizon is shallow (50–600 m) (Feely et al. 2004). There is therefore a *high risk* that ocean acidification may have substantial impacts on the structure and function of these deep-water ecosystems due to *high severity*, *exposure* and *vulnerability*.

Deep-sea fauna has evolved under conditions of relative environmental stability (Yu et al. 2010) and may therefore be particularly vulnerable to the current rapid changes in seawater chemistry (Figure 5.25). The past stability of their habitat and their lower metabolic processes due to lower temperature and sparse and sporadic food availability (Gooday and Turley 1990) may indicate a lower adaptive capacity to future environmental variability. This contrasts to organisms that inhabit warmer, food rich and environmentally dynamic shallow coastal waters where adaptive capacity may be inherently greater due to this environmental instability (Barry et al. 2011; Somero, 2012).

Tropical coral reefs support diverse and productive ecosystems and exist in warm waters with high saturation states of aragonite that are used by reef-building organisms such as corals and calcareous red algae to construct the reef. Healthy coral reefs form three-dimensional calcium carbonate structures that provide habitats for about one million species. The projected rate of change of ocean acidification in tropical waters is greater than that seen in polar waters (Figure 5.25 although tropical waters are very unlikely to reach undersaturation, so acidification could arguably be less *severe*. However, *exposure* is *high* due to the high density of coral reefs and the large number and diversity of organisms they support. Coral reefs also seem very *vulnerable* to ocean acidification, with declines in coral calcification associated with declining aragonite saturation state even though saturation states are >1 (Kleypas and Langdon, 2006; Andersson and Gledhill 2013). Although not all corals species exhibit negative responses to reduced pH (CBD 2014) studies have already shown a 16 per cent decrease in reef calcification rates over the last two decades which may be attributed to increasing acidification (De'ath et al. 2009). A year-long *in situ* experiment net community calcification in a Great Barrier coral reef is depressed compared with values expected for preindustrial conditions, indicating that ocean acidification may already be impairing coral reef growth (Albright et al. 2016) If reef growth declines faster than natural physical and biological reef erosion there will be a net loss in reef over time.

An examination of coral reef biodiversity in the vicinity of a natural CO_2 vent revealed notable loss of coral diversity, recruitment and abundance and reef integrity when pH decreased from 8.1 to 7.8, with reef development stopping below pH 7.7 (Fabricius et al. 2011). The loss of habitat complexity and its provision of essential refugia had indirect impacts on larger reef-associated invertebrates that may not be directly vulnerable to ocean acidification (Fabricius et al. 2014).

Coral reef communities can alter their own seawater chemistry, through processes of photosynthesis, respiration, calcification, and dissolution (Kleypas et al. 2011; Anthony et al. 2013). Coral reefs located within or immediately downstream of seagrass or eelgrass beds, for example, may find refuge from ocean acidification (Palacios and Zimmerman 2007; Manzello et al. 2012). On the other hand, the rate of acidification in some coral reef ecosystems may be more than three times faster than in the open ocean due to local or regional disturbances to drivers of seawater carbonate chemistry (Cyronak et al. 2014).

Tropical coral reefs are also *vulnerable* to ocean warming, with episodes of warming leading to coral bleaching, as well as local stressors such pollution, sedimentation, invasive species and poor fisheries practices. The combined action of these multiple stressors raises the *risk* of the loss of the majority of tropical coral reefs globally (Gattuso et al. 2014; IPCC 2014; Burke et al. 2015,).

Research needs and gaps

Future coastal conditions are more difficult to project in models due to greater heterogeneity (Artioli et al. 2014) than found in the open ocean (Figure 5.6.2) because of the interactions with sediment processes and input from rivers or melting sea-ice (Salisbury et al. 2008; Hoffmann et al. 2011; Yamamoto et al. 2012). Increased understanding of these more dynamic coastal systems and their influences on the severity and variability of coastal pH is essential to assess the risk to coastal ecosystems and the provision of food resources to society (Turley and Gattuso 2012; Mathis et al. 2014).

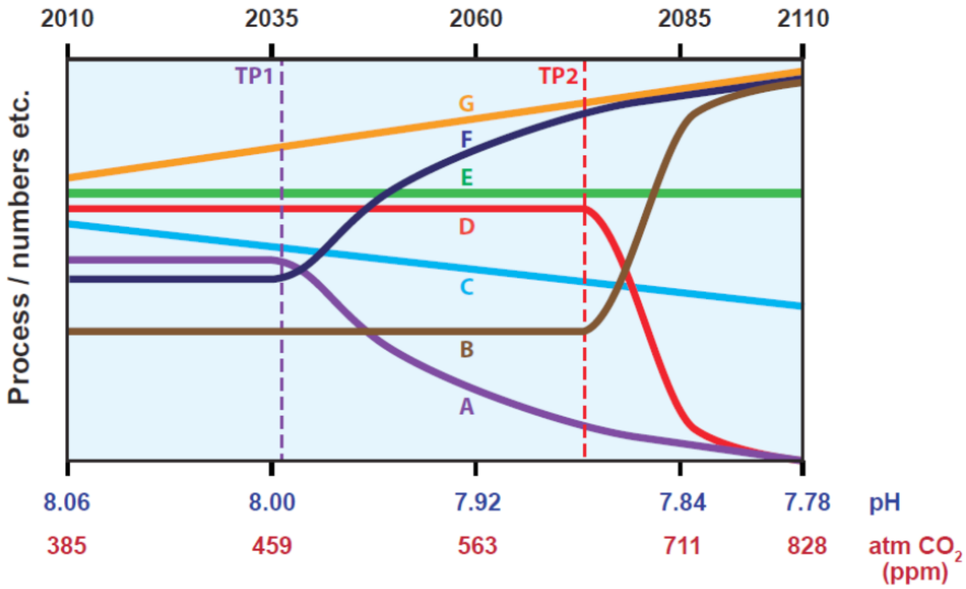
Understanding the long-term ecosystem-level consequences of ocean acidification is critical. However, scaling up understanding of the impact of ocean acidification on complex ecosystems from controlled experiments on single species is a formidable challenge requiring deep understanding of the role of the different species within an ecosystem, the dependency and interaction between the large number of species comprising the ecosystem and how these community dynamics may alter over time as ocean acidification progresses.

For instance, different species will react differently and at different time-scales. Some organisms could decline gradually but others could reach non-linear shifts - thresholds or “tipping points” - at different times. Some species could increase gradually; others could increase rapidly taking advantage of the vacant niches, while others may not change (Figure 5.28). How these responses and interactions are played out within a complex foodweb or ecosystem is difficult to predict and is a multidisciplinary research challenge.

It also requires a better understanding of how different organisms can control their internal pH, including pH at the site of calcification and how trade-offs of energy supply to different processes may enable them to either withstand or succumb to ocean acidification (Figure 5.26). It is also important to study the weakest link in an organism’s physiology and life cycle. A better understanding of which organisms are capable of long-term acclimatization or adaptation is required and whether there is sufficient phenotypic plasticity in a population to enable their survival in a future ocean, is required.

Predicting impacts of changing biodiversity or community dynamics on ecosystem function also requires expanding the scope of current experimental research to multi-level foodwebs and complex ecosystems (for example: Brussaard et al. 2013). Of this, a central challenge is to evaluate the importance of trophic cascades, the distribution of interaction strengths within natural communities and how they change with community composition.

Figure 5.28. A conceptual representation and simplification of potential different reactions of different species (A-G) comprising an ecosystem to increasing acidification (decreasing pH) with time. Some organisms could decline gradually (C) but others (A and D) could reach non-linear shifts - tipping points (TP1 and TP2) - at different times. Others could increase gradually (G), others could increase rapidly (B and F) taking advantage of the vacant niches, and others may not change (E). The time-scales of such tipping points and the implication on ecosystem structure and function are largely unknown.



Other stressors acting at the same time as ocean acidification, such as ocean warming and deoxygenation, and non-climate related local stressors such as pollution, nutrient runoff from land, and over-exploitation of marine resources, will increase *risk* to marine ecosystems (Gattuso et al. 2015; See Chapter 5.41, 4.2, 4.3, Section 6 and 7 for further context). This underlines the need to carry out multi-stress impact assessments on whole communities. That is, changes in ecosystem structure and function cannot be projected by investigating individual-level impacts in isolation, or by considering stressors separately. Scaling up to ecosystem impacts requires approaches that account for long-term, multi-scale responses to multiple stressors, in an ecosystem context (Queros et al. 2014).

Policy-makers, decision-makers, marine managers, industry and other stakeholders need to understand the *risk* posed to marine ecosystems, and the goods and services they provide society, of different concentrations and rates of anthropogenic CO_2 emissions and therefore the progression of ocean acidification. *Risk* of impacts from ocean acidification will depend on the likelihood of severe alterations in the normal functioning of an ecosystem. This will depend on the *severity* (of which strength and speed are components) of ocean acidification, and the *exposure* and *vulnerability* of organisms to ocean acidification especially those playing key roles in ecosystems. The higher the *severity*, *exposure* and *vulnerability* the greater the *risk* of impact to numbers of organisms and therefore to ecosystems.

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Chapter 5.7 Biodiversity Baselines in the Global Ocean

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5.7 Biodiversity Baselines in the Global Ocean

5.7.1 Summary and Key Messages

Summary

This chapter provides baselines on what is currently known about the taxonomic, biogeographic, and conservation status of marine species using the world's largest marine biodiversity database, the Ocean Biogeographic Information System (OBIS; iobis.org).

The ocean may be home to one million or more species, with 230,000 so far described by science. The age of discovery continues, with the rate of description of new marine species higher than ever, suggesting that most will be discovered by the end of this century. The importance of species diversity for marine ecosystem functioning is well known. It is therefore important to know which species live where, why, in what abundance, and how these factors are changing through time.

Despite increased biodiversity monitoring since the 1950s globally, with daily averages of 120 sampling events and 1 800 observations in OBIS, 98.7 per cent of the ocean volume can still be regarded as severely under-sampled and all we know of 62 per cent of all marine species might be based on a single record. Assessments of completeness based on nonparametric richness estimators confirm that many species remain to be sampled in most parts of the world's ocean. For only 1.5 per cent of all marine regions, knowledge of species richness is >80 per cent complete. For >50 per cent of the ocean, however, no reliable estimate could be calculated and even in highly-sampled regions such as Europe, there are still many spots with over 30 per cent undiscovered or unreported species. When restricted to fish, completeness scores are higher globally, particularly in coastal areas, but not in open waters.

Understanding where species occur is a necessary first step towards identifying areas of *high* richness, endemicity, or threat, and is thus essential for effective conservation planning. For those areas with sufficient data, several biodiversity indices agree that Southeast Asia, the Southwest Pacific, the Gulf of Mexico and the Caribbean Sea are notably rich in biodiversity. This agreement is encouraging given the significant gaps and biases in OBIS data.

According to the Red List of the International Union for Conservation of Nature (IUCN), 17 per cent of marine species assessed are considered to be threatened with extinction and 20 are extinct. When plotted in OBIS, areas of greatest importance to species known to be threatened include the Caribbean and Atlantic Coast of the USA, waters between Eastern Africa and Madagascar, and the Indo-Pacific. However, considering that little is known of rare species, true rates of threat in marine species may be substantially higher, and spatially more distributed, than current estimates suggest. In addition, OBIS lists almost 500 species that have >10 observations but have not been recorded at all in the last 50 years.

Monitoring ocean biodiversity is expensive and can be risky, and requires highly skilled people. Very few marine regions or taxonomic groups have benefitted from long-term monitoring programs; hence stocktaking remains far from complete. Publishing existing biodiversity data into open data repositories such as OBIS provides the most cost-effective means to address this shortfall, and we hope that momentum in this direction can be maintained, alongside new efforts to discover and document the diversity and distribution of life in the ocean. In addition, we recommend focused efforts to monitor the abundance of key species at all trophic levels, potentially as part of a global initiative such as the Global Ocean Observing System (GOOS).

Key Messages

- Biodiversity is our natural capital, our life insurance. Understanding how much the ocean impacts us and how we impact the ocean is critical to managing our world;
- Knowledge of ocean biodiversity is highly variable: there is much more data from recent decades, and some areas of the world are far better studied than others; and

- Over 99 per cent of Earth's habitable space is marine, yet for 99 per cent of this vast realm we lack the basic biodiversity knowledge required for effective management.

5.7.2 Main Findings, Discussion and Conclusions

Taxonomic knowledge - how many species are there in the ocean?

The most basic metric of biodiversity is the number of species, and for decades scientists have been seeking to determine how many species there are on land and in the ocean. Recent estimates range from fewer than a million to 2.2 million marine species (Appeltans et al. 2012; Mora et al. 2011), much lower than past estimates of >10 million species (Grassle and Maciolek, 1992). Nonetheless, considerable uncertainty remains around the proportion of species still to be discovered (30-90 per cent; Appeltans et al. 2012; Mora et al. 2011). An authoritative listing of all currently known species on which to base such estimates is now available in the World Register of Marine Species (WoRMS; Boxshall et al., 2014), an international effort involving over 200 taxonomists. WoRMS currently lists >400,000 marine species names, of which 227,000 are accepted. The total number of described species is probably close to 230,000. WoRMS also makes it easier to track the rate of new species descriptions. Approximately 20,000 marine species new to science have been described in the past decade, and the rate of new species discoveries shows no sign of slowing down. This is due to increased taxonomic effort, new technologies, and access to previously unexplored and remote habitats.

An overview of species richness across all major eukaryotic groups, together with estimates of the number of unknown species, is given in Appeltans et al. (2012). Undiscovered species are unevenly distributed across taxa: several thousand, perhaps even >100,000 species remain to be discovered in macro-invertebrate groups such as Mollusca and Crustacea, but >50 per cent of species in most phyla are already known, and at current description rates most species will be discovered by the end of this century. For example, around 5,000 marine fish species remain to be discovered, which implies complete description of this group within three decades at the current rates of 150 new species described per year.

Despite the oceans constituting >99 per cent of Earth's available living space (Dawson, 2012), there are probably around six times fewer species in the ocean than on land. Much of this discrepancy is explained by the rapid diversification and co-evolution of terrestrial flowering plants and insects (Vermeij and Grosberg, 2010), which together comprise about 65 per cent of all species on Earth. In contrast, the ocean harbours greater evolutionary diversity and variety in life forms: life originated there, and over a third of all animal phyla remain uniquely marine, whereas only one is unique on land (May, 1994).

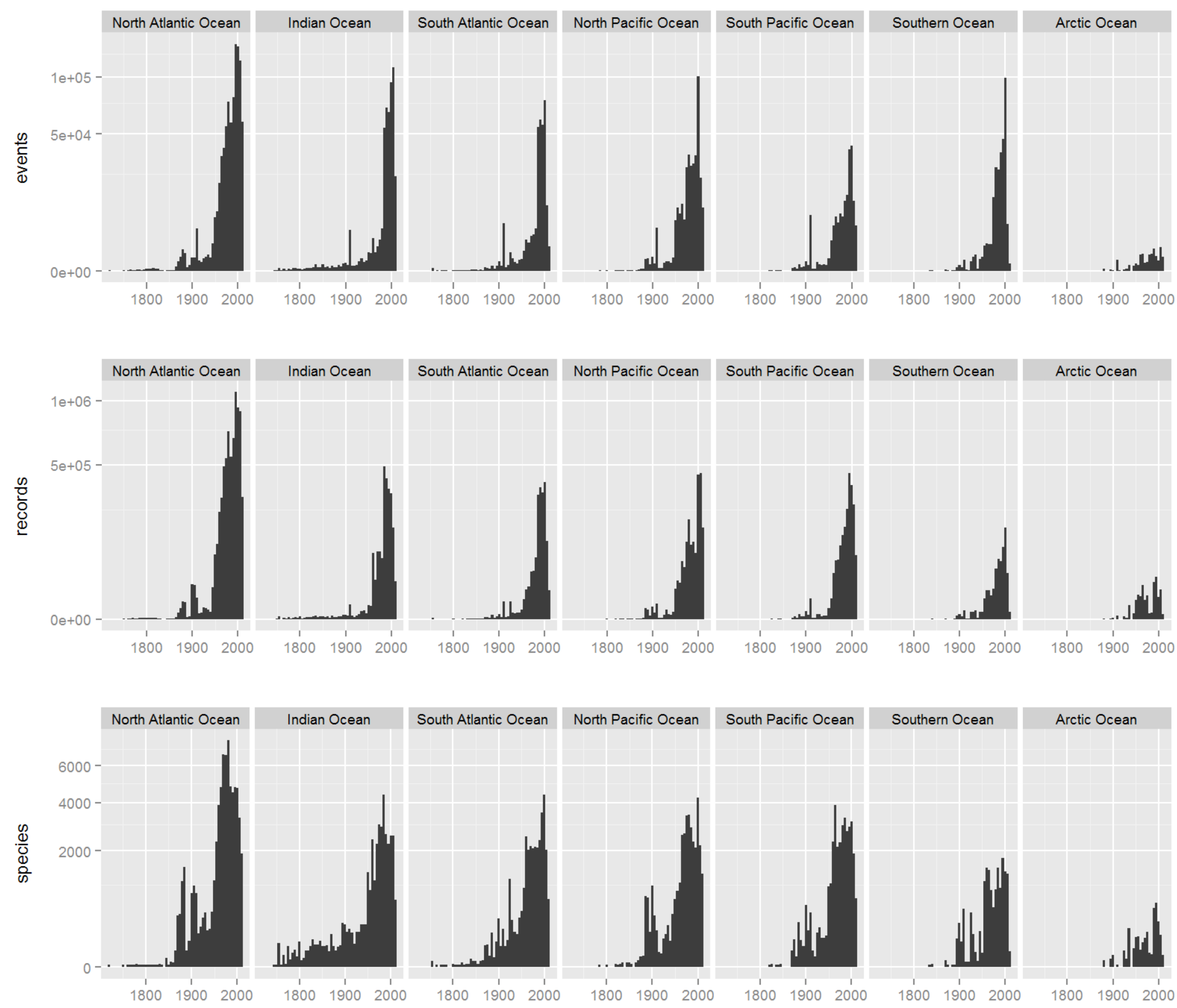
These figures do not consider the diversity of Bacteria and Archaea, which is *likely* to be at least an order of magnitude higher than eukaryotic diversity. However, due to the *high* uncertainty around prokaryotic diversity, as well as the difficulty of applying standard species concepts to these groups, they are not treated here.

Biogeographic knowledge of marine biodiversity

The importance of species diversity for marine ecosystem functioning is well known (Solan et al. 2012). It is therefore important to know which species live where, why, in what abundance, and how these factors are changing through time.

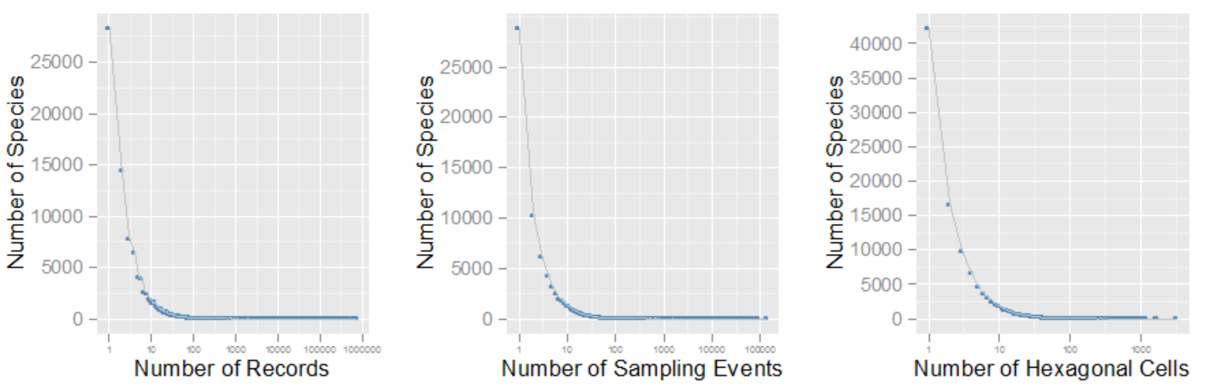
The 38 million distribution records in the Ocean Biogeographic Information System (See Methods) cover 114,000 marine species from bacteria to whales. Records are drawn from a total of 37,753 sampling days between 1562 and 2014. Figure 5.29 shows the number of sampling days, records, and species over time for each major ocean basin. Early peaks in species numbers are observed in the Indian Ocean, but species records in all regions begin to increase in the late 19th century, and especially as sampling effort intensified worldwide in the mid-20th century. Since the 1960s, sampling has been intensive, with daily averages of 120 sampling events and 1,800 observations. Over this period, the North Atlantic has been the most heavily sampled ocean basin. Globally, the number of species reported peaked with a decadal maximum of 40,000 species observed in the 1980s, earlier than the peak of 800,000 sampling events and 10 million records in 1990s. Again, the North Atlantic dominates this trend, where the relative number of observed species was twice as high as in other ocean basins during the 1970s-1980s, but drastically decreased afterwards.

Figure 5.29. Number of sampling events (top), records (middle) and species (bottom) in OBIS per major ocean basin through time.



Most species in OBIS are known from very few records (Figure 5.7.2). Only 1,133 (1 per cent) species have been observed >1,000 times. The 'average' species (median values) is known from 5 records, 2 grid cells (*c.*100,000 km^2), and 2 sampling events, and 25 per cent of species only have a single record. Previous analyses have also found that most species are known from few records; for instance, around 30 per cent of all species have only been collected once and are thus 'uniques' (Thessen et al. 2012; Lim et al. 2012); and more generally rarity is the norm in marine species (Connolly et al. 2014). If all marine species that are not recorded in OBIS are known only from their type locality, the prevalence of uniques could be as high as 62 per cent.

Figure 5.30. Number of species with different number of total OBIS records (left), distinct sampling events (centre), and number of occupied hexagonal grid cells (right). The x-axis is logarithmic in each case. Most species have very few records, from few sampling events, and occur in few hexagonal cells - very often just a single record is available.



Sampling effort on a geographical scale is provided by mapping the global distribution of the number of sampling days, records, species and phyla. Each variable is shown on an equal area icosahedron grid (Carr et al. 1997) containing 2,562 cells each of *c*. 200,000 km^2. The highest number of sampling events (Figure 5.31) occurred in Northwest Europe, Northeast US and South Africa, with high levels of sampling in the oceanic North Atlantic and Northwest Pacific due to the Continuous Plankton Recorder Survey. Generally there have been fewer sampling events in the Southern Hemisphere, especially in the open ocean and in Southeast Asia, although areas of more intensive sampling exist on the Patagonian Shelf, Southern Africa, Eastern Australia and around New Zealand. The highest number of records (Figure 5.32) is clearly concentrated around coastal areas but with gaps off Chile, Ecuador, Mexico, north-eastern South America, Angola, North-Africa, Tanzania, Somalia, the Red Sea, Southeast Asia and the Northwest Pacific. The number of observed species (Figure 5.33) is often correlated with sampling effort with high numbers of species reported around the UK and Ireland, Northeast US, Gulf of Mexico, South Africa, the Mozambique Channel, Northeast Australia (Great Barrier Reef), New Caledonia and the Antarctic Peninsula. However, parts of Southeast Asia and the Southwest Pacific Islands also have high species numbers, despite little sampling effort. High species richness does not necessarily mean all taxonomic groups are equally well represented or sampled everywhere. In addition, the number of species per phylum varies from one to many thousands. Nonetheless, the number of phyla sampled per grid cell provides an indicator of gaps in sampling coverage (Figure 5.34). Interestingly, compared to other regions with comparably low sampling intensity, the Indian Ocean is rich in phyla.

Figure 5.35 shows the number of species recorded in each major taxonomic group for the continental shelf (<200m depth) and open ocean (>200m depth) regions of each ocean basin. The Arctic Ocean, the Southern Ocean and the North Pacific have fewer species in OBIS compared to other regions. The three largest taxonomic groups (Pisces, Crustacea and Mollusca) have the greatest representation in all regions except for the Polar seas. In the Arctic Ocean the three largest groups are Crustacea (25.0 per cent), Annelida (11.6 per cent), and Foraminifera (10.5 per cent), whereas Crustacea (19.0 per cent), Mollusca (11.5 per cent), and Bryozoa (11.3 per cent) dominate in the Southern Ocean. Crustacea constitute between 18.5 per cent (Indian Ocean) and 25.0 per cent (Arctic Ocean) of all species in a region, Pisces vary between 2.9 per cent (Southern Ocean) and 23.7 per cent (North Pacific), and Mollusca between 10.4 per cent (Arctic Ocean) and 19.9 per cent (Indian Ocean).

Figure 5.31. Global map showing the number of sampling days in OBIS per hexagonal grid cell of c. 200,000 km².

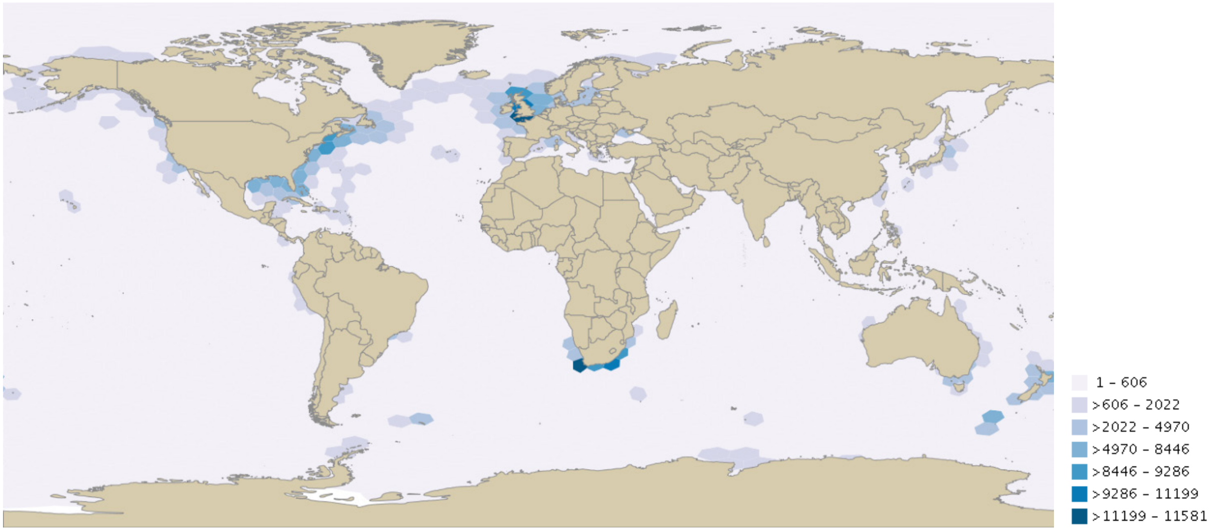


Figure 5.32. Global map showing the number of records in OBIS per hexagonal grid cell of c. 200,000 km².

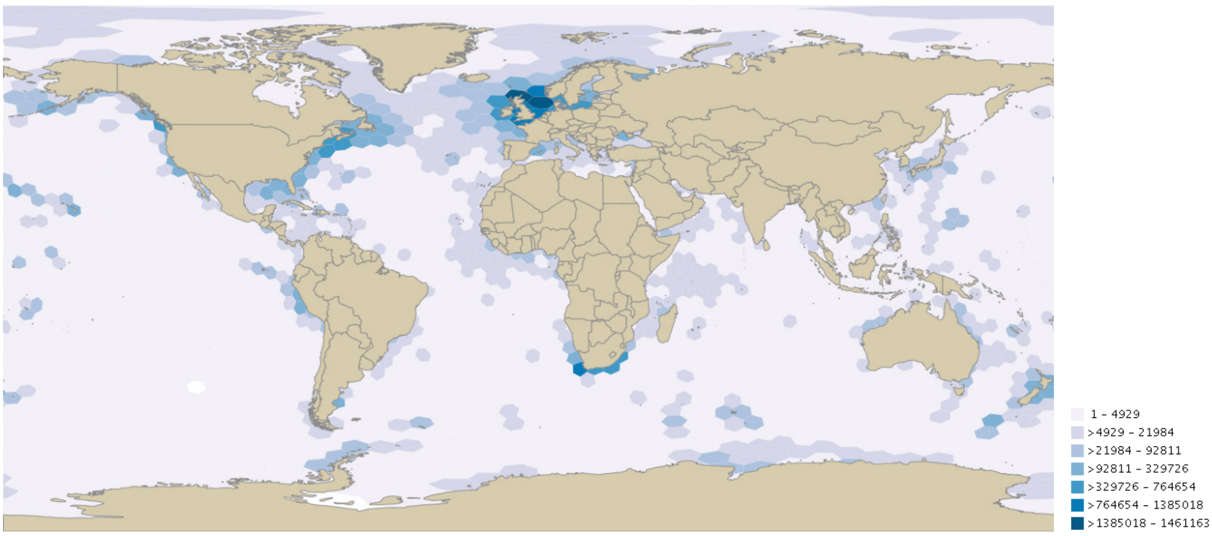


Figure 5.33. Global map showing the number of species in OBIS per hexagonal grid cell of c. 200,000 km².

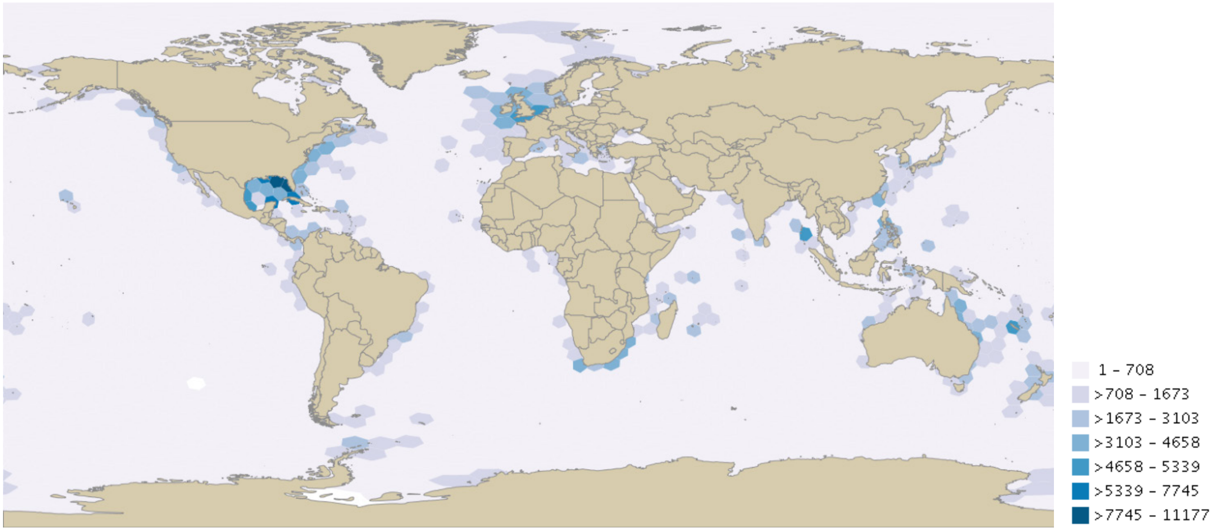


Figure 5.34. Global map showing the number of phyla in OBIS per hexagonal grid cell of c. 200,000 km².

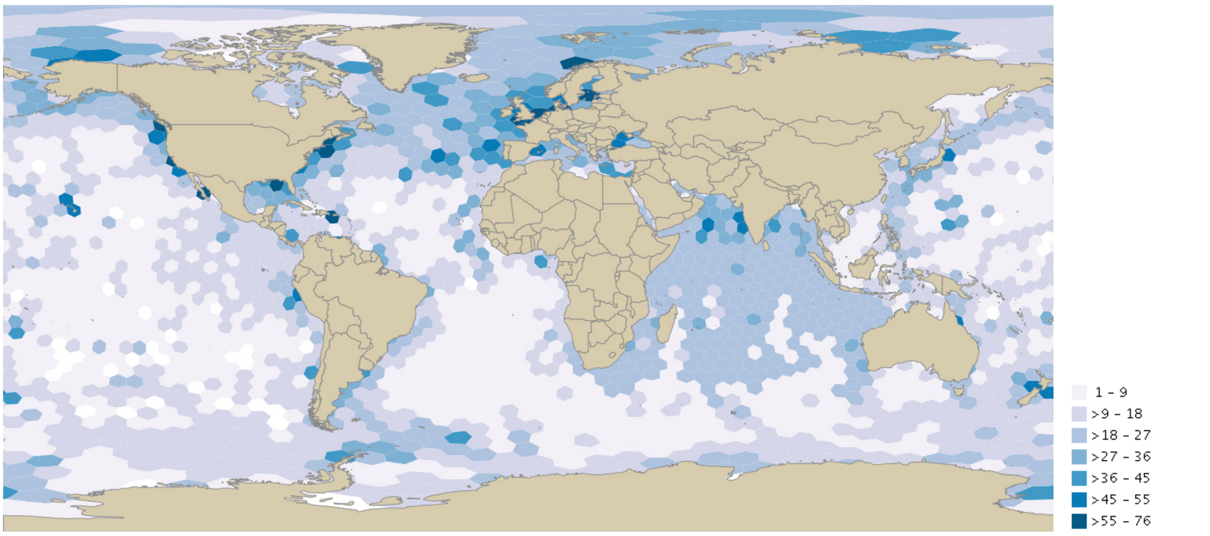
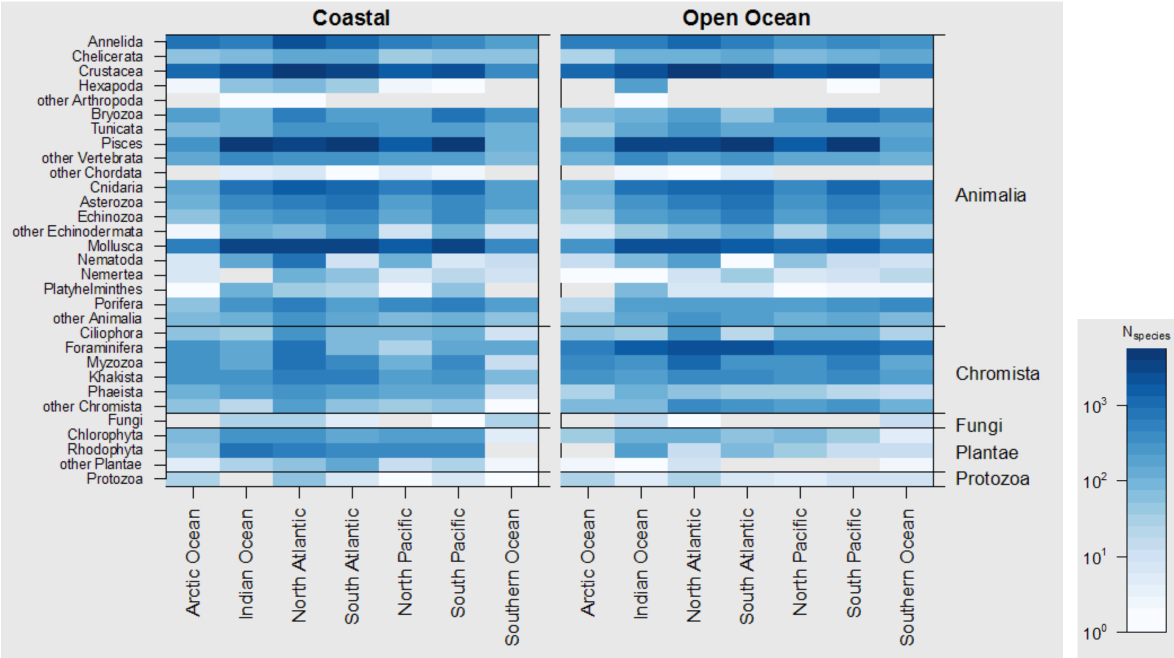


Figure 5.35. Number of species in OBIS per major taxonomic group, per ocean basin (divided in coastal/continental shelf and open ocean/deep sea).

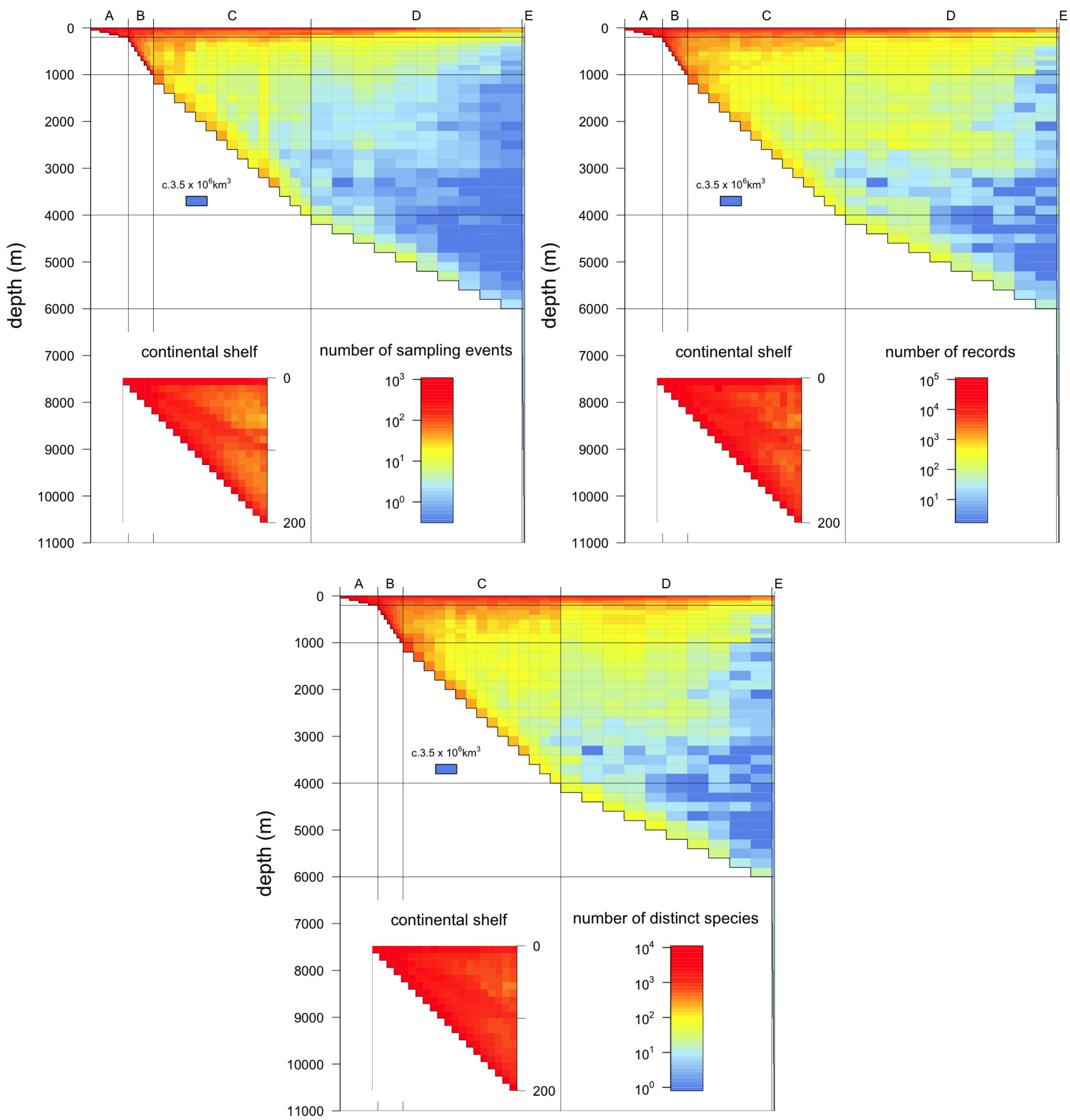


Figures 5.36 shows the distribution of sampling events, records and species in the water column using the c. 19 million OBIS records with sampling depth information (see also Table 5.7.1). This figure updates Webb *et al.* (2010), which used c. 7 million records. Values in each cell are standardized to the cell's volume. Sample depth varies from the sea surface to 10,900 m. The seas above the continental shelf (0-200m) are clearly the most heavily sampled, followed by the mesopelagic continental slope (200-1,000m deep). In contrast, there are only two species records for every 100,000km^3 above the abyssal plain (4,000-6,000 m), a zone that represents 70 per cent of the ocean volume. In fact, all zones with bottom depth deeper than 1,000 m (zones C, D, E in Figure V and Table 5.7.1) are severely under sampled. Together these zones make up 98.7 per cent of the total ocean volume, or c. 98.5 per cent of the entire planet's habitable volume.

Table 5.7 Number of sampling days, species distribution records and species within each depth zone of the global ocean (see also Figure 5.36). Actual counts are followed in parentheses by numbers normalized per 105 km³. The contribution of each zone to the volume of the global ocean is also shown.

Zone	Sampling days	Records	Species	% Ocean Volume
A: Continental shelf (0-200m)	529,248 (13,471)	10,154,841 (258,467)	89,418 (2,276)	0.31
B: Mesopelagic continental slope (200-1,000m)	266,846 (1,961)	2,086,305 (15,330)	42,200 (310)	1.07
C: Bathypelagic continental slope (1,000-4,000m)	339,696 (100)	2,428,958 (713)	43,743 (13)	26.77
D: Abyssal plain (4,000-6,000m)	103,038 (12)	778,213 (87)	17,650 (2)	70.32
E: Hadal zone (>6,000m)	1,790 (10)	21,039 (106)	1,749 (9)	1.56

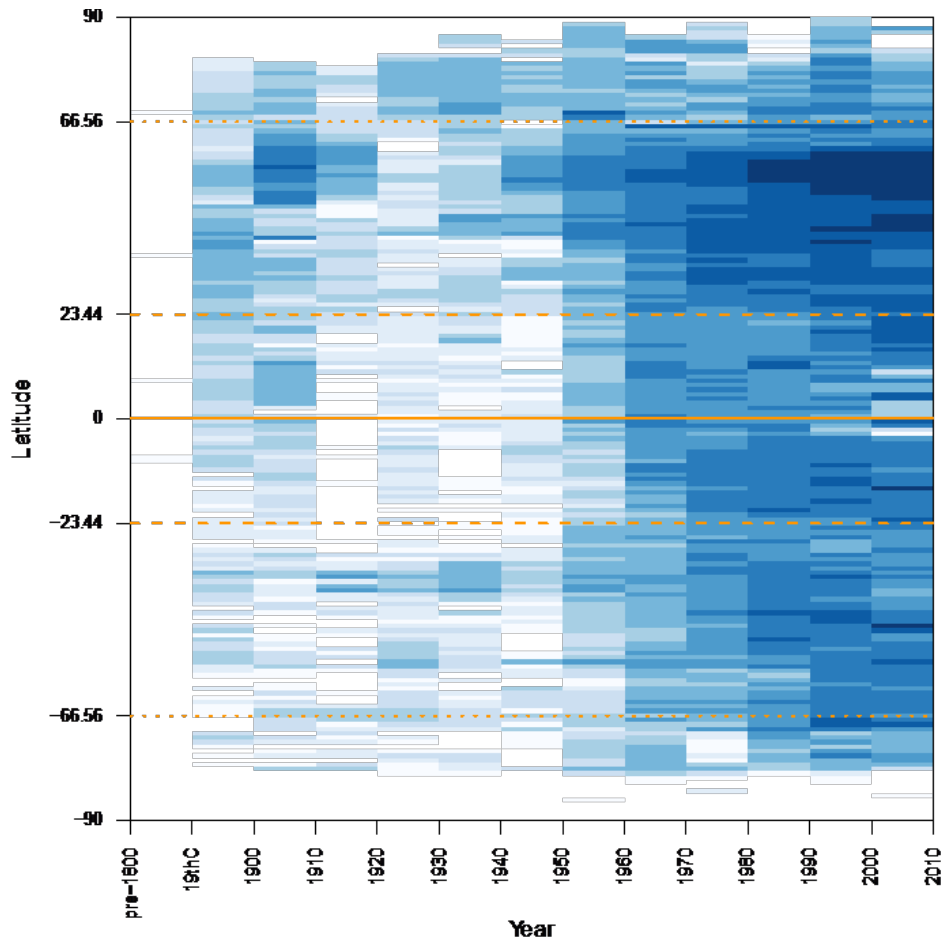
Figure 5.36. Standardised depth figures with the global distribution of sampling days (a), records (b) and species (c) in OBIS. The inset shows the continental shelf (zone A) in greater detail, where the highest values are recorded.



Figures 5.37, 5.38 and 5.39 show how species distribution records have accumulated through time by latitude, longitude, distance from the nearest land, and depth. Figure 5.37 shows the clear trend towards more sampling starting from the 1950s-1960s, initially in northern temperate regions but with progressively more sampling in the Southern Hemisphere, the Tropics, and Polar regions. In all decades since, most sampling has been within 250 km of the coast, although since 1950 sampling has increased up to 1750km out to sea (Figure 5.38). Almost no sampling has occurred in the remotest parts of the ocean > 2000 km from land, except for a few records from the 1960s. Although the deep sea remains poorly sampled, sampling the shelf (for example: 500-1,500m) has increased through time, with 70x more records in the 1990s (*c.*170,000) than in the 1950s (*c.* 2,500, Figure 5.39). Sampling between 3,000-5,000m peaked in the 1970s (*c.* 7,500 records), dropping to *c.* 1,600 records in the 2000s, and sampling between

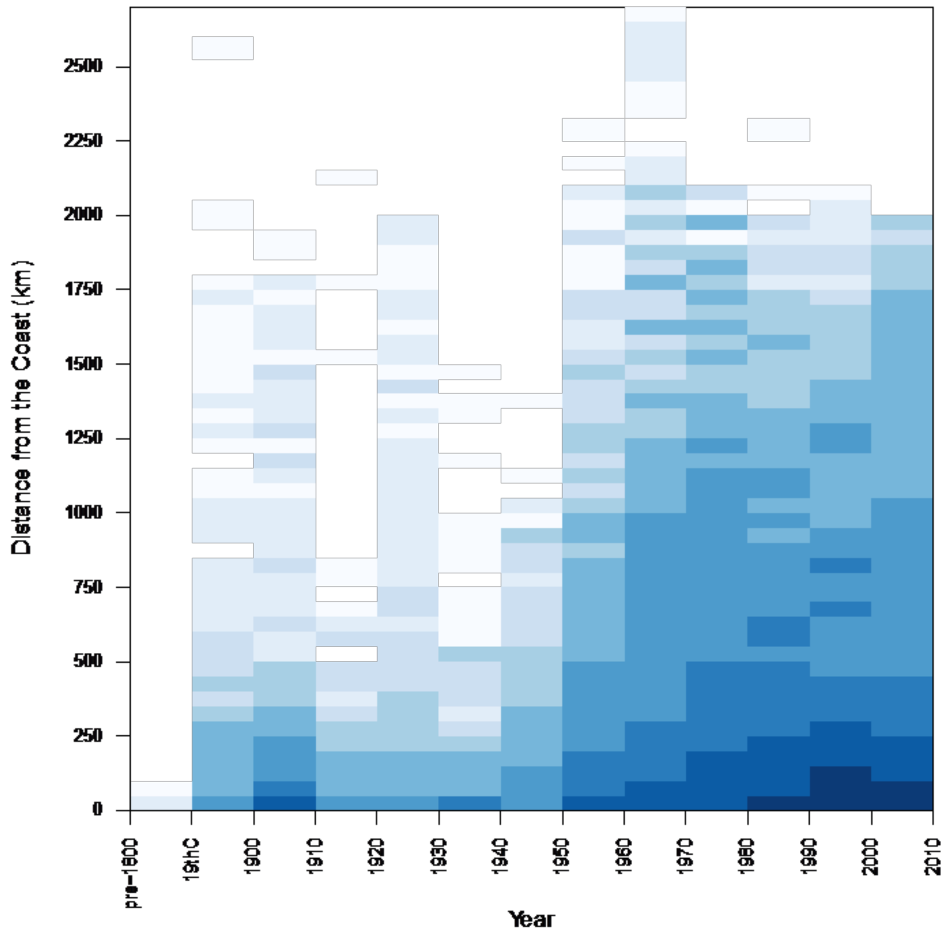
1,000-3,000m peaked in the 1990s (*c.* 78,000 records), down to *c.* 37,000 records in 2000s. The peaks in the 1970s correspond with the origins of quantitative deep-sea ecology (Sanders and Hessler 1969) and the discovery of hydrothermal vent communities (Spiess et al. 1980). Recent drop-offs may be due to the time lag between sampling events and transfer of data to OBIS.

Figure 5.37. The number of species distribution records per decade in OBIS per latitude and longitude.



Understanding where species occur is a necessary first step towards identifying areas of *high* richness, endemicity, or threat, and is thus essential for effective conservation planning. A complete map of species richness could be achieved in theory by globally comprehensive sampling until no new species are found in any region. Given the large shortfall in both taxonomic descriptions and spatial sampling outlined above, this is not practical for all groups in the ocean, although existing data have allowed global analyses of certain taxonomic or functional groups (for example: Roberts et al. 2002, Tittensor et al. 2010). For larger sets of species, species richness estimators can be used to estimate the total number of species across a spatial grid. For instance, the Chao2 index uses the frequency of rarely observed species (those occurring either once or twice in a sampling unit such as a spatial grid cell) to estimate the *likely* number of undetected species, and thus to extrapolate from samples to estimates of total species richness (Gotelli and Colwell, 2011; Chao et al. 2009). Figure 5.40 maps the Chao2 estimate of species richness globally, together with estimates of the completeness of OBIS coverage (number of species observed in OBIS divided by Chao2 estimated species richness). Some areas in Southeast Asia have *very high* estimates of species richness. However, overall estimates still appear to be strongly influenced by sampling intensity (compare Figure 5.40 with Figure 5.32), with higher estimated richness in the (well sampled) North Sea than in many parts of the (poorly sampled) tropics.

Figure 5.38. The number of species distribution records per decade in OBIS as a factor of distance away from the nearest land.



To address to some extent the different levels of taxonomic completeness of surveys in different parts of the world, Figure 5.40 also provides maps for fish only. Surveys aiming to sample the entire fish community are not uncommon, and together fish represent 50 per cent of all records in OBIS.

The completeness maps provide an overview of the current status of knowledge. For 56 per cent of the grid cells no reliable Chao2 estimate (nor completeness score) could be calculated because (i) the number of unique species in that area was higher than 50 per cent or (ii) the confidence intervals were so high that the estimate would be unreliable. Only 3 per cent of those areas for which Chao2 could be calculated (for example: 1.5 per cent of all marine regions) have a completeness score >80 per cent, suggesting that many species remain to be sampled in most parts of the world's ocean. Completeness scores were somewhat higher for fish, but estimates of total richness were largely restricted to coastal areas in this case. Even regions like Europe with high sampling intensity still have many areas with over 30 per cent undiscovered or unreported species. Clearly the higher sampling effort in those areas in the Southern Hemisphere noted in 2.1, such as the Patagonian Shelf and the part of the Southern Ocean south of Australia, has resulted in relatively high completeness scores.

Other biodiversity indices attempt to correct for sampling bias in other ways. Figure 5.41 maps global diversity patterns from OBIS data based on three alternatives. The Hulbert index (or ES50) calculates the expected number of species in a random selection of 50 records (Figure 5.41a). Hill numbers (Hill 1973) account for species' relative abundance (here, number of records in OBIS). Hill1 can be roughly interpreted as the number of species with 'typical' abundances (Figure 5.7.8b); Hill2 (Figure 5.7.8c), which discounts rare species, can be interpreted as the equivalent

Figure 5.39. Three plots showing the number of species distribution records for depths of ‹200m, 200-1000m, and ›1000m in OBIS. The colour scale is re-set for each plot, so that dark blue means many more records in the ‹200m plot than in the ›1000m plot. The depth resolution changes too (10m -› 50m -› 500m).

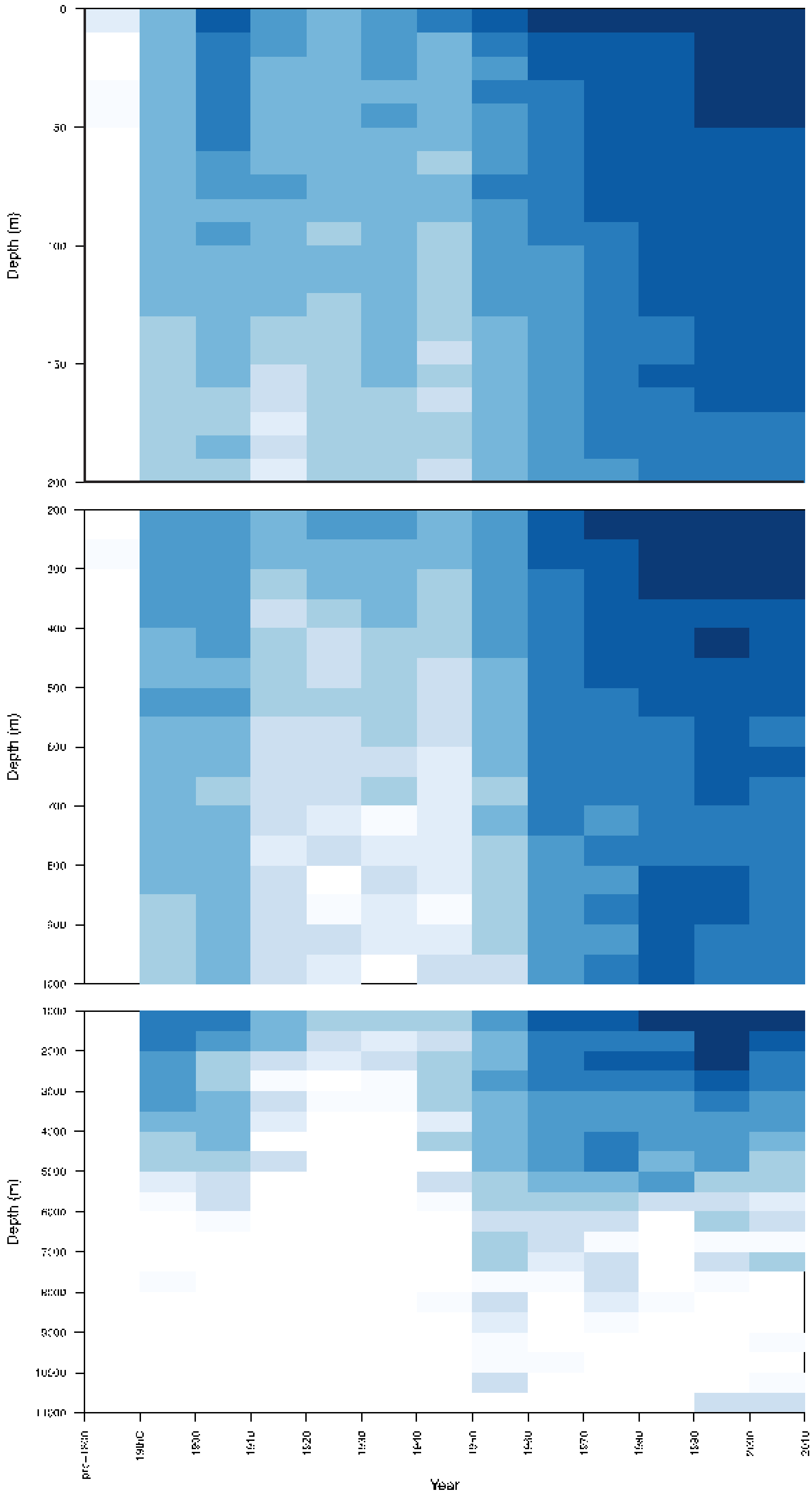


Figure 5.40. Global map showing the total species richness estimates and completeness scores per hexagonal grid cell of c. 200,000 km² based on the unbiased non-parametric Chao2 index using data from OBIS. (a-b) includes all biota, (c-d) is restricted to fish data from OBIS.

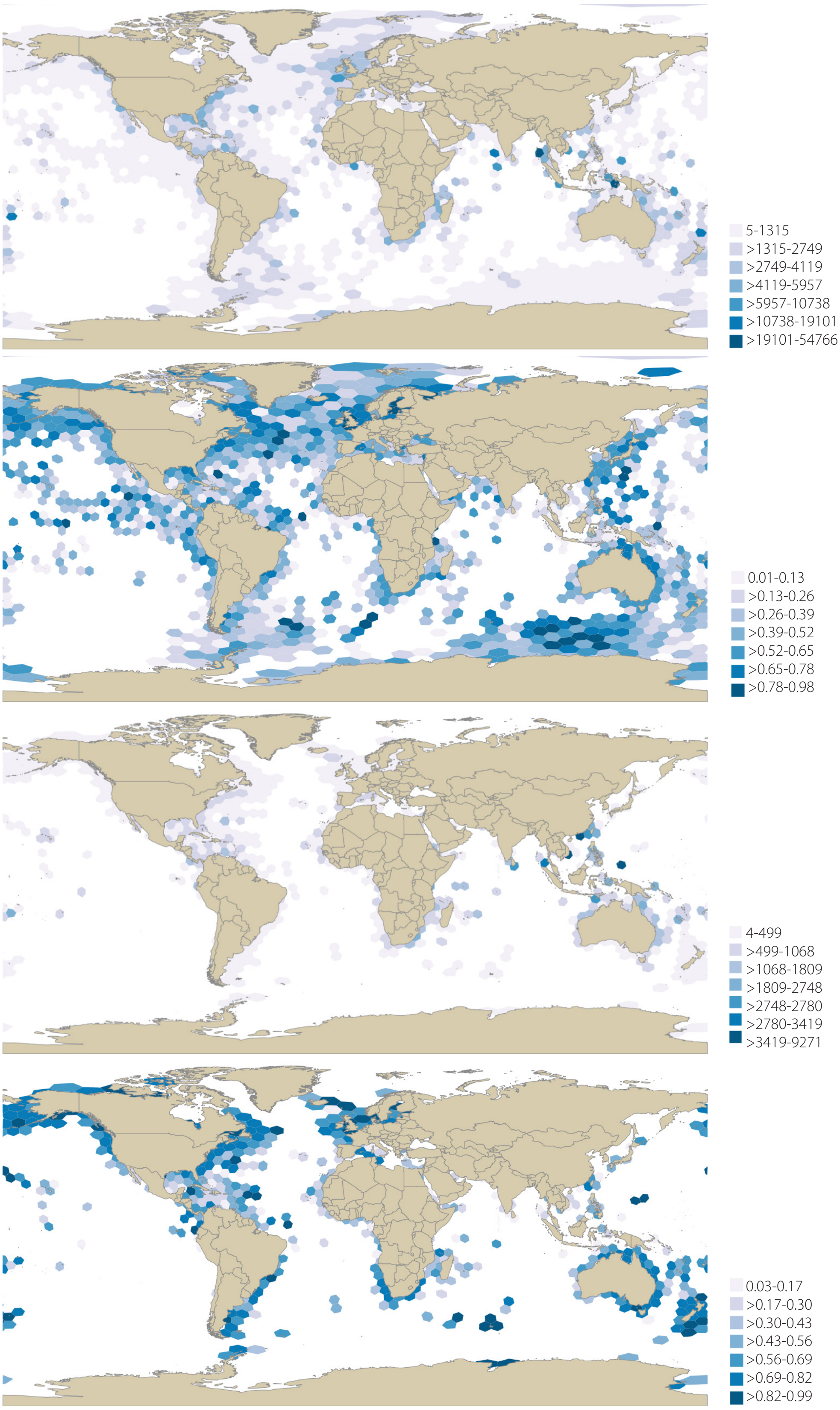
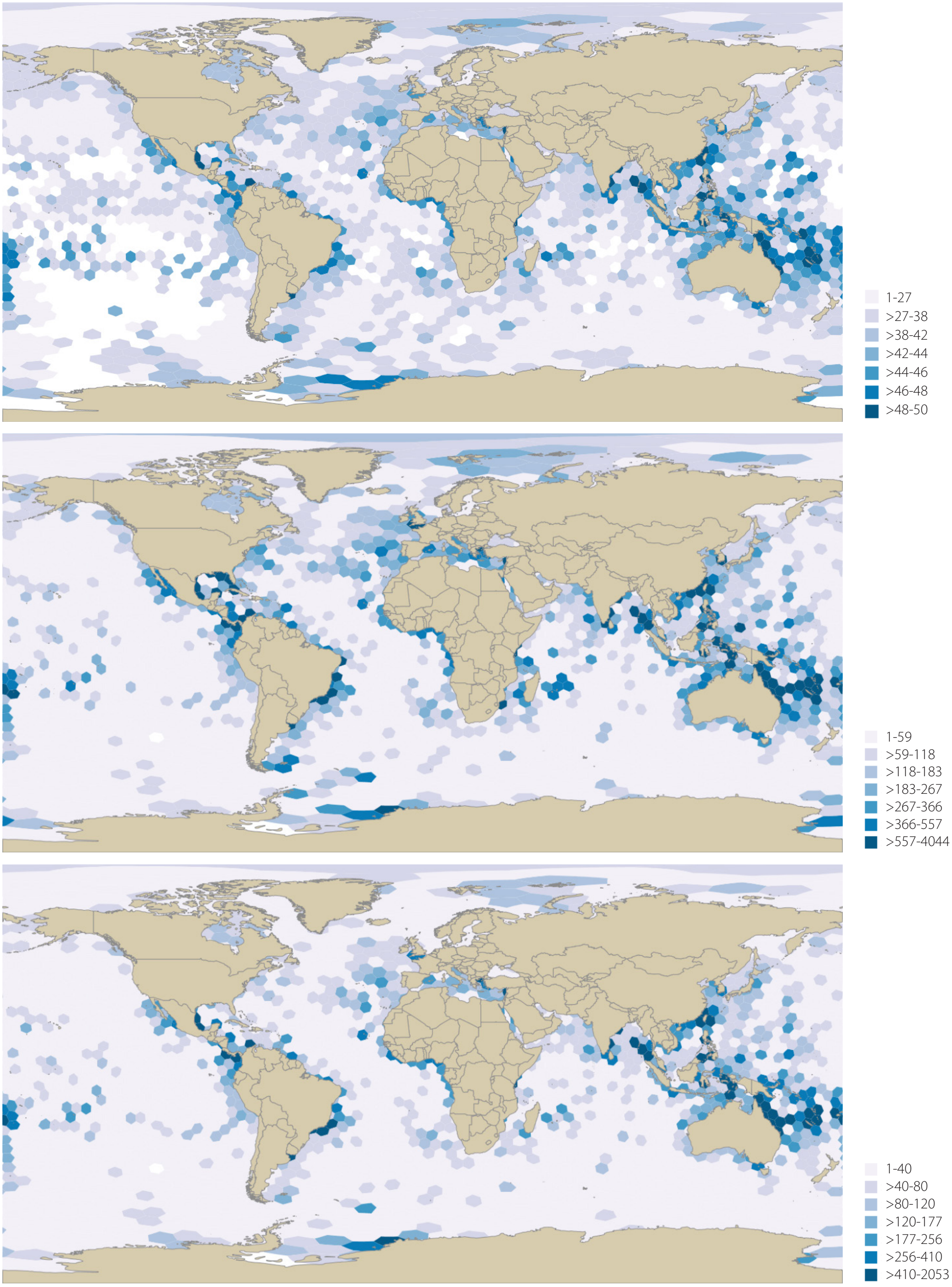


Figure 5.41. Global map showing biodiversity richness indices based on Hulbert index (a), Hill1 (b) and Hill2 (c) per hexagonal grid cell of c. 200,000 km².



to the number of more dominant species and so is less sensitive to sample size than Hill1. Each of these indices has its own issues (Gotelli and Colwell, 2001), especially when applied to such a large and heterogeneous dataset as OBIS; yet there is general agreement that Southeast Asia, the Southwest Pacific, the Gulf of Mexico and the Caribbean Sea are rich in biodiversity. Together, indices like Chao2, ES50, and Hill numbers can help to identify regions that are especially rich or especially poorly sampled, helping to set priorities for future exploration of the ocean.

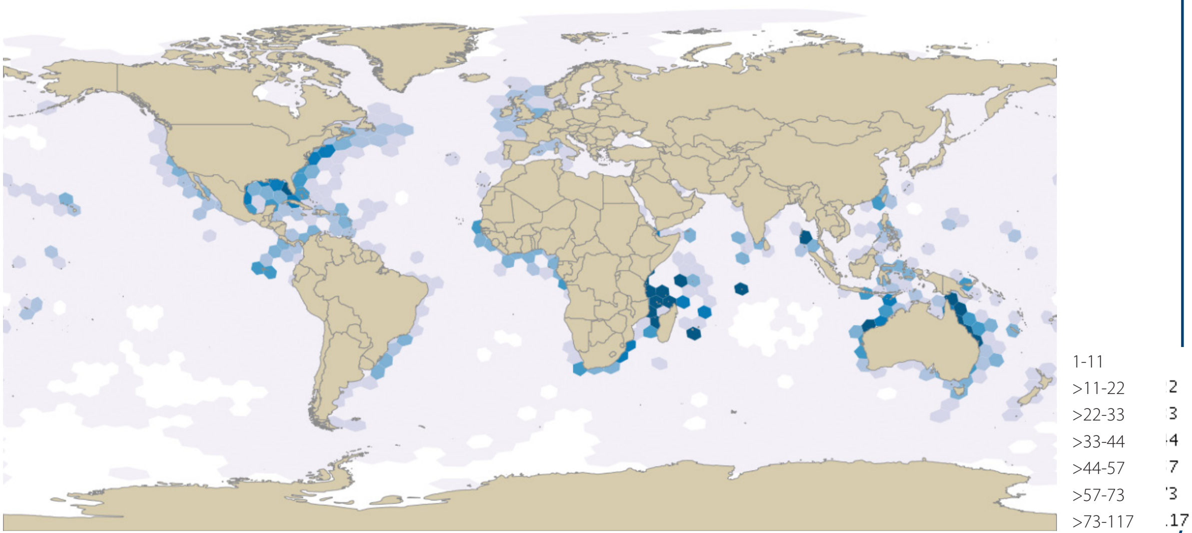
Threats to biodiversity

A recent comprehensive inventory of threats across 24 key global ocean areas was provided by the Census of Marine Life (PLoS One, 2010). Briefly, overfishing, habitat loss, and pollution are the greatest threats to biodiversity in all regions, followed by invasive species and impacts of climate change. Establishing biodiversity baselines requires that recent declines and extinctions of marine species due to these pressures are quantified.

Only 4 per cent of described marine species (9,554 out of 230,000) have been assessed by the IUCN, of which 2,730 (29 per cent) are rated as Data Deficient (DD), too poorly known to assign to an IUCN category. Of the remaining 6,824 species, 1,194 (17 per cent) are considered to be threatened with extinction (IUCN categories Vulnerable VU, Endangered EN or Critically Endangered CR) and 20 are extinct. For the best-known taxonomic groups, rates of extinction risk across assessed species average 20-25 per cent (Webb and Mindel, 2015).

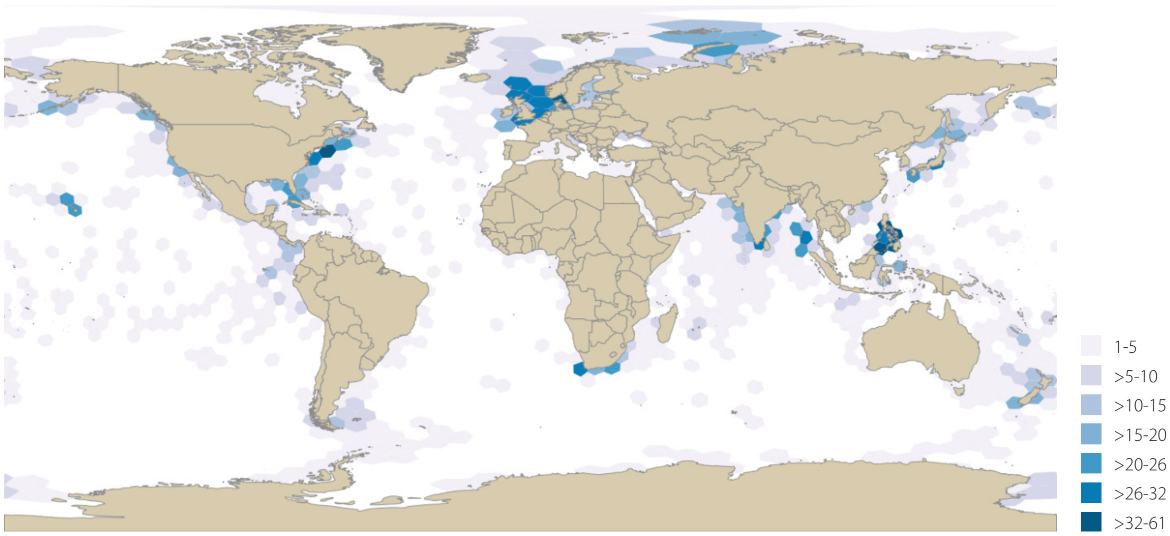
Areas of greatest importance to species known to be threatened (IUCN categories VU, EN, and CR) include the Caribbean and Atlantic Coast of the USA, waters between Eastern Africa and Madagascar, and the Indo-Pacific (Figure 5.42). However, given that DD species often have characteristics typical of threatened species (Pimm et al. 2014, Dulvy et al. 2014) and may occur in different regions from species known to be threatened (Pimm et al. 2014), true rates of threat in marine species may be substantially higher, and spatially more distributed, than current estimates suggest.

Figure 5.42. Global map showing the number of threatened species per hexagonal grid cell of c. 200,000 km² following the IUCN Red List Species categories EN, CR and VU based on species distribution records from OBIS.



OBIS allows us to identify some priority species by tracking occurrences through time. For instance, 472 species have >10 records in OBIS but have not been recorded at all in the last 50 years. These pseudo-extinctions have occurred notably in the Baltic and the equatorial coast of Western Africa (Figure 5.43), and are worthy of further investigation.

Figure 5.43. Global map showing the number of "pseudo-extinct" species per hexagonal grid cell of c. 200,000 km^2, i.e. those with <10 records in OBIS but not observed anymore in the past 50 years.



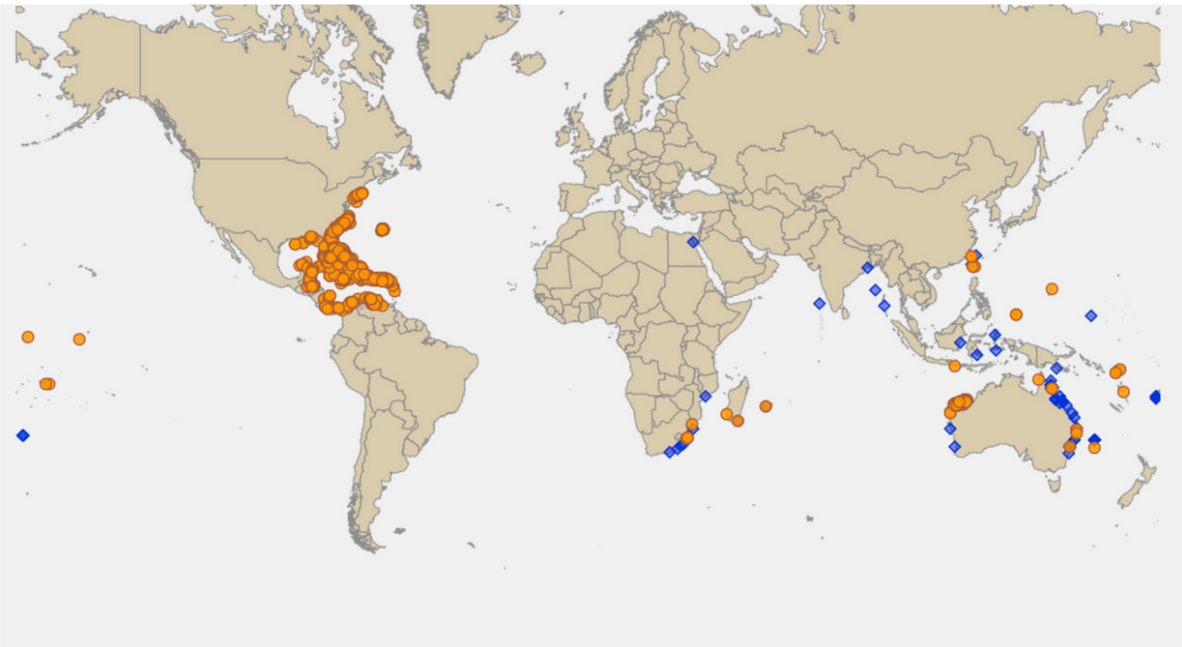
Non-native species are an increasing threat to marine environments and their biodiversity (Carlton, 2000; Rilov and Crooks, 2009). Invasions encompass both natural expansion of a species' geographic range, and direct introduction by humans. Regions have on average of 122 aliens, although some regions have many more: >600 (c. 4 per cent) of all Mediterranean species originated in another ocean area, and high numbers of aliens are also reported for Atlantic Europe and the Baltic Sea, New Zealand and Australia. Molluscs, crustaceans, and fish are the most common alien species (Costello et al. 2010). The Invasive Species Compendium (http://www.cabi.org/isc) lists the alga *Caulerpa taxifolia* and several invertebrates (for example: green crab *Carcinus maenas*, sea walnut *Mnemiopsis leidyi*, veined Rapa whelk *Rapana venosa*) as particularly significant invasive species with impacts including decreased local biodiversity and collapsed fisheries.

Differentiating native and introduced species requires baseline taxonomic and biogeographic knowledge. OBIS data provides time series of observation records of species in different geographical regions. A good example application traces the spread of the lionfish (*Pterois volitans*) in the Caribbean since its first report in 1985 (Figure 5.44) (Schofield, 2009). This species may eventually cause significant reduction in local biodiversity and abundance due to the fact that it is a voracious top predator from an early stage, has a *very high* fecundity, and resists environmental changes (Albins and Hixon, 2008; Betancur-R et al. 2011).

5.7.3 Conclusions and Recommendations

The ocean may be home to one million or more species, of which 230,000 have been described by science. The age of discovery continues, with the rate of description of new marine species higher than ever, suggesting that most will be discovered by the end of this century. It is timely then, to summarize what is currently known about the taxonomic, biogeographic, and conservation status of marine species. This study aimed to provide such a baseline, using the 38 million observations of 114,000 marine species contained in the world's largest marine biodiversity database, the OBIS. Knowledge of which species live where is highly variable: some regions are now well known, but there are also vast volumes of the oceans for which we have little or no knowledge. We know most about large, charismatic, and

Figure 5.44. Global map showing the lion fish invasion in the Caribbean Sea since 1985, based on distribution records in OBIS (orange are all species distribution records after 1985).



commercially important taxonomic groups, but most species are small and rare (scarce) or endemic (confined to small geographical areas), making them hard to identify and difficult to observe. This is reflected by the fact that the average species has just five observations in OBIS, with at least 25 per cent of species represented in the database by only a single record. On the conservative assumption that half of the remaining described marine species, not currently recorded in OBIS, are also only known from their type locality, the global prevalence of 'uniques' (species only ever observed once) could be as high as 62 per cent.

Marine biodiversity monitoring intensified worldwide in the mid-20th century, starting in the Northern Hemisphere, and progressively increasing in the Southern Hemisphere, the Tropics and Polar Regions. Most biodiversity records come from the continental shelf, but through time, sampling has intensified further away from the coast and deeper into the ocean. However, sampling remains low in very remote places (>2,000 km from land) and at >5,000m depth, and 98.7 per cent of the ocean volume (all zones with bottom depth deeper than 1,000m) can be regarded as severely under-sampled. As a consequence, there is not enough data to make a reliable estimate of species richness for more than half the ocean. For those areas with sufficient data, multiple biodiversity indices all show that South-East Asia, the South-West Pacific, the Gulf of Mexico and the Caribbean Sea are notably rich in biodiversity. This agreement is encouraging given the significant gaps and biases in OBIS data.

Increasing threats to biodiversity are causing many local population extirpations, but so far the IUCN has only documented 20 global marine species extinctions. However, around 20 per cent of marine species that have been formally assessed by the IUCN are considered to be currently threatened with extinction. Many of these threatened species occur in the most biodiversity rich and poorly monitored regions. In addition, 28 per cent of assessed species have been classified as Data Deficient (of which many may be at risk), and 96 per cent of marine species have not been assessed at all. Taking this into account, rates of extinction risk in the sea appear comparable with those on land. This is supported by the large number of species (472), which have been observed at least 10 times, but never in the last 50 years. Whether any of these are extinct remains to be established, but the picture of scarcity, decline, and risk is clear.

Changes in community composition have also been driven by increased rates of species invasions, a trend *likely* to be exacerbated as species shift their distributions in response to the changing climate. Such disruptions can have severe impacts and may alter the carrying capacity of the local ecosystem, sometimes resulting in irreversible change. Using global-scale databases to understand biodiversity baselines can help in efforts to rapidly detect change and to distinguish invasions from natural variations.

Monitoring ocean biodiversity can be expensive and risky, and requires highly skilled people. Very few marine regions or taxonomic groups have benefitted from long-term monitoring programs, hence stocktaking remains far from complete. Publishing existing biodiversity data into open data repositories, such as OBIS, provides the most cost-effective means to address this shortfall. It is hoped that momentum in this direction can be maintained, alongside new efforts to discover and document the diversity and distribution of life in the ocean. In addition, it is recommended that focused efforts are used to monitor the abundance of key species at all trophic levels, potentially as part of a global initiative such as the GOOS.

5.7.4 Notes on Methods

The biggest international initiative ever to document what lived, lives and will live in the ocean was the decade-long Census of Marine Life (2000-2010), which united 2,700 scientists from 80 nations. The Census developed a central data platform, the Ocean Biogeographic Information System (OBIS), providing an integrated map of life. This now operates and continues to grow under the auspices of UNESCO's Intergovernmental Oceanographic Commission, as a project of the International Oceanographic Data and Information Exchange (IODE) program. As of December 2014 OBIS holds 38 million observations from 1,550 datasets provided by 500 institutions in 56 countries, with new records being added all the time. The data is freely accessible online (www.iobis.org) and is used around the world for research, global and regional assessments, marine spatial planning and conservation policies. Google Scholar returns >1,000 publications that have cited OBIS (October 2014), and still grows at a rate of 7 papers per month. As the world's largest database on marine biodiversity, OBIS provides the best available source of information for this baseline chapter.

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Chapter 6
Fisheries

Chapter 6.1 How Sustainable are open Ocean Fisheries?

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Fisheries

6.1 How sustainable are open ocean fisheries?

6.1.1 Summary and Key Messages

Following a brief definition of the open ocean (in terms of geomorphology, physical oceanography and marine biology), a description is provided of the system of 200 mile Exclusive Economic Zones (EEZs) produced by the UN Law of the Sea Convention (UNCLOS), which defines the open ocean legally as the ocean beyond national jurisdiction. The functioning of open ocean ecosystems, which represent 60 per cent of the world's ocean, is then discussed with emphasis on the role of tuna and other large pelagic fishes, whose catches have now probably peaked. The main factor currently affecting the sustainability of these fisheries is their governance, which is largely entrusted to Regional Fisheries Management Organizations (RFMOs). The difficult task of these organizations, however, is hampered by their lacking the authority necessary to restrict the efforts of countries exploiting offshore pelagic fish. In the medium to long-term, the multiple effect of CO_2 emissions will increasingly impact the pelagic ecosystem of the open ocean, and undermine the sustainability of the fisheries based thereon.

Key messages

- The open ocean is home to large but thinly spread populations of large pelagic fishes which gather and concentrate even more thinly spread, and otherwise inaccessible, prey resources;
- These prey gathering and concentration processes rely on fine-tuned evolutionary adaptations which can – and *likely* will – be easily disrupted as primary production and other key ecosystem processes are rapidly modified by ocean warming, increased stratification and lowered pH; and
- To mitigate ecological disruptions, catch quotas should be as low as possible, and fished areas interspersed by as many unfished marine reserves as possible.

6.1.2 Main Findings, Discussion and Conclusions

Since the establishment of the UN Law of the Sea Convention (UNCLOS) in the early 1980s, the open ocean has a *legal* definition (Crother and Nelson 2006), which now largely overrides earlier, oceanographic or biological definitions. UNCLOS defines the open ocean as all the waters beyond national jurisdiction, beyond the 200 mile limit of the Exclusive Economic Zones (EEZs) along the coast of maritime countries (Figure 6.1) (See Glossary Box 1) Thus defined, the open ocean comprises about 60 per cent of the world's ocean. It can be subdivided by the large 'statistical areas' used by the Food and Agriculture Organization of the United Nations (FAO) to report fisheries catch data (Table 6.1).

Before the discussion on the sustainability of the open ocean fisheries, it is appropriate to briefly review, in part based on Pauly (1995a), the ecological basis of fish production in the open ocean and the functioning of open ocean ecosystems. It is the continued functioning of the latter which ultimately determines the sustainability of ocean fisheries (Longhurst 2007).

The ecological zones of the oceans can be defined according to different sets of criteria. One of the most widely cited zonation scheme was proposed by Longhurst (1998, 2007), which is mainly based on the mixing regime dominant in various 'provinces', of which the WARM province is one. Unfortunately, these provinces do not overlap with the 19

Figure 6.1. The extent and delimitation of countries' Exclusive Economic Zones (EEZs), as claimed by individual countries, or as defined by the Sea Around Us based on the fundamental principles outlined in UNCLOS (200 nautical miles or mid-line rules), and the FAO statistical areas by which global catch statistics are reported. This map also identifies high sea areas as defined here (see also Table 1).

Table 6.1 Open Ocean areas by FAO statistical areas

Area defined here	FAO Statistical Areas	Surface area (10^6 km^2)
1) Arctic	18	9
2) North Atlantic	21 & 27	21
3) Central Atlantic	31 & 34	29
4) South Atlantic	41& 47	36
5) Indian Ocean	51 & 57	61
6) North Pacific	61 & 67	29
7) Central Pacific	71 & 77	82
8) South Pacific	81 & 87	59
9) Antarctic	48, 58 & 88	36
10) Mediterranean	37	3
Total	--	364

FAO Areas in Table 6.1 and Figure 6.1. Another more basic classification scheme would consist of differentiating the entire ocean into an enormous body of cold water (-2° to 20°C), on top of which floats a thin but wide lens of warmer water which is deepest in the tropics.

Cold, deeper water is generally rich in nutrients – mainly nitrates, silicates and phosphates (Dugdale and Wilkinson 1998; Fauzi et al. 1993; Montagna et al. 2006) – but does not receive enough sunlight to support all the primary production they otherwise could: the nutrients are too deep for light to reach them, or in high latitudes they receive light only during a short summer season (Levinsen and Nielsen 2002). Conversely, warm waters receive sufficient light, but often lack nutrients – hence the desert-like nature of the central gyres of the ocean (Jena et al. 2013).

Massive primary production occurs wherever nutrients and light are brought together by mixing processes. Typically this is in the uppermost 10 to 100 m of the ocean. In high-latitude, colder-water areas, much of the primary productivity occurs during the well-lit summer period, when storms de-stratify the upper layers of the sea, thus regenerating the nutrients built up during the winter storms, but depleted by the first massive populations of phytoplankton, the spring bloom (Siegel et al. 2002)

The basis of open ocean production

Stratification and superficial nutrient depletion are far more of a problem in low-latitude areas, where the warm surface waters are much lighter than the waters in deeper layers and are thus harder to de-stratify. There, massive production occurs only when a mechanism stronger than the occasional storm breaks the thermocline and pumps nutrient-rich, deep water to the surface (Stigebrandt and Djurfeldt 1996). Major upwellings occur where regular, equatorward winds exert stress on the coastal waters, which are deflected offshore by the Coriolis force and replaced by upwelled water (Bakun 1990). In the open ocean, upwellings are generally confined to the edges of large eddies, for example: in the North Atlantic along the Gulf Stream, and along the Equator where the winds and the Coriolis force create divergence zones where water bodies are pushed from the equatorial zone, and replaced by upwelled water (Dugdale and Wilkinson 1998). Note that the slackening of the global winds transporting heat from the tropics to the poles predicted under most climate change scenarios implies a stronger stratification of the open ocean (Capatondi et al. 2012), and hence a decline of its biological production (for example: Polovina et al. 2011).

The central area of the warm-water lens alluded to earlier harbours another type of system in which light and nutrients are combined to yield extremely high rates of organic production: coral reefs, which are specialized in trapping nutrients from the surrounding waters (Crossland et al. 1991). Successful trapping of nutrients leads to more coral growth, and the deposition of calcareous skeletons that builds structures capable of trapping even more nutrients (Muscatine et al. 1977). This feedback loop enables some coral reefs to standout, cathedral-like, in otherwise barren expanses of highly stratified tropical seas.

The high seas in the Atlantic, Indian and Pacific Oceans also harbour thousands of seamounts (Kitchingman et al. 2007). A number of these seamounts have been visited by large industrial bottom trawlers targeting accumulated biomass of pelagic armourhead (*Pseudopentaceros wheeleri*), alfonsin (*Beryx splendens*), orange roughy (*Hoplostethus atlanticus*) and other similarly long-lived, but relatively small fishes feeding on zooplankton and micronekton concentrated around seamounts (Pitcher et al. 2010; Drazen et al. 2011). These limited fisheries, usually conducted as pulse-fishing operations, are never sustainable, and not further dealt with here.

Where warm, nutrient-poor waters seal off a deep basin, as in the central gyres of the oceans, primary and secondary production remain low, in spite of intricate adaptations by numerous species of phyto- and zooplankton to these impoverished habitats (Gonzalez et al. 2002; Montoya et al. 2004). Foremost among these adaptations are those that enable nutrients to be recycled quickly and economically within the euphotic layer (Eppley et al. 1973; Liu et al. 1997). This reduces the leakage of detritus from the surface to the deeper layers, and ultimately to the sea floor, resulting in lower biomasses of benthic, or bottom-living, organisms below the central gyres (Ekman 1967).

Migration as the key to living in the open ocean

The key adaptation of central gyre organisms, but one suitable only to fast-swimming animals, is to range over a large area and to feed opportunistically wherever food patches occur (Bushnell and Holland 1997; Bertrand et al. 2002). This defines the niche of tropical tuna, of dolphinfish (*Coryphaena*) and other large fast-growing pelagic fish such as yellowfin (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*), whose density, when averaged over their entire area of distribution, is always small, but which can have a large absolute biomass because of their capacity to tap into the production of entire ocean basins (Sibert et al. 2006).

In the open ocean, it is the zooplankton that serves as key link to the fish (See Chapter 5.3) (Figure 6.2). This is because most fish feed on zooplankton, either when their larvae graduate from the less challenging capture of single-cell organisms (Nakagawa et al. 2007) or as adults specialized in filtering or particulate feeding on zooplankton

(Bertand et al. 2002). Here, however, the sardines and their relatives, the common zooplanktivores in coastal areas are replaced by lanternfish (Family Myctophidae) and their relatives (Tsarin 1997).

Another link to larger, higher trophic level fish is the micronekton, composed on very small fishes, crustaceans, cephalopods and jellyfish (Brodeur and Yamamura 2005; Polovina et al. 2014.) whose ability to perform vertical migrations (Maynard et al. 1975) distinguishes them from zooplankton, for example: a community of drifting organisms.

Zooplankton and micronekton organisms have not evolved individual defence mechanisms against larger fish. Rather, populations of weak and small organisms can maintain themselves through the very patterns of occurrence/non-occurrence of their consumers, and because large consumers and predators, when feeding on patches, cannot afford the energetic costs of "finishing them off" down to the last individuals, or to return to freshly grazed areas (Bakun 2011). Indeed, life can be precarious for large predators and consumers, which generally will not find enough food in any small area to maintain a viable population. All large predatory fish must consequently undertake feeding migrations of various lengths (Harden Jones 1968).

The best migrators of all are the warm-blooded tropical tunas, for example: yellowfin and skipjack, whose entire lives, once they have left the food patch in which they hatched, consist of nothing but high-speed searches from one food patch to the next, starving if they fail to reach, in time, a new patch of life-sustaining, high-density food (Smith 1985). In such cases, and this will have involved many older adults in earlier times, when fishing was less important, large pelagic fishes became part of the plankton fall that feed deep seafloor communities. This leakage from pelagic food webs is utilized by such organisms as large amphipods and macrourid fishes (grenadiers/rattails) specialized on nekton falls (Sainte-Marie 1992; Pearcy and Ambler 1974; Smith 1985).

Comparative studies across a wide range of taxonomic groups and ecosystems have confirmed that the ratio of food consumed to flesh produced is only about ten per cent for *all* consumers, at all trophic levels (for example: Christensen and Pauly 1995). This implies another form of leakage: the energetic loss of 90 per cent of the biomass consumed at each trophic level within oceanic food webs.

Thus, one obvious temptation is to suggest that the fisheries can increase their yield from the open ocean – about two per cent of primary production (Pauly and Christensen 1995) – by humans substituting themselves for the upper elements of the trophic pyramids leading to the presently observed yields. However, the major prey of tuna and other large pelagic fishes – notably mesopelagic fishes – is too dilute to be harvested economically, even if their abundance turns out to be higher than previously assessed (Irigoien et al. 2014).

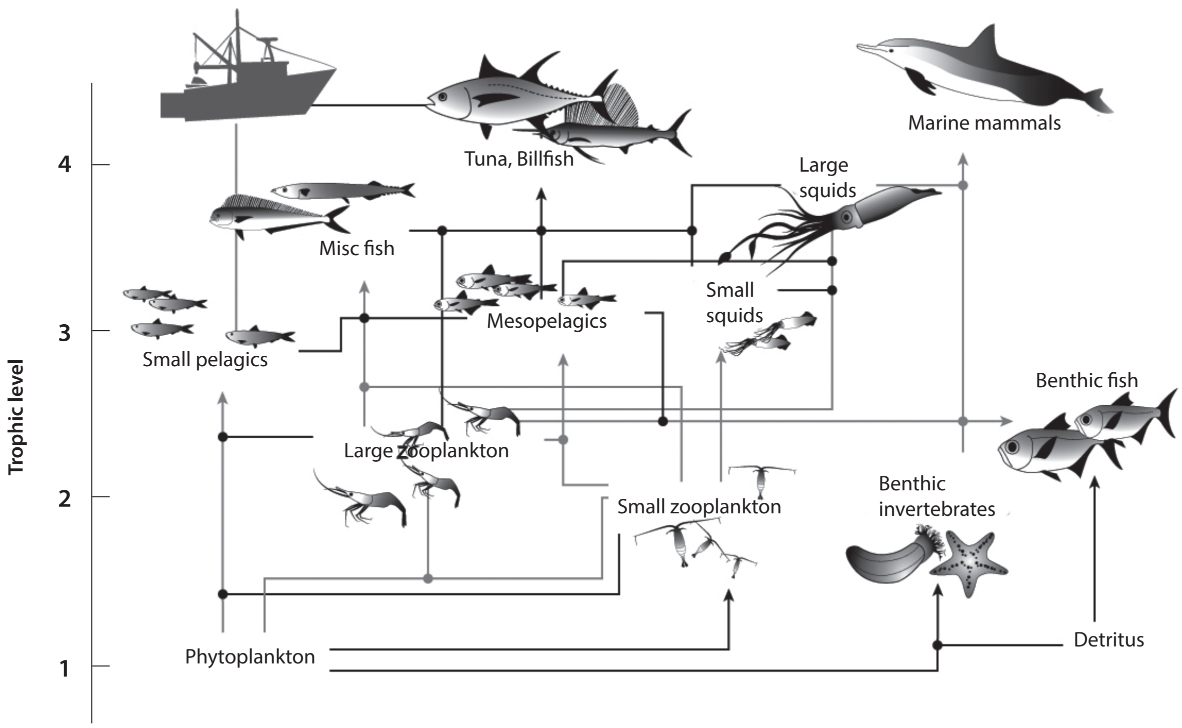
On the other hand, 'fishing down the marine food web' is occurring within the upper trophic level groups in Figure 6.2, for example: catches of large tunas, billfishes and sharks have decreased while the catches of lower trophic-level fishes including mahi mahi, pomfrets and other smaller pelagics have increased (for example: Polovina and Woodworth-Jefcoats 2013).

Within-year variability in open ocean ecosystems

The smallest physical features inducing ocean variability are minute turbulent vortices, lasting perhaps a few seconds, used by single-celled algae to break the 'skin' of nutrient-free water surrounding them and by zooplankton organisms to transport food particles within reach of their grasping appendages (Rothschild et al. 1989). These vortices, occurring at different scales, play a crucial role at very small scales connecting food aggregates and fish larvae. They also illustrate the fractal nature of the marine realm, as do eddies and fronts (Belkin et al. 2009) at larger scales.

The next most important high-frequency scale is the 24-hour rhythm of day and night, where the daytime accumulation of photosynthesis products, and the net production of oxygen (O_2) alternate with the night time net respiration and excretion of carbon dioxide (CO_2), with the balance over a 24-hour cycle being usually positive, so that overall about half a trillion tonnes (wet weight) of phytoplankton biomass are synthesized every year (Longhurst 2007).

Figure 6.2. Schematic representation of a generic pelagic food web (adapted from Figure 12 in Pauly and Christensen 1993). The 'Large zooplankton', 'Mesopelagics' and 'Small squids' groups jointly define a broad 'Micronekton' group, which also includes jellyfish, while the large fish groups ('Tuna, Billfish' and 'Miscellaneous fish') should be seen as including various pelagic sharks. Note also that the 'Small pelagics' disappear as one moves offshore until they are functionally replaced by 'Mesopelagics' in the open ocean, and that benthic fish and invertebrates are extremely sparse under the oceans' central gyres.



In most fish, feeding usually occurs during daytime, whereas the night provides protection from predators (Helfman 1986), and even time for sleep (for example: in herrings). However, some open ocean taxa groups depart from this intuitive scheme and have turned the succession of days and night into a resource that they actively use (Watanabe et al. 1999). Thus, tropical and subtropical lantern fish and their mesopelagic relatives spend most of the day in cold, deep water, typically 5° to 10°C at 300 to 1000 metres, migrating at dusk to feed in the mixed layer surface (30-100 metres), where the water is warmer (25-30°C) and rich in zooplankton and micronekton organisms that they can see despite limited moon- or starlight. At dawn, they migrate back to their mesopelagic night-time habitat, where the low temperature reduces their metabolic requirements– an adaptation that, along with their exploitation of the surface layers, has made these fishes the most abundant in the world in terms of total biomass (Gjøsaeter and Kawaguchi. 1980; Lam and Pauly 2005; Irigoien et al. 2014). However, because of their low density (few milligrams per m^3), myctophids and other mesopelagics have not yet become the targets of a major fishery.

Between-year variability of open ocean ecosystems

Among the major interannual events affecting marine ecosystems, the El Niño Southern Oscillation (ENSO) events affecting the Pacific Ocean are the most prominent (Gergis and Fowler 2009). ENSO events cause massive intrusion of warm ocean water into coast upwelling systems and, by interrupting that supply of cold, deep, nutrient-rich water, starves these systems of the high throughput of nutrients that they usually experience (Pennington et al. 2006).

El Niño events are part of even larger oceanic and atmospheric processes interlinking entire ocean basins, and causing similar or complementary effects on far-away continents (Diaz et al. 2001).

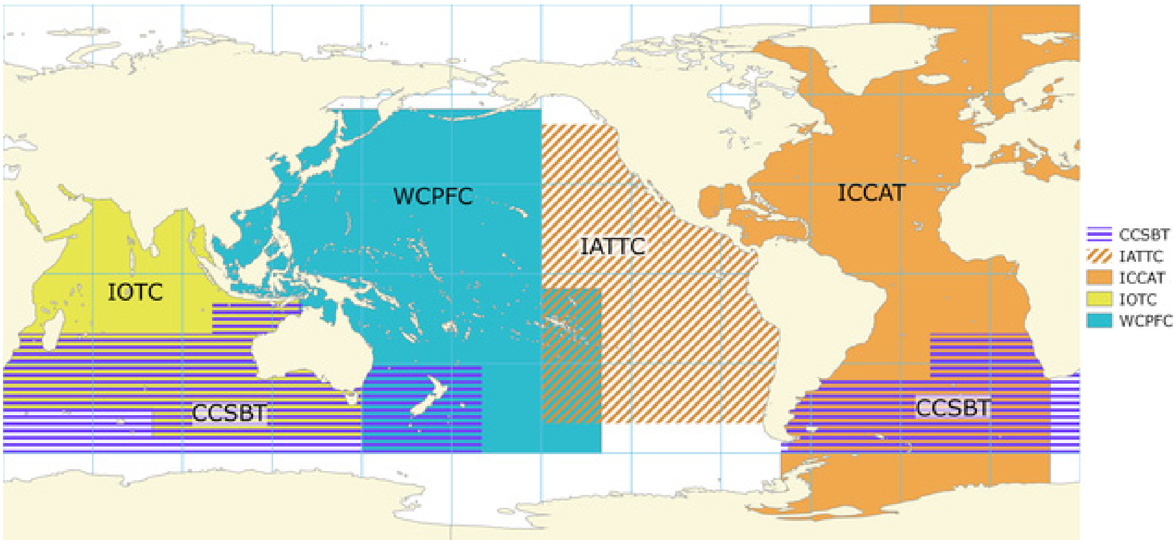
Longer-term cycles spanning decades (from commercial fisheries) or even hundred and even thousands of years have been documented and used for hind- and forecasting climatic changes (see for example: Verdon and Frank 2006), but this issue is not pursued here. Rather, the previous consideration of trophic mechanisms are combined with issues of variability and the biology and dynamics of pelagic fish populations to provide the basis for assessing the sustainability of open ocean fisheries.

Prerequisites for sustainable open ocean fisheries

Emerging in the early 1980s following decades of international negotiations, UNCLOS established that the continental shelves, from which most of the ocean's catch originates, now belong to coastal countries and form the core of their EEZs. Even so, access continues to be largely open, especially along the coastlines of developing countries that are eager to earn whatever little cash fishing access agreements can provide and/or that are unable to patrol their water and to apprehend illegally operating vessels (Belhabib et al. 2014). While some of these issues appear difficult, the legal framework (UNCLOS) exists for their resolution (Juda 1987).

The situation is different for the open ocean, as defined in Figure 6.1, where, anyone can fish. This is because the current system of RFMOs covering the open ocean (see Figure 6.3), cannot legally prevent any country from exploiting the fish resources of the high seas (Cullis-Suzuli and Pauly 2010). One of the rare exceptions is fishing with driftnet, which was banned by the General Assembly of the UN, and thus can be pursued only illegally (Freestone 1995).

Figure 6.3. RFMOs for highly migratory fish stocks (tuna and associated species) in the open ocean



Source: Boundaries provided by the FAO, Fisheries and Aquaculture Department.

The RFMOs attempt to make the best of the resources they are tasked to manage, but they are only capable of doing what their member countries allow them to do, and the results, thus are underwhelming. This particularly applies to the actual state of the stocks that they are responsible for, most of which are currently in worse shape than at the time the RFMO in question was created (Cullis-Suzuki and Pauly 2010).

The 'shifting baseline' phenomenon (Pauly 1995b) easily explains the strange rhetoric surrounding the activities of RFMOs. Thus, in recent years, it has been possible, mainly through the constant pushback from environmental Non-Government Organisations (NGOs), to stabilize the much-reduced biomass of Atlantic bluefin tuna (*Thunnus thynnus*) and even to allow it to rebuild. This was immediately celebrated as a major achievement, and seen as a reason to immediately increase the Total Allowable Catch (TAC) of this fish, even though its biomass continues to be extremely low (Mackenzie et al. 2009; Taylor et al. 2011).

Similarly, in the North Pacific, basin-wide quotas or fishing mortality level caps for bigeye tuna, yellowfin tuna, and striped marlin have been implemented. Meanwhile, in the Hawaiian-based (US) longline fishery, shark finning is prohibited and protected species bycatch is monitored by an observer with caps on the bycatch of turtles. If these caps are reached, the fishery is closed (Polovina et al. 2014). However, many of these measures pertain to a single country, with other actors showing far less concern about the long-term fate of the fisheries' resource base (mainly tuna), not to mention bycatch species, such as leatherback turtle (*Dermochelys coriacea*) (critically endangered through much of its range (http://www.iucnredlist.org/details/6494/0)).

Indeed, the debate about the sustainability of open ocean tuna fisheries is extremely acrimonious, with the tuna industry and scientists working for RFMOs generally stating that the major stocks of tuna (notably yellowfin and skipjack) are in relatively good shape while conceding that some tuna species (for example: bigeye; *Thunnus obesus*) may be overfished (Hampton et al. 2005; Sibert et al. 2006). In contrast much of the NGO community is of the opinion that tuna fisheries are overexploiting their resource base, though their evidence is not usually peer-reviewed and need not be cited here.

It is probably correct that the major stocks of yellowfin and skipjack are doing relatively well (Juan-Jordo et al. 2011). However, to hope that tuna catches, which have been increasing almost linearly from 1950 to the turn of the 21st century, will continue to do so in the next decades is probably unwarranted. Moreover, the loss of species (for example: leatherback turtles, see above, or seabirds), other than those targeted (tuna, billfishes) along with the strong reduction of their biomass (opinion vary as the exact level of this reduction) is changing the fabric of open ocean ecosystems, and hence the long-term sustainability of open ocean fisheries, our last topic.

Long-term sustainability of open ocean pelagic fisheries

It should be unnecessary to couple 'long-term' with 'sustainability', since sustainable operations can be maintained in the long term, by definition (Frazier 1997). Considering such definition, current open ocean fisheries cannot be sustainable. This is because growth, in a finite ocean, is inherently limited. Indeed, the current overall growth of global tuna catches is due exclusively to the Pacific tuna fisheries, as tuna fisheries elsewhere reached a peak in the Atlantic in the early 1990s, while the Indian Ocean tuna fisheries peaked in the early 2000s. Further detail is provided in Chapter 6.3.

This also applies to the increasing effort devoted to extracting these catches (Davidson et al. 2014), whose sophistication also keeps increasing, and now involves fish aggregating devices (FADs) that communicate with satellites (Dagorn et al. 2013).

Moreover, these fisheries will increasingly be impacted by increasing CO_2 emissions, inducing both ocean warming and acidification. The former effect has already begun to shift poleward the distribution of exploited marine fishes (Cheung et al. 2013), a trend predicted to accelerate in the next decades (Cheung et al. 2009, 2010), even if in the Pacific at least, an eastward shift of large pelagics is predicted for the near future (see Chapter 6.4). These distribution shifts can be predicted to have a massive effect on the finely-tuned processes alluded to above by which primary production in channelled up the food web of the open ocean ecosystem (Doney et al. 2009). Jointly with increased stratification (Polovina et al. 2011), these effects can be expected to have deleterious, though hard to quantify, impact on pelagic food webs.

This is the reason why ecosystem-based fisheries management, in the open ocean should consist of establishing large marine reserves where these natural processes can work, and where higher fish biomass could be expected to maintain themselves. Indeed, this approach can be viewed as one of the few avenues left, in addition to conservative catch quotas – for mitigating some of the expected ecological disruptions to open ocean food webs (Polovina et al. 2014).

Some authors (White and Costello 2014; Sumaila et al. 2015) have suggested, moreover, that a complete closure of the open ocean would not only lead, overall, to higher global fisheries catches, but would also lead to improved sustainability of the exploitation of tuna and other large open ocean fish (which would be exploited only when their migrations take them into the EEZs of maritime countries). Also, such closure would lead to a more equitable distribution of open ocean resources between countries, which currently are exploited mostly by a dozen countries with distant-water fleets (Sumaila et al. 2015). This, however, would require a major reform of UNCLOS.

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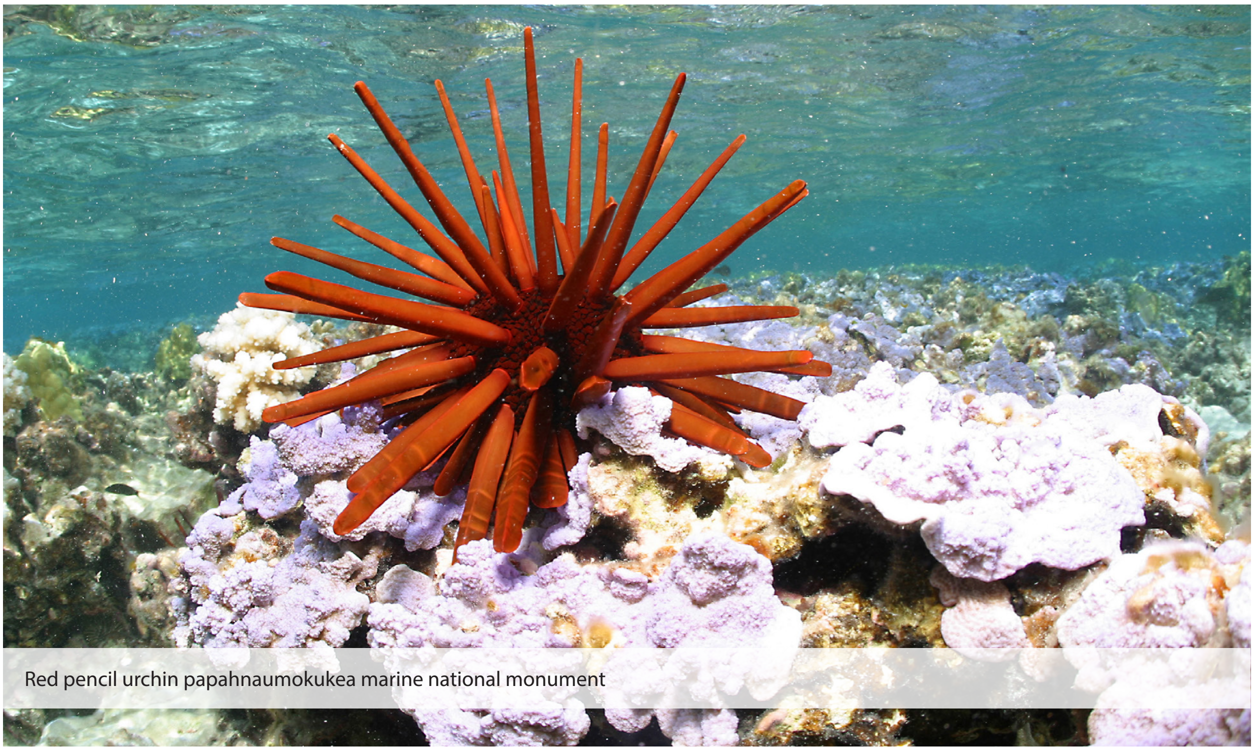

Red pencil urchin papahnaumokukea marine national monument

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Chapter 6.2 Fisheries Indicators for Open Ocean Areas: Catch from Bottom Impacting Gear, Marine Trophic Index, Fishing-In-Balance Index and Demersal Fishing Effort

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6.2 Fisheries Indicators for Open Ocean Areas: Catch from Bottom Impacting Gear, Marine Trophic Index, Fishing-In-Balance Index and Demersal Fishing Effort

6.2.1 Summary and Key Messages

A set of indicators including catch from bottom impacting gear, Marine Trophic Index (MTI), Fishing-in-Balance index (FiB) and demersal fishing effort are used to quantify risks in different regions of the open ocean, for example: areas beyond Exclusive Economic Zones (EEZ). The percentage of global catch from bottom impacting gear to the total global catch in the open ocean reached its peak at 13 per cent in 1955 and then declined to 4.8 per cent in 1963 and fluctuated between 5 per cent and 11 per cent in the following 30 years. The MTI fluctuated between 3.5 and 3.8 in the past 60 years in the open ocean, whereas the mean FiB kept increasing since 1950 and became stable in the recent 10 years. The increasing trend in the FiB represents an expansion of the ecosystem exploited by fisheries due to a geographic expansion of fisheries to new grounds. However, FiB should be interpreted in conjunction with MTI. The total effective effort of demersal catch in the open ocean reached its peak at 25 million kilowatts in 1979 and then declined. The effective demersal effort fluctuated between 1 and 11 kilowatts in the most recent 30 years.

Key messages

- Though the proportion of the global fish landings in the open ocean coming from bottom impacting gear has stabilised in the last 60 years, some regions of the open ocean – in particular the southwestern and northwestern parts of the Atlantic Ocean – have very high proportions of fish landings coming from bottom impacting gear in the past decade;
- The mean Fishing-in-Balance (FiB) index has increased steadily since the 1950s, suggesting both a geographical expansion of the fisheries and, jointly with the trends of Marine Trophic Index (MTI), a decline of the mean trophic level of the catch, (for example: the phenomenon known as 'fishing down' marine food webs), in some areas, notably the Southwest Atlantic Ocean; and
- Substantial increase in the use of bottom trawls in the Antarctic Ocean in the early 1980s led to a sharp peak of global effective effort of demersal catch in this period. However, some regions of the open ocean, for example: the southwestern part of the Atlantic Ocean (FAO 41) shows increasing trends of effective effort and demersal catches since the 1950s.

6.2.2 Main Findings, Discussion and Conclusions

Proper management of the open ocean, here defined as the oceanic areas beyond countries' Exclusive Economic Znes (EEZs), is required as fishing has expanded into this area in the wake of overexploitation of coastal waters, increasing demand for fish driven by increasing world population and higher incomes, provision of government subsidies, and technological advances (Pauly et al. 2002; Swartz et al. 2010). Here, a set of indicators including catch from bottom impacting gear, Marine Trophic Index (MTI), Fishing-in-Balance index (FiB) and demersal fishing effort are used to quantify risks in different regions of the open ocean.

Catch from bottom impacting gear

Bottom impacting gear are overwhelmingly bottom trawls (with some 'pelagic' trawls operating near the sea floor), although dredges are used in some shallow areas, for example: off New England and in the English Channel. The fraction of the spatialized FAO catches derived from these gear were estimated by Watson et al. (2006a, 2006b); in the open ocean, where shallow waters (where dredges could be used) are extremely rare. The catch of bottom impacting gear is essentially the catch of deep-sea trawlers. This is particularly the case in the North Atlantic, where long-lived deep sea fish species are exploited that are extremely hard, if not impossible to fish sustainably (Norse et al. 2012).

The time series catch from bottom impacting gear types in the open ocean is shown in Figure 6.4. The annual trend of the percentages of catch from bottom impacting gear to the total catch in the open ocean is shown in Figure 6.5. This percentage reached its peak at 13 per cent in 1955 and then declined to 4.8 per cent in 1963 and fluctuated between 5 per cent and 11 per cent in the following 30 years. The percentage reached another peak at 13 per cent in 1999 and then declined again. The percentage has fluctuated between 7 per cent and 11 per cent in the recent 5 years.

Figure 6.4. Annual catch from bottom impacting gear in the open ocean from 1950 to 2010.

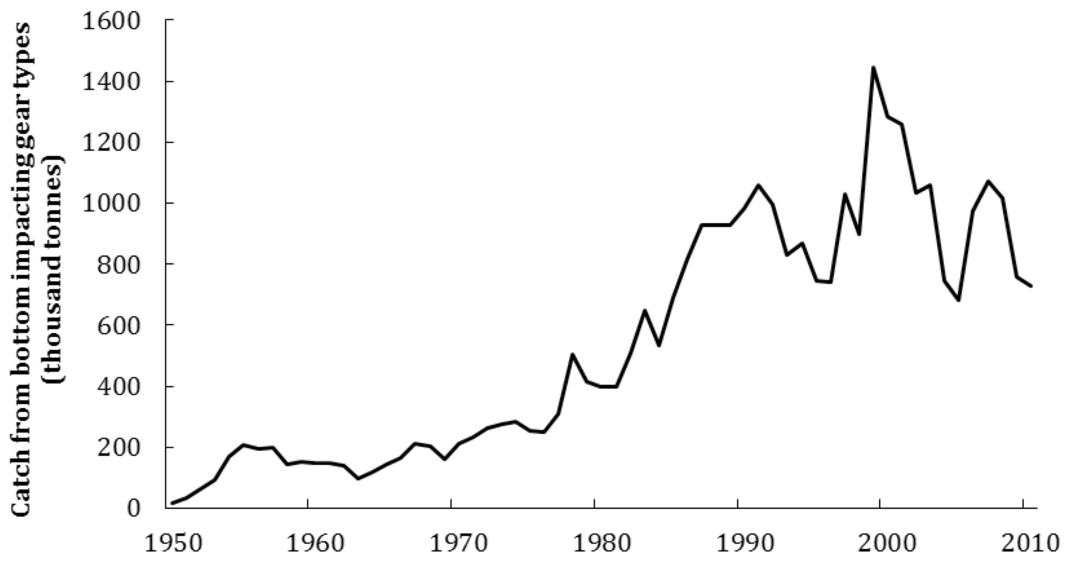
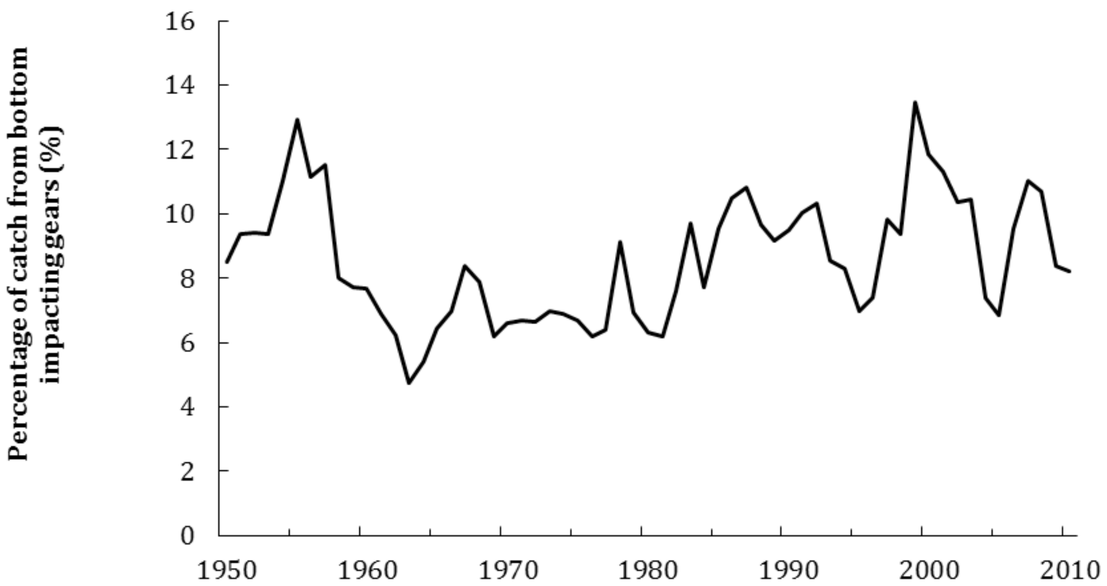
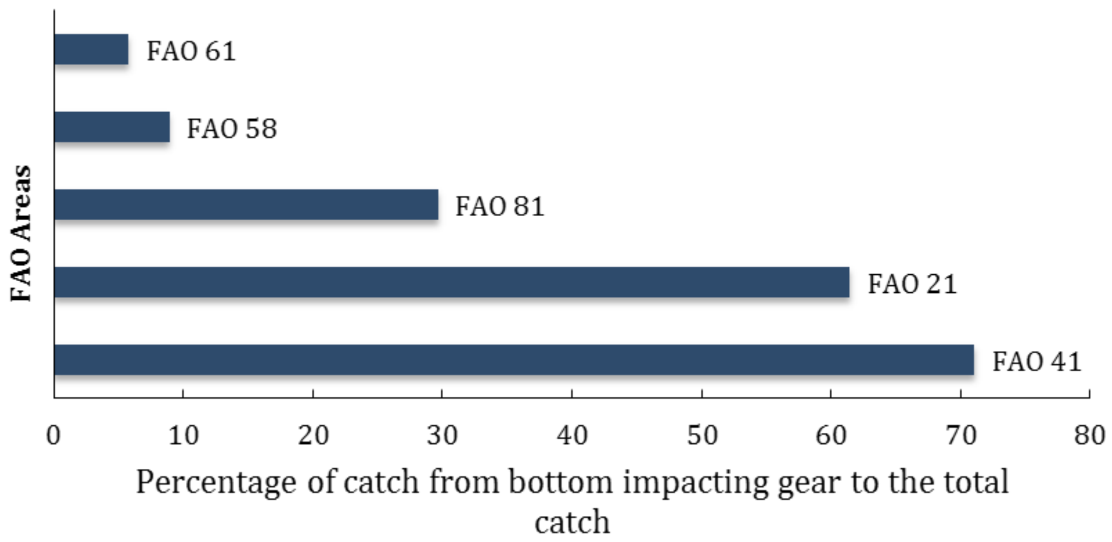


Figure 6.5. Percentage of annual catch from bottom impacting gear to the total catch in open ocean from 1950 to 2010.



The average annual percentage of catch from bottom impacting gears to the total catch in each of the top 5 FAO areas[31] with the highest percentages in the past 10 years (2001 to 2010) is shown in Figure 6.6. The southwestern part of the Atlantic Ocean (FAO 41) had the highest average percentage of catch from bottom impacting gears (for example: 71 per cent) in the past decade. The northwestern part of the Atlantic Ocean (FAO 21) had the second highest percentage of catch from bottom impacting gears (for example: 61 per cent). The high percentage in Southwest Atlantic (FAO 41) is due to the intensive use of bottom trawling in this area, whereas the extensive use of dredge in Northwest Atlantic (FAO 21) contributes to the high percentage in this area. The Arctic Ocean (FAO 18) and Southeast Pacific (FAO 87) and Eastern Central Pacific (FAO 77) have the lowest percentage of catch from bottom impacting gears (for example: less than 1 per cent respectively).

Figure 6.6. The average annual percentage of catch from bottom impacting gears to the total catch in each of the top 5 FAO areas[32] with the highest percentages in the past 10 years (2001 to 2010).



Marine Trophic Index (MTI)

The MTI is an indicator used by the Convention on Biological Diversity (CBD) and it expresses the mean trophic level (mTL) of the fisheries catch in an area. When a fishery begins in a given area, it usually targets the largest among the accessible fish, which are also intrinsically most vulnerable to fishing (Cheung et al. 2007). Once these are depleted, the fisheries then turn to less desirable, smaller fish. This pattern has been repeated innumerable times in the history of humans (Jackson et al. 2001) and also since the 1950s, when landing statistics began to be collected systematically and globally by the FAO.

The mTL (and hence the MTI) for all fisheries landings in the open ocean has been calculated. Figure 6.7 shows the change in mTL from 1950 to 2010. The MTI fluctuated between 3.5 and 3.8 in the past 60 years in the high seas. The MTI for all fisheries landings in each FAO in the high seas has also been calculated. Here, we used FAO 41 (Southwestern Atlantic Ocean) to illustrate changes in marine trophic level through time (Figure 6.8). The mTL in this FAO area fluctuated between 3.7 and 4.2 between 1950 to the mid-1980s; then, this index remained around 3.8.

31 See Chapter 6.1 Figure 1 for Map of FAO Fishing Areas
32 See Chapter 6.1 Figure 1 for Map of FAO Fishing Areas

Figure 6.7. Marine trophic level in the open ocean

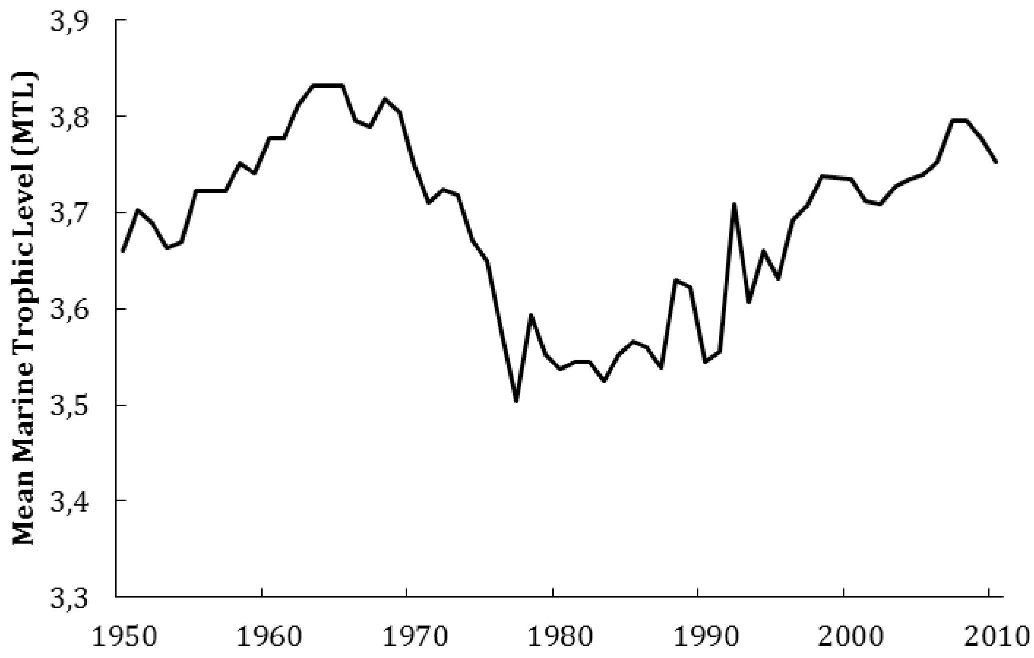
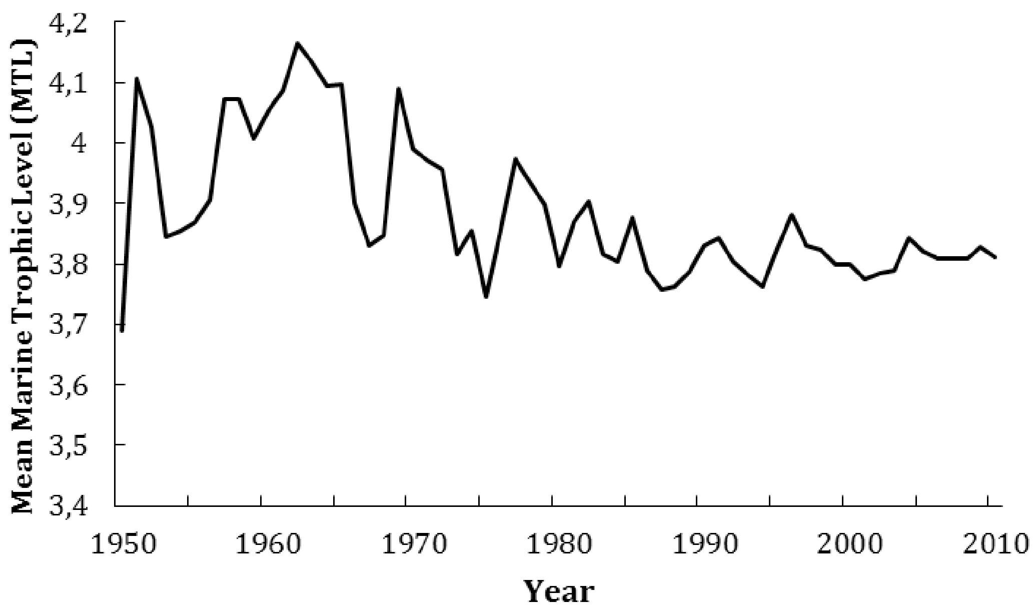


Figure 6.8. Marine trophic level in the open ocean of FAO 41 (Southwestern Atlantic Ocean).



Fishing-in-Balance Index (FiB)

The Fishing-in-Balance (FiB) index measures a geographic expansion, showing an increase when a fisheries expands. It is best analysed jointly with the Marine Trophic Index (MTI) – for which both indexes allow an understanding of the status of socks and an assessment of the changes in the ecosystem and potential impacts on human wellbeing. The trend of Fishing in Balance (FiB) index in the open ocean is shown in Figure 6.9, and should be interpreted

Figure 6.9. Fishing-in-Balance (FiB) index in the open ocean. The increasing trend of the FiB index suggests that the fisheries have expanded their area of operations.

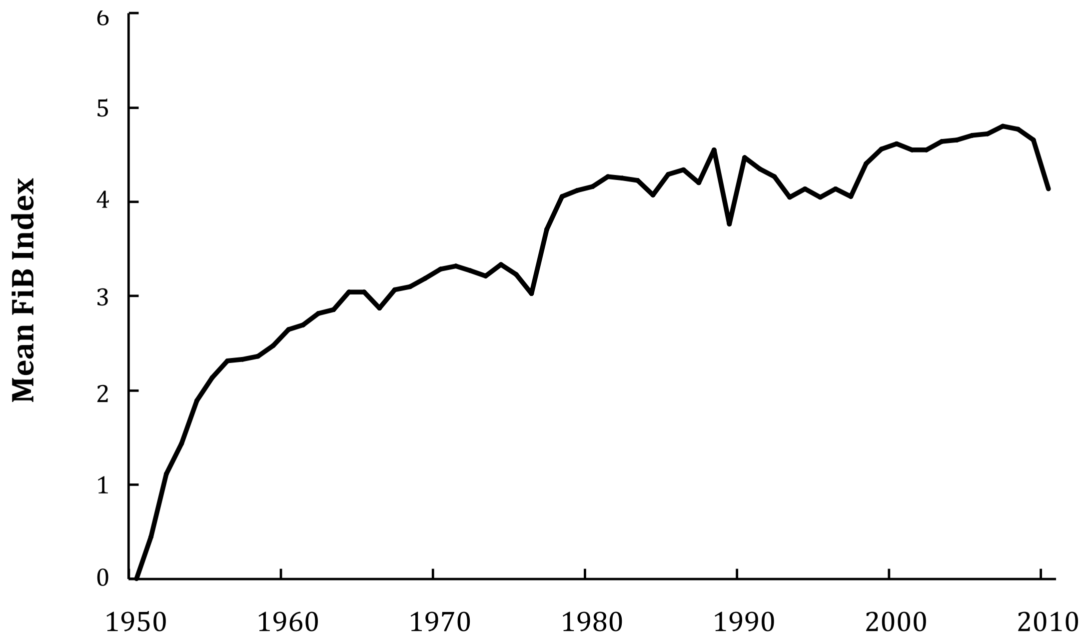
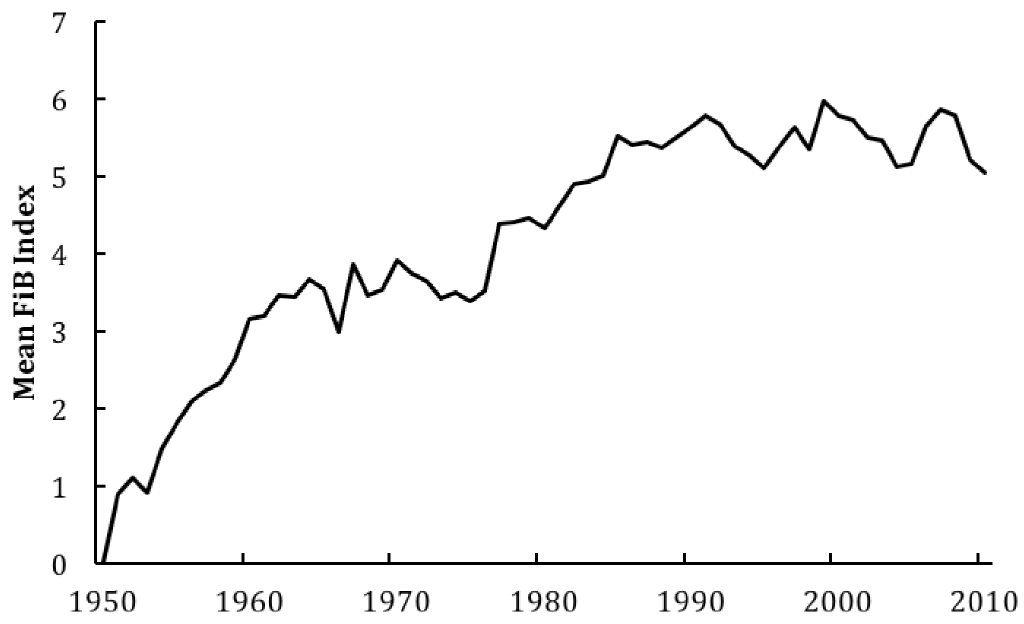


Figure 6.10. Fishing-in-Balance (FiB) index in FAO 41 (Southwestern Atlantic Ocean) in the open ocean.



in conjunction with Figure 4. Here, the increasing trend in FiB is probably due to a geographic expansion of the fisheries to new grounds, which in effect expands the size of the ecosystems they exploit (Kleisner et al. 2014). FAO 41 (Southwestern Atlantic Ocean) was used as an example of a trend of the FiB index in an FAO area (Figure 6.10). This graph should be interpreted in conjunction with Figure 6.8.

Demersal Effort

Fishing effort is any activity, such as the deployment of vessels, used to catch fish during a conventional period, for example: one year. Here, the cumulative power of the engine of fishing vessels is used as a measure of *nominal* effort, which is converted to *effective* effort through multiplication by an annual technological factor reflecting improvements in locating fish (for example: through echosounders and navigation (GPS)). The total effective effort of demersal catch reached its peak at 25 million kilowatts in 1979 and then declined to 3.8 million kilowatts in 1982 (See Figure 6.11). The effective demersal effort fluctuated between 1 and 11 kilowatts in the most recent 30 years. The peak in the early 1980s is mainly due to the substantial increase in the use of bottom trawls in the Antarctic Ocean during this period (Figure 6.12). Overall, there is an increase in effort from the 1950s to the recent years, for example: in the Southwest Atlantic (FAO 41) in Figure 6.13.

Figure 6.11. Effective fishing effort of demersal catch in the open ocean from 1950 to 2006.

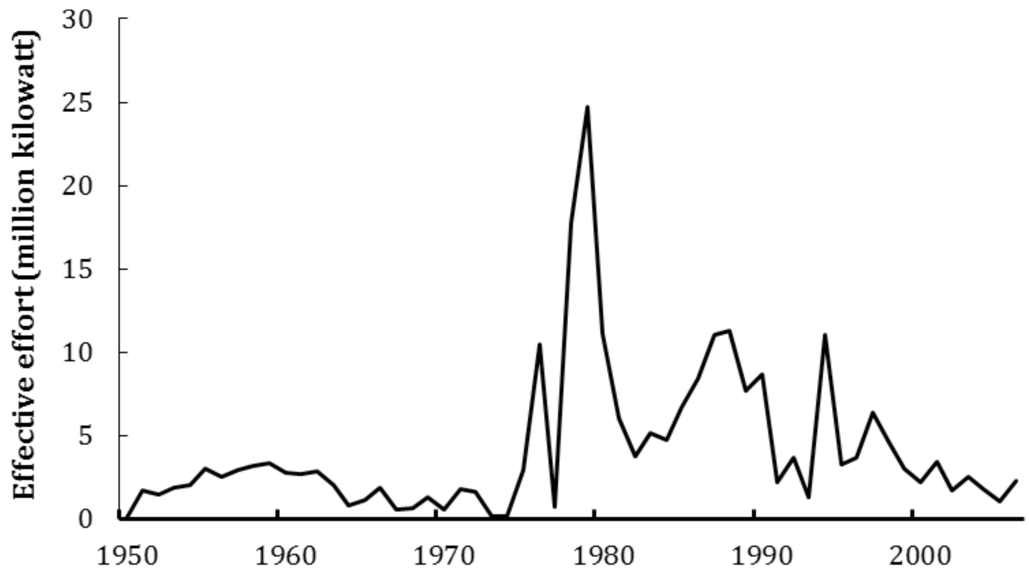


Figure 6.12. Effective effort of demersal catch of the open ocean waters of the Antarctic Ocean (FAO 48) from 1950 to 2006.

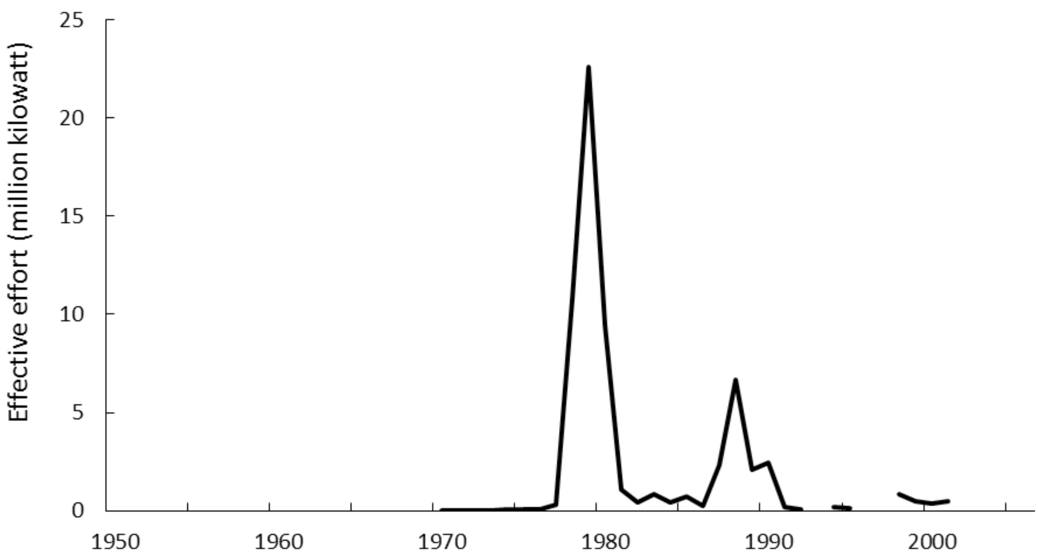
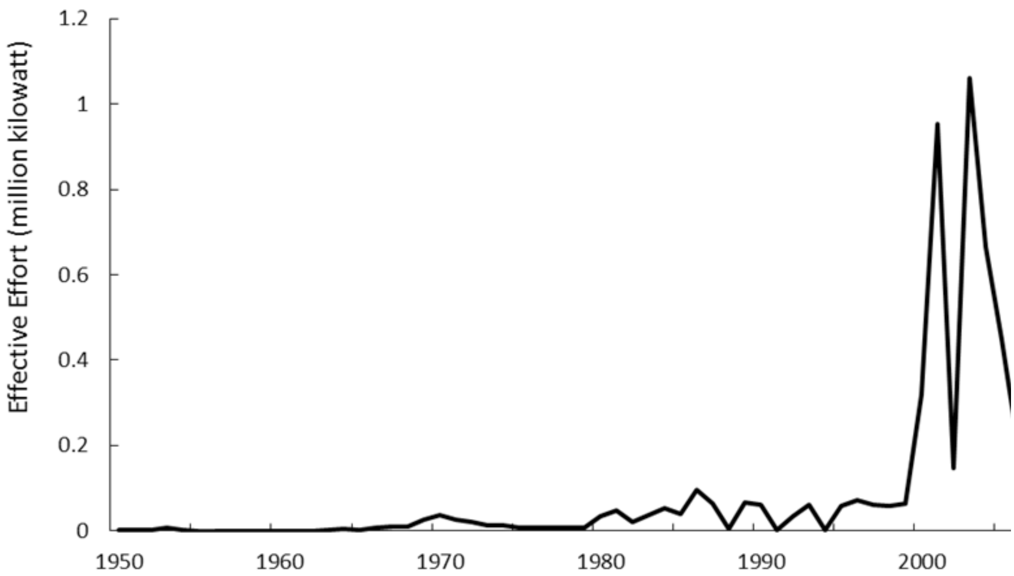


Figure 6.13. Effective effort of demersal catch of the open ocean waters of the Southwest Atlantic (FAO Area 41) from 1950 to 2006.



Discussion and Conclusions

The different indicators and graphs presented here contribute to an overview of the general status of fisheries and ecosystems in the open ocean. It accounts for the characteristics of fisheries, ecology of the exploited species and ecosystems. The global status of fisheries in the open ocean is mixed and the indicators do not always give consistent messages. Even given these limitations, these indicators evaluated current catch and related fisheries data and provide some information for developing policies for ecosystem-based fisheries management, for example: by identifying areas where management and/or mitigation measures are particularly needed. Also, some studies (for example: White and Costello 2014, Sumaila et al. 2015) suggested that closing the high seas would benefit the world as a whole by generating net gains in both catch and landed value and even the distribution of benefits among coastal countries. Thus, the information provided here can be used to further more equitable and environmentally sound policy. This information can also provide guidance on information gaps (for example: spatial effort data) and areas for research (for example: large scale, fisheries-independent biomass estimation), so that ecosystem-based management of fisheries can be strengthened in the open ocean.

6.2.3 Notes on Methods

This chapter documents the application of some fisheries-related indicators to highlight the level of risk within the open ocean. This was based on catch data spatialized using an approach developed by Watson et al. (2004), which relies on splitting the world ocean into more than 180,000 spatial cells of ½ degree latitude-longitude and mapping onto these cells, by species and higher taxa, all catches that are extracted from the corresponding areas. The catches in these spatial cells were regrouped into higher spatial aggregates, for example: the open ocean areas in each of the 19 FAO statistical areas.

Given that aggregates of spatial cells were combined with other data (for example: the catch from bottom impacting gear types and demersal effort data), subsequently, other time series could be derived for example: of indicators of the degree to which FAO areas may be degraded. Here, a description of the methods used to calculate the indicators including the catch time series from bottom impacting gear type, Marine Trophic Index (MTI), Fishing-in-Balance (FiB) index and demersal effort are provided. It should be noted that there are no scientifically defined thresholds for the indicators included in this chapter. Thus, the indicators were interpreted by expert opinions.

Bottom Impacting Gear

Annual landings from bottom impacting gear types by each FAO statistical area in the open ocean were extracted from *Sea Around Us* global catch database from 1950 to 2010.

Marine Trophic Index (MTI)

With a trophic level assigned to each of the species in the FAO landings data set, Pauly et al. (1998) were able to identify a worldwide decline in the mean trophic level of fish landings, a phenomenon they called "fishing down marine food webs". This was replicated in numerous local studies (see www.fishingdown.org).

However, landings reflect abundances only crudely. A fishery that has overexploited its resource base, for example: on the inner shelf, will tend to move to the outer shelf and beyond (Morato et al. 2006; Watson and Morato 203). There, it accesses hitherto unexploited stocks of demersal or pelagic fish, and the MTI calculated for the whole shelf, which may have declined at first, increases again, especially if the 'new' landings are high (Kleisner et al. 2014). This is the reason why the diagnosis as to whether fishing down occurs or not depends on whether a geographic expansion of the fishery has taken place. This is more *likely* than not, given the observed global tendency toward expansion (Swartz et al. 2010).

Fishing-in-Balance

To facilitate the interpretation of MTI-trends, an index of Fishing-in-Balance (FiB) was developed by Pauly et al. (2000), who defined it such that its value remains the same when a downward trend in mean trophic level is compensated for by an increase in the volume of 'catch', as should happen given the pyramidal nature of ecosystems and transfer efficiency of about 10 per cent between trophic levels (Pauly and Christensen 1995). As defined, the FiB index increases if landing increases more than compensate for a declining MTI. In such cases (and obviously also in the case when landings increase and the MTI is stable or increases), the FiB index increases indicate that a geographic expansion of the fishery has taken place, for example: that another part of an ecosystem is being exploited (Bhathal and Pauly 2008; Kleisner et al. 2014).

Demersal Effort

Demersal effort is quantified by multiplying the power of the vessels' engines and the numbers of days they are at sea in a year. A database of the nominal fishing effort deployed by the world's maritime countries was created by Anticamara et al. (2011) which was spatialized by Watson et al. (2013), and which was used to estimate demersal fishing effort from 1950 to 2006 (Figure 8). The 'nominal' effort estimated in this manner can be made to reflect gradual technological improvements in fish finding and catching, which are equivalent to increases of nominal effort of 1 – 3 per cent per year (Pauly et al. 2002; Pauly and Palomares 2010). Here, this technological improvement factor was set at 2.42 per cent per year, based on a meta-analysis of published efficiency increase (Pauly and Palomares 2010).

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Chapter 6.3 Tuna Catches from 1950 to 2010: who catches what and where will this end?

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6.3 Tuna Catches from 1950 to 2010: who catches what and where will this end?

6.3.1 Summary and Key Messages

The world catch of tuna in the open ocean, taken beyond the Exclusive Economic Zones (EEZs) of maritime countries, has increased from about 125,000 tonnes per·year^{-1} in the early 1950s to a plateau of about 3.5 million tonnes per·year^{-1} from 2000 to 2010. This overall catch, consisting of declining landings from the Atlantic and Indian Oceans and increasing landing from the Pacific is not likely to increase in the future, or even to be maintained. Most of this catch, consisting of skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*) and albacore tuna (*T. alalunga*) is traditionally taken by Japan, South Korea and Taiwan, but new entrants are attempting to increase their share, notably in the Pacific. Given the current states of tuna stocks in the open ocean and the effects of ocean warming on tuna stocks, this should result in increased competition among the subsidized fleets of developed countries with distant-fishing fleets, and between established fleets and new entrants. Of these new entrants, three are developing countries (Indonesia, the Philippines and Mexico) which appear among the 10 countries with the largest tuna catches in the open ocean.

Key messages

- The major stocks of tuna in the open ocean are either fully exploited or overexploited, with current abundance near or lower than 50% of unexploited biomass. This precludes higher catches that would be sustainable;
- Of the three oceans, the Atlantic has the tuna stocks whose catch declined first (in the 1990s), followed by the Indian Ocean (2000s). Only the Pacific Ocean has increasing catches, but stagnating and declining catches can be expected there, given the current increasing trend of multinational fishing effort; and
- The increasing fishing effort of traditional tuna fishing countries, and the added effort of new entrants to open ocean tuna fisheries will, given the present state of the stocks, result in higher competition and economic losses, likely to be offset by subsidies.

6.3.2 Main Findings, Discussion and Conclusions

While tuna have been exploited for thousands of years - for example in the Mediterranean (Tekin 1996) - their exploitation mostly depended on tuna populations being within reach of coastal (mainly fixed) fishing gear (Ravier and Fromentin 2001).

Oceanic tuna, on the other hand, became systematically exploited only after the Second World War, first using pole and lines (which required live baitfish), then longlines, driftnets and purse seines (Majkowki 2007). Since the 1970s, purse seine operations have been increasingly aided by fish aggregating devices (FADs). This started in the southern Philippines, where '*payaos*' initially consisted of bundled palm fronds and/or bamboo rafts (Floyd and Pauly 1984). With rapidly changing technology methods worldwide now consist of sophisticated concrete and/or steel contraptions with electronics capable of monitoring the tuna and other fish they attract, and of communicating via satellite with the fleet that has deployed them (Dagorn et al. 2007).

In this Chapter, the main trends of tuna catches in the open ocean beyond areas of national jurisdiction (outside of EEZs, or their equivalent areas in the years before they could be claimed), are presented and discussed, after a brief presentation of where the catch data originate, and how they are distinguished between open ocean and EEZ areas. The period covered is 1950, when the FAO began publishing annual effort statistics, to 2010, the last year for which the *Sea Around Us* was able to assemble consistent catch data.

The growth of open ocean tuna fisheries and catches

Figure 6.14 illustrates the growth of tuna catches in the open ocean resulting for the increased power and sophistication of the vessels and gear used in the tuna fisheries. Note the flattening of the graph since 2000. Correlating to this, Table 6.2 details the 10 countries with the highest tuna catches in the open ocean between 2000 and 2010, and as well shows how catches in these countries have changed markedly per decade since 1950.

Figure 6.14. Annual catch of tuna species in the open ocean from 1950 to 2010.

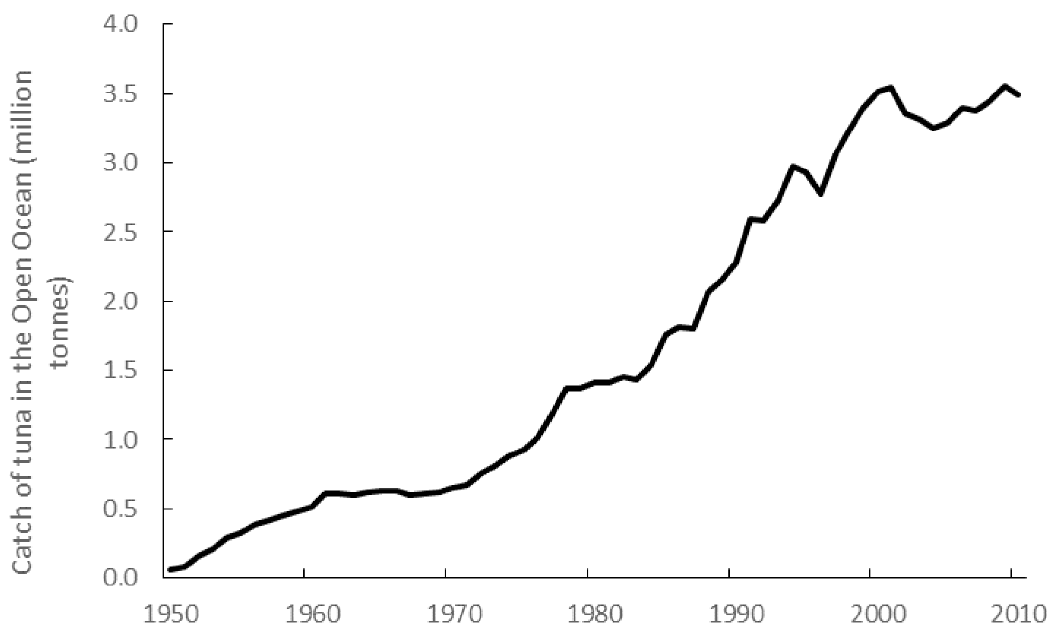

Table 6.2 Decadal catch of tuna in the open ocean from the 1950s of the top 10 countries with the highest landings from 2000 to 2010

Country	Annual mean catch (103 t)					
	1950 – 1959	1960 - 1969	1970 - 1979	1980 - 1989	1990 - 1999	2000 - 2010
Japan	1,640	3,929	3,469	5,451	8,246	4,617
Taiwan	53	246	563	1,148	2,764	2,351
South Korea	1	110	1,199	1,954	3,197	2,339
Indonesia	0	124	338	977	2,269	1,945
Spain	9	39	258	717	1,377	1,188
Ecuador	0	0	101	314	727	1,121
Philippines	86	106	716	955	1,032	1,027
Mexico	8	44	138	742	1,226	917
France	19	171	490	818	1,106	721
USA	971	1,155	1,504	1,500	1,334	689

Although requiring open waters, tuna are also caught within the 200 mile (EEZs) of maritime countries, particularly in the Western Central Pacific. Thus, the catch of tuna that is currently taken in the open ocean (Figure 6.14) is only about 65 per cent of the total catch of tuna in the world ocean. These tuna are mainly taken by Japan, South Korea and Taiwan (Table 6.2). The main species caught in the open ocean are skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) (Table 6.3).

Table 6.3 Annual mean decadal catch from the 1950s, of the top 10 species (or groups) with the highest landings in the open ocean from 2000 to 2010.

Common name	Scientific name	Mean annual catch (103 t)					
		1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2010
Skipjack tuna	*Katsuwonus pelamis*	777	1,233	2,815	5,640	11,365	10,440
Yellowfin tuna	*Thunnus albacares*	937	1,862	3,025	5,444	9,053	7,122
Bigeye tuna	*Thunnus obesus*	347	1,067	1,631	3,017	4,833	3,282
Albacore	*Thunnus alalunga*	457	1,180	1,306	1,610	1,975	1,443
Kawakawa	*Euthynnus affinis*	86	103	238	495	677	654
Tunas, bonitos & mack.	*Scombridae*	5	122	208	585	842	540
Longtail tuna	*Thunnus tonggol*	0	6	132	233	328	507
Southern bluefin tuna	*Thunnus maccoyii*	115	331	299	211	128	91
Pacific bluefin tuna	*Thunnus orientalis*	110	193	154	148	127	71
Atlantic bluefin tuna	*Thunnus thynnus*	18	27	23	23	29	23

Table 6.4 gives the location of these catches in terms of the statistical areas used by the Food and Agriculture Organization of the United Nations (FAO). As might be seen, FAO Area 71 (Western Central Pacific), with an average of 1.4 million tonnes per year and FAO area 77 (Eastern Central Pacific), with 0.5 million tonnes per year, show the highest tuna catches.

Table 6.4 Average annual catch of tuna species in the open ocean part of each FAO Statistical Areas (see Figure and Table 6.1) by ocean, from 2000 to 2010.

Ocean	FAO	Annual tuna catch (10^3 t)
Pacific	71	1,365
	77	468
	87	280
	61	210
	81	29
	67	13
Indian	51	463
	57	272
Atlantic	34	203
	47	39
	41	35
	31	30
	27	8
	21	1

Conclusion - status of open ocean tuna stocks

Figure 6.14 suggests that the catches of tuna from the open ocean reached a plateau, and the detailed, stock-by-stock analysis of Juan-Jorde et al. (2011) suggest that these catches will not increase anymore. A few species (notably Atlantic Pacific and Southern bluefin tuna) have been severely overfished (Fromentin 2009; Mori et al 2001) and will require lower quotas to recover. In addition the fishing mortality on the few species that presently contribute the bulk of tuna catches (yellowfin, albacore, skipjack and bigeye tuna) are, as a whole, currently experiencing the fishing mortality roughly generating maximum sustainable yield (Majkowski, 2007; Sibert et al. 2006). Hence additional effort increases are more *likely* to decrease than to increase catches. Also, the biomass of the most abundant species are near or below 50 per cent of their unexploited values (Juan-Jorda et al. 2011), which also precludes sustainable catch increases.

These generalizations hide obvious differences between oceans and species; thus, the open Atlantic Ocean, where catch has been declining since the mid-1990s, is more impacted than the Indian Ocean, where open ocean catches are stagnating (and declining if that entire ocean is considered) and the Pacific Ocean, where catches are still increasing (Miyabe et al. et al. 2004). Similarly, large tuna species (notably the three bluefin tuna species) are far more impacted than the small tuna, for example: skipjack (Juan-Jorda et al. 2011).

Scenarios for future developments

It is now obvious that long distance from coastlines has ceased to protect oceanic tuna populations and hence the pelagic ecosystems of the open ocean. Instead, the level of fishing effort that is deployed in the open ocean as only a function of the cost of fishing (and especially the cost of fuel; Lam et al. 2011) relative to the ex-vessel value of the tuna catch, which can be extremely high (Swartz et al. 2012).

To the extent that distant-water countries are willing to continue subsidizing their distant-water tuna fleet (and they seem to be, see Sumaila et al. 2010, 2013), the cost factor becomes less important and fishing effort is thus *likely* to continue to increase. With total catch not being able to follow suit, tuna fishing in the open ocean will turn into a zero-sum game, with some new players, such as China (Pauly et al. 2013), displacing more established players. Whether the developing countries with EEZs near the open ocean areas with high tuna catches (for example in the South West Pacific, or the Indian Ocean) will be able to increase their share of open ocean catches - or even acquire one - is an open question, as is the long-term sustainability of the stocks.

The above considerations, however, do not account for the effects of ocean warming, and the increased stratification and acidification of the open ocean, discussed in Chapters 6.1 and 6.4. These effects will eventually probably impact the distribution and recruitment of tuna wherever they occur. Thus, it is difficult to give a positive prognosis for the future of open ocean tuna fisheries. For further information on the potential influence of ocean warming and acidification on marine ecosystems, see Sections 4 and 5 of this Report.

6.3.3 Notes on Methods

The method used for this report, to map fisheries catches onto about 180,000 half degree longitude and latitude spatial cells, has been described by Watson et al. (2004) and Pauly et al. (2008) in some details, and is summarized in five steps:

1) Assemble the catch data to be mapped, here consisting mainly of the catch data reported by member countries to FAO, and distributed via the Fishstat database after their assignment to FAO statistical areas, complemented by data from the FAO's 'Atlas of Tuna and Billfish Statistics[33]';
2) Create, for each taxon (species, genus or family) for which at least one country reports landing, distributions range map (for tuna mainly based on FishBase[34]);

33 www.fao.org/fishery/statistics/tuna-atlas/4/en
34 www.fishbase.org

3) Allocate the catch reported in (1) to the distribution range in (2) subject to the constraint that an access agreement (or traditional access in pre-EEZ times) must exist for the catch to be allocated to cells that are part of an EEZ other than that of the reporting country;
4) When necessary, identify the reason(s) why a catch cannot be allocated, which may be due to (a) a faulty distribution map, (b) the non-availability of an access agreement, or (c) one or several other constraints – omitted here - not being met;
5) Aggregate the half degree cells (and the catch assigned to them) into a large area of interest, for example: the EEZs of maritime countries, Large Marine Ecosystems, or here, the open ocean part of FAO statistical areas (Watson et al. 2004; Pauly et al. 2008, and Sea Around Us[35]).

Acknowledgements

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COUNTERPOINT: The above chapter is the opinion of the authors. There are differing views on the status of tuna stocks. The reader is encouraged to explore widely, for example, the International Seafood Sustainability Foundation (ISSF) Technical Report 2015-03-A: *Status of the World Fisheries For Tuna* (November 2015) uses more recent data:

http://iss-foundation.org/resources/downloads/?did=602

35 www.seaaroundus.org

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Chapter 6.4 Fish Catch Potential in the Open Ocean Under Different Climate Change Projections

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6.4 Fish Catch Potential in the Open Ocean Under Different Climate Change Projections

6.4.1 Summary and Key Messages

The open ocean, for example: the oceanic area beyond the 200 mile Exclusive Economic Zone (EEZ) of maritime countries, will be increasingly impacted by climate change, as will coastal areas of the ocean. These changes are investigated using a bio-climate envelope model capable of reproducing and amplifying the observed poleward migration of fish exploited by fisheries under the IPCC Special Report on Emission Scenario (SRES) A2. The results are an overall predicted reduction of 20 per cent of the potential catch of the open ocean to 2030 and 34 per cent to 2050. The strongest declines of potential catch should occur in the intertropical belt, because increasing stratification will depress primary and secondary production and because no fish will replace those tropical fish that migrate poleward. Declines are also expected in Antarctica, because the life cycle of the currently abundant krill (*Euphausia superba*) is tied to shelf ice, that is expected to melt away.

Key Messages

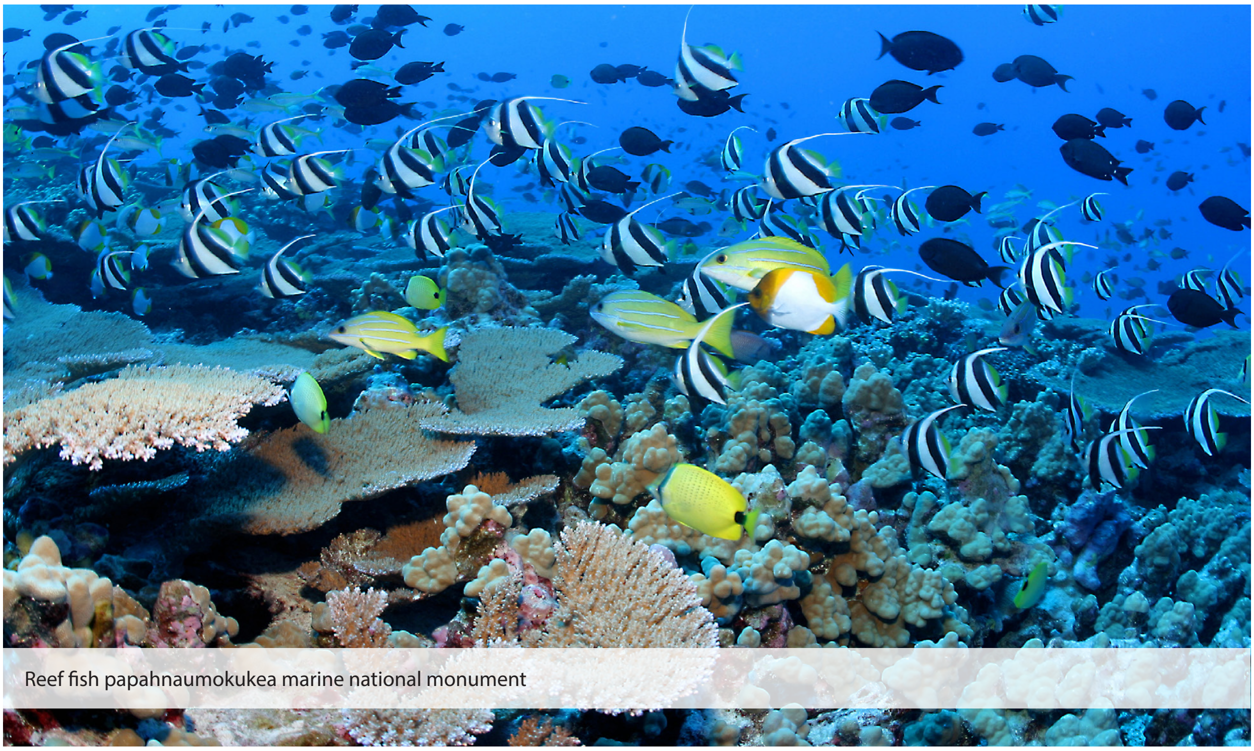
- Future climate change will *likely* have an impact on future fish catch in the open ocean, which may have large implications for the fishing industries, economies and livelihoods of many countries;
- Open ocean potential fish catch is projected to decline by 20 percent by 2030 and by 34 percent by 2050; and
- The greatest declines are projected to occur in the inter-tropical belt and in Antarctica.

Along with other non-climatic factors such as changes in markets, demographics, overexploitation, management and governance regimes, climate change is a major issue that will shape fisheries in the future. Although several studies suggested that management interventions and stressors other than climate changes may have a greater impact on fisheries than climate change in the short term (Eide 2007, Daw et al. 2008), increasing changes in ocean climate still pose a major threat to world fisheries in the long term. Rising water temperatures, as well as related changes in ice cover, salinity, carbon dioxide levels, dissolved oxygen and circulation may intensify shifts in the range of marine species that are already occurring (Polovina 1996, Clark et al. 2003, Drinkwater 2005, Rose 2005, Cheung et al. 2008a; 2013). These may include negative impacts on coral (Graham et al. 2007, Hoegh-Guldberg 2007), a decline in phytoplankton (Boyce et al. 2010), and range change and earlier migration of diadromous species (IPCC 2007). Change in ocean temperatures and primary productivity may cause the poleward shift of distribution boundaries of commercially important marine fishes and shellfish in the world ocean (Cheung et al. 2009, 2013). The combined effects of distribution shift and changes in ocean primary productivity under climate change could lead to global redistribution of maximum potential catch (Cheung et al. 2010). A recent study also showed that warmer temperature may lead to a decrease in maximum body sizes of marine fishes (Cheung et al. 2012). These predicted changes have great implications on people dependent on fish for food and income, and thus economics of their society as a whole. This chapter investigates how fisheries in the open ocean may be affected by climate change.

6.4.2 Main Findings, Discussion and Conclusions

Impact of climate change on global marine fisheries

Marine fisheries productivity is *likely* to be affected by the alteration of ocean conditions including water temperature, ocean currents and coastal upwelling, as a result of climate change (for example: Bakun, 1990; IPCC, 2007; Diaz & Rosenberg, 2008). Such changes in ocean conditions affect primary productivity, species distribution, community and food web structure that have direct and indirect impacts on distribution and productivity of marine organisms. For the open ocean, the within-year and inter-annual variability are controlled by ocean circulation, which is affected by the change in global climate. (See Chapter 4.1 for more context) For example, the frequency and intensity of the El-Niño-Southern Oscillation (ENSO) - which is a naturally occurring event that leads to change in the ecosystems, rainfall and weather patterns in the Pacific and other parts of the world - are also modified by global warming


Reef fish papahnaumokukea marine national monument

(Collins et al. 2010). However, the direction of change and the impact on the frequency of ENSO events under climate change is still uncertain. For example, in the Pacific, Lehodey et al. (2010) project a largely eastward shift (rather than poleward) for bigeye tuna under climate change: with an east-west gradient in temperature in the equatorial region that is apparently still stronger than the north-south gradient.

Another example is the Meridional Overturning Circulation (MOC), which is sensitive to the patterns of atmospheric forcing. A recent study suggested that Atlantic MOC is more sensitive to the changes in freshwater input due to global warming than that proposed in the fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR4 – this is the previous IPCC Report; Dijkstra 2014). The influence of climate change on ocean circulation patterns may lead to change in species migration pattern, organism dispersal patterns and species interactions (Doney et al. 2012) and eventually the productivity of fisheries.

Empirical and theoretical studies show that marine fish and invertebrates tend to shift their distributions according to the changing ocean climate, generally towards higher latitude and deeper water (Cheung et al. 2011). There are already numerous studies showing that the change in distribution and catch potential coincided with increasing sea temperature, for example, the large increase in the catch of horse mackerel (*Trachurus trachurus*) in the North Sea (Reid et al. 2001). Other examples include the northward shift of Atlantic cod (*Gadus morhua*) in North Atlantic and Barents Seas (Rose 2005, Brander et al. 2006), and the northward shift of landings of four species (lobster (*Homarus americanus*), yellowtail flounder (*Limanda ferruginea*), summer flounder (*Paralichthys dentatus*) and red hake (*Urophycis chuss*)) in the northeastern United States (Pinsky and Fogarty 2012).

Thus, there is some confidence in predictions that a shift in species distribution and reduction in maximum body size of fish will cause the change in maximum catch potential in various countries (Cheung et al. 2010, 2012). Large scale re-distribution of global catch potential may result from climate change, with an average 30 – 70 per cent increase in high-latitude regions and a decrease of up to 40 per cent in the tropics (Cheung et al. 2010). The magnitude, variability and overall direction of change in total catch will be different across different parts of the ocean based on the location of the fishing grounds, and targeted species.

It is predicted that climate change will not only change the magnitude of landings, but also their composition. This may lead to the redistribution of fishing efforts across different fisheries, targeted species and fish locations. As such, all these changes would then impact on the economics of fisheries of the fishing nations, global food security, energy supply and food prices (Sumaila et al. 2011).

Projection of catch potential in the 2030s and 2050s

Using the methods described at the end of this chapter, the projected change in the catch potential in the open ocean for 2030 and 2050 were derived. Results are shown in Figures 6.15 and 6.16.

Figure 6.15. Change in projected catch potential (%) under climate change scenario (SRESA2) in the 2030s.

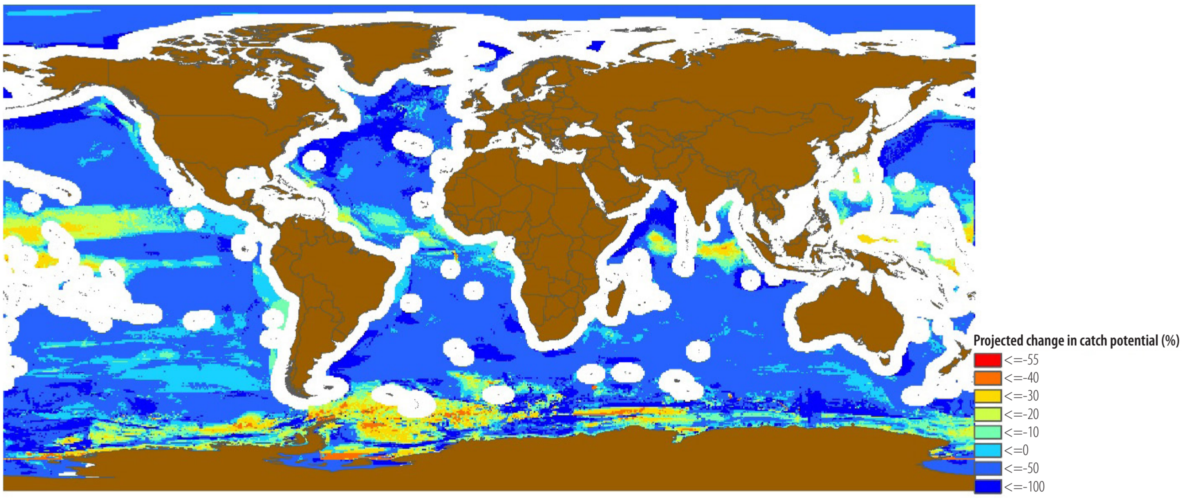
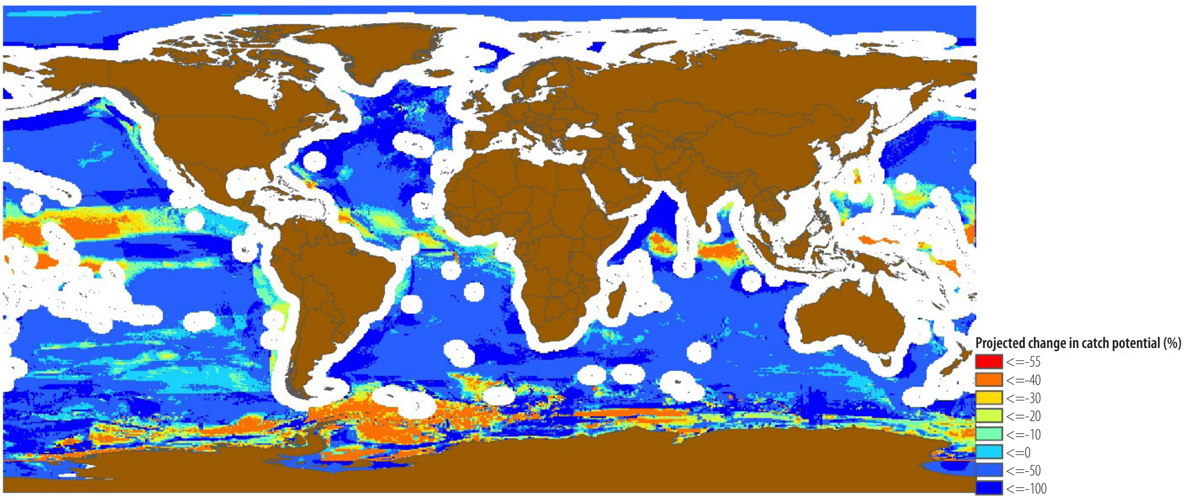


Figure 6.16. Change in projected catch potential (%) under climate change scenario (SRESA2) in the 2050s.



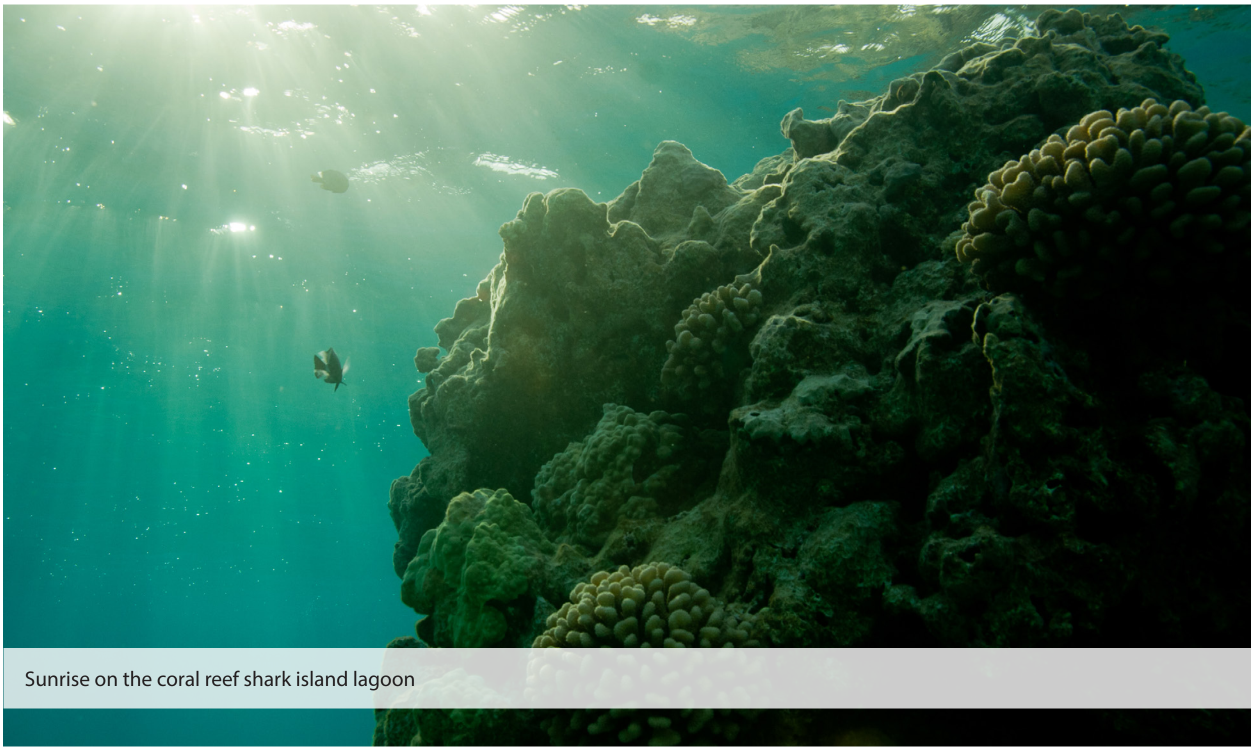
Results suggest that climate change may have a large impact on the distribution of maximum catch potential – a proxy for potential fisheries productivity – by the 2030s and the 2050s. Such a redistribution of catch potential is driven by projected shifts in species' distribution ranges and by the change in total primary production within the species' exploited ranges (Sarmiento et al. 2004; Cheung et al. 2008a).

The global catch potential decreases by 20 per cent from the current status in the 2030s under the high emission scenario, for example: SRES A2 (Nakicenovic and Swart 2000) as described in the methods section at the end of this Chapter. The longer term effect is even stronger, with a predicted global catch potential drop by 34 per cent from the current status in the 2050s. The catch potential decreases most in the tropics, particularly in the central Pacific region, in both the 2030s and the 2050s (Figure 6.15 and 6.16), where increased stratification (Polovina et al. 2011) should reduce primary and secondary production. As well, equatorial species shifting to higher latitudes are not likely to be replaced. In contrast replacement of species adapted to temperature changes in subtropical, temperate and polar regions is *likely*. The results of modeling also predict massive reduction of catch potential around Antarctica, *likely* due to the life cycle of krill (*Euphausia superba*) being strongly linked to Antarctic shelf ice, which is predicted to melt away (Marschall 1988; Nicol 2006). In addition, the planktivorous competitors of krill (salps), which are experiencing an increase in the region (Atkinson et al. 2004), are not exploited by fisheries. Consequently, the fishery potential of the Antarctic region is *likely* to significantly decline. The situation in the Arctic is predicted to be different: sea ice associated endemic species of fish are expected to be replaced by cold temperate species of economic value to the fisheries industry.

The projected change in maximum catch potential in the open ocean may have large implications for global food supply and food security issues. If the decrease in catch potential in the tropical regions directly translates to actual catch decreases, climate change may have a negative impact on food security in many countries. Such communities may already have high socioeconomic vulnerability to climate change in fisheries (Allison et al. 2009). The shift of catch potential may also render fishing activities more costly as fishing boats may have to move to other fishing grounds which maybe further offshore. Large industrial fishing fleets and distant water fleets, may have to travel further to fishing grounds at higher latitudinal regions in order to locate the marine fish and invertebrates that are predicted to migrate under climate change. Hence, travel distance for fleets may increase, which is *likely* to lead to an increase in fishing cost. In addition, as most marine fisheries resources in the world are currently fully exploited, over-exploited or collapsed and the global marine catch appears to reach or has exceeded its biological limits (Pauly et al. 2002; FAO 2008), it is expected that climate-induced changes in catch potential will strongly affect global fisheries production and food supply.

Conclusions

In the models applied for this work, the projection of global catch potential under climate change predicts that open ocean fisheries are vulnerable to impacts. This in turn will have consequences on future food supply from the open ocean and in turn, the livelihood of people and countries depending on marine fisheries. Estimates suggest that the high-range greenhouse gas emission (SRES A2) could result in an overall reduction, and a redistribution of world-wide catch potential in the open ocean for example: with an average of 30–70 per cent increase in high-latitude regions and a drop of up to 40 per cent in the tropics. This redistribution would impact industrial fleets operating in the high seas and hence the economics and food security of the countries fishing in the open ocean.



Sunrise on the coral reef shark island lagoon

6.4.3 Notes on Methods

Models and scenario for projection

Distribution shift of exploited marine species was investigated using a dynamic bioclimate envelope model (Cheung et al. 2008b, 2009). Cheung et al. (2008a) has developed an empirical model that predicts maximum catch potential based on primary production and distribution range of 1,066 species of exploited fishes and invertebrates. Our analysis included 1066 species of exploited marine fishes and invertebrates, representing a wide range of taxonomic groups, ranging from krill, shrimps, anchovy and cod to tuna and sharks. These are the species that for which there is distribution information. Overall, they contributed 70 per cent of the total reported global fisheries landings from 2000 to 2010 (*Sea Around Us* database: http://www.seaaroundus.org). The remaining 30 per cent of the global landings were reported in the original FAO fisheries statistics as taxonomically aggregated groups such as groupers (Epinephelidae) and snappers (Lutjanidae). Given that the species composition of these aggregated groups is unknown, they were not included in the analysis. An updated version of this model was applied to evaluate how changes in primary productivity and species distributions under climate change would potentially affect the productivity of fisheries in the open ocean. Only one climate model was used here because of limited resource.

In our analysis, SRES A2 scenario (Nakicenovic and Swart 2000), which assumes carbon dioxide concentration at 720ppm by year 2060, representing high-range of greenhouse gas (GHG) emissions was considered. The A2 scenario was selected because it is consistent with the current level of emissions (Rahmstorf et al. 2007) and is conservative regarding the level of global economic growth (Van Vuuren and O'Neil 2006). The A2 scenario describes a very heterogeneous world with regionally orientated economic development, high population growth, and slow technological changes (IPCC 2000, 2007). Under this scenario, the average temperature is projected to increase by 3.4°C by the 2100s relative to the current temperature. The A2 scenario is between the Representative Concentration Pathway (RCP) 6.0 and 8.5 new scenarios in the IPCC 5th Assessment Report (IPCC, 2013).

The climate projections were extracted from the outputs of Earth System Model (ESM2.1), which is a comprehensive ice-land-ocean-atmosphere coupled general circulation model including both physical climate and ocean biogeochemical dynamics, generated by the Geophysical Fluid Dynamics Laboratory (GFDL) of the United States National Oceanic and Atmospheric Administration (NOAA; Dunne et al. 2010). Ocean current, bottom temperature, sea surface temperature, sea ice extent, sea surface oxygen concentration, bottom oxygen concentration, salinity and primary productivity data were extracted from the GFDL ESM2.1. The outputs from the coupled model has variable resolution with grid 1° cells at latitudes higher than 30°N and 30°S, and a higher resolution towards the equator. To match with the resolution of species distribution maps in the *Sea Around Us*[36] database, the nearest neighbour method was used to interpolate the physical variables from the ESM2.1 to the resolution of 30' in latitude and longitude. This interpolation method allows us to avoid making complicated assumptions about the relationship between the coarser-resolution model outputs and their downscaled values.

Only one scenario and one climate model were included because of resource limitation. This may lead to uncertainties in the results, however, the results are still valid as the data were based on the published results from a global climate change study (Cheung et al. 2010). More than one climate change scenario and multi-model ensemble should be adopted in the future study as well as using the most recent IPCC projections to reduce these uncertainties. Also, caution is needed regarding the projected migration of fish and invertebrate species, especially from the tropical regions, as it is difficult to assess which group of species – if any – will be replacing those that have migrated out of the tropical areas.

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Chapter 7
Pollution

Chapter 7.1 Pollution Overview in the Open Ocean

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GESAMP (The Joint Group of Experts on Scientific Aspects of Marine Protection) is an inter-Agency body of the United Nations (UN), providing independent advice on many aspects of marine environmental protection since 1969. In 2009, GESAMP published a Report on Open Ocean Pollution, as a contribution to the development of the UN World Ocean Assessment (http://www.worldoceanassessment.org/). This has recently been reviewed and revised with the most current information. This Chapter summarises the findings of the revised report Pollution in the Open Oceans 2009 – 2013, GESAMP Reports and Studies Series 91, (2015) and readers may consult this for further information, including an extensive list of references (See http://onesharedocean.org/open_ocean/pollution).

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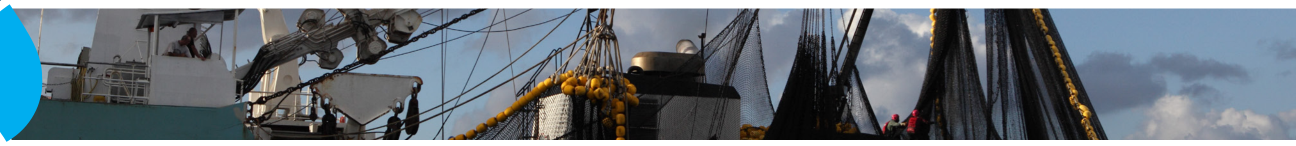
Pollution



7.1 Pollution Overview in the Open Ocean

7.1.1 Summary and Key Messages

Marine pollution is, by definition, damaging to marine organisms and ecosystems and may interfere with legitimate uses of the sea. In accordance with Part XII of the Law of the Sea Convention and various other international agreements, contracting parties are obliged to prevent, reduce and control pollution of the marine environment.

Monitoring the deep ocean, beyond the 200m depth contour, is technically difficult and costly. Furthermore, pollution monitoring by coastal states tends to be focused on the shallower shelf sea areas which are often most affected by contamination from land-based sources. Consequently, the amount of scientific information relating to conditions in the open ocean is small in comparison to near-shore areas. There are no fixed criteria of marine pollution. Thus, pollution indicators to a great extent are determined by existing scientific methodologies. For the most part, they consist of measurements of particular substances in samples of water, sediment, biological issues and atmospheric deposition. Substances routinely monitored are those with hazardous properties, known to arise from human activities, for which analytical methods exist (for example: they can be accurately detected and quantified). However, the mere presence of a substance introduced by human activity is not always harmful and does not necessarily constitute *pollution*. Environmental concentrations that approach or exceed those known to be harmful (effect levels) are important indicators but such levels are seldom found in the open ocean. An obvious indicator of pollution is evidence of biological effects but to date the techniques and opportunities available for recording biological impacts in the open ocean are limited. A very useful indicator is a trend in either inputs of contaminants or their environmental concentrations; trend monitoring requires repetitive measurements over long periods of time. In the case of the open ocean, trend monitoring of inputs is restricted to atmospheric deposition (for example: measurements at island stations and on ships).

The recent scientific literature has been reviewed for some of the principal ocean contaminants resulting from human activities, specifically: nutrients, carbon dioxide (CO_2), mercury (Hg), marine debris, Persistent Organic Pollutants (POPs), noise and radioactivity. It was found that the deep ocean, occupying about 65 per cent of the Earth's surface, is significantly contaminated with the by-products of human activities; all major ocean basins are affected. Substantial quantities of contaminants are introduced from land, through shipping, and via the atmosphere. Scientific knowledge of pollution in the open ocean is steadily improving and some important advances have been made in the past five years. No early decline in the bio-availability of mercury is predicted and without mitigation atmospheric inputs of CO_2 will increase acidification of surface waters. Inputs of the nutrient nitrogen, which are already significantly elevated downwind of industrialized regions, are predicted to increase to the end of the century. In the Arctic, environmental levels of some recently manufactured POPs are on the increase. Various taxonomic groups are adversely affected by noise generated by shipping, sonar devices and seismic surveys. The high incidence of marine debris, such as nets on the seabed that cause entanglement, and plastic fragments that that are ingested by many different species, is increasingly apparent.

Inputs and environmental levels of the contaminants examined are not uniformly distributed either geographically or with depth and, depending on the substance or disturbance, certain sectors (for example: water, sediments, organisms) are far more exposed than others. Effects are not always visible or easily detectable. Only in the cases of marine debris, human induced noise and acidification by atmospheric CO_2, can cause and effect be readily demonstrated. Nevertheless, it is *very likely* that substantial and progressive changes in the physical and chemical properties of ocean ecosystems will, in time, produce a biological response. Some changes, such as increasing inputs of nitrogen to low-nutrient waters, or increasing acidity, could trigger changes in primary production that influence entire food chains including the production of fish, birds and mammals. Other changes may impact on food safety (for example: *high* levels of mercury in fish) or cause changes in the behaviour and survival of sensitive species (for example: POPs in the tissues of whales and dolphins).

It is considered that atmospheric inputs of CO_2 and nitrogen, as well as the extent of solid debris (for example: plastics, netting) in the water column and on the seabed, are matters of special concern. Attention is also drawn to another, rapidly emerging threat which is the exploration and extraction of minerals and hydrocarbons on or within the deep ocean seabed. The potential of such activities for large-scale uncontrollable impacts, as shown by the recent oil leakage in the Gulf of Mexico, is substantial and not sufficiently recognized.

Information on the temporal and spatial extents of contaminants in the deep ocean is sparse but in most cases, through deduction and modelling, is sufficient to determine general patterns. There is a pressing need for time-series datasets from strategically selected sites to more accurately discern trends; this requires greater commitment to long-term funding for such measurements. Whereas the effects of certain contaminants on species and communities can be seen locally, or shown experimentally, the real impact at ecosystem level is largely unknown. Indeed, taking into account the complex relationships within ocean ecosystems, it is *likely* that such understanding will remain beyond the capabilities of science for the foreseeable future. Nevertheless, it is reasonable to assert that the cumulative effects of multiple stressors on some ocean communities, eventually will force changes in the structure and function of those communities that will be damaging and possibly irreversible. Indeed, they may already have done so. This scenario is even more *likely* when taking into account other major changes such as those that result from fishing pressure and the upward trend in water temperatures. Accordingly, there is a strong case for more effective measures to reduce inputs of contaminants to the ocean. The full assessment report for pollution in the open ocean has been published in the GESAMP Report & Studies Series 91 (GESAMP 2015a) and is an update of the GESAMP Report and Studies Series 79 from 2009.

Key Messages

- The deep ocean occupies about 65% of the Earth's surface and is significantly contaminated with the by-products of human activities;
- A major perturbation in the natural cycle of nitrogen has potentially significant impacts on marine ecosystems, especially in waters with low ambient nutrient concentrations;
- Uptake of CO_2 from the atmosphere into the upper layers of the ocean is responsible for declining pH levels in seawater with serious implications for marine life;
- The extent of solid debris such as plastics and netting in the water and on the seabed is a major concern;
- The exploration and extraction of minerals and hydrocarbons on or within the deep ocean seabed is a rapidly emerging threat; and
- Greater investment in contaminant trend monitoring (time-series datasets) is urgently required.

7.1.2 Main Findings, Discussion and Conclusions

One of the many ways in which human activities impact on the open ocean is through the introduction of substances and energy that are by-products of domestic, agricultural and industrial practices. When the physical, chemical and biological changes caused by such introductions are damaging to marine life or human health, they are regarded as 'pollution'. The actual extent of marine pollution by any particular substance, or form of energy, will depend on the form, amount and rate of introduction, the input pathway and location, as well as its inherent properties (for example: toxicity, persistence, bio-concentration). It can also depend on how it interacts with other pressures exerted by anthropogenic activities such as fishing and climate change. Marine pollution may be manifest as effects on individual marine species (for example: population level), communities or ecosystems, affecting their survival, reproduction or even their long-term sustainability.

Environmental conditions in the open ocean play a pivotal role in regulating future life on Earth. With the open ocean constituting international waters, no individual state or region has sole responsibility for such action, nor would unilateral actions prove effective. Consequently, the issue requires a transboundary management solution.

The previous review of scientific publications concerning pollution in the open ocean (GESAMP 2009), identified priority issues that, in the opinion of the experts involved, warranted special attention by governments and by environmental regulators. The parameters of most concern were inputs of nitrogen (N) and partial pressure of CO_2 and their potential effects on ecosystem function. This chapter summarises the review of new data and scientific perspectives on the open ocean that have emerged in the past five years. Not all of the topics covered by the 2009 report are addressed in the same degree of detail while coverage of certain other topics has been extended for the new Report Series 91 (2015a). For example, contamination arising from shipping activities, ballast water and dumping is now considered of lesser priority in the open ocean whereas new information has enabled improved assessments of ocean noise, mercury and microplastics. Recognizing the substantial releases of radioactivity from the Fukushima (Japan) Dai-ichi nuclear power plant in 2011, the report includes a summary of the incident and consequential levels of radionuclides both in the ocean and the atmosphere.

Nitrogen (N) & Iron (Fe)

Nitrogen (N) from anthropogenic sources (industry and agricultural livestock) continues to dominate N inputs from the atmosphere to the ocean. The concentration of N in the atmosphere has probably been increased by at least a factor of three due to anthropogenic activities over the last ~150 years. This major perturbation in the natural cycle of N has potentially significant impacts on marine ecosystems, especially in the nutrient-depleted gyres of the major ocean basins. Significant advances have been made in the modelling of N fluxes to the ocean; fluxes are projected to increase in the years up to 2100 (Lamarque, et al. 2013). Studies in the marginal seas downwind of the intense N emission regions of East Asia, have reported observable impacts of N deposition on the biogeochemistry of the ocean. Due to the essential role of iron (Fe) in photosynthesis (and thus its links to N), the effect of anthropogenic emissions in increasing the flux of soluble Fe (from combustion sources, or through enhancing solubility of Fe from mineral dust) to the ocean has also received considerable attention (Moffet et al. 2012). The importance of this soluble Fe input to the ocean is difficult to quantify because it occurs against the background of a very large Fe input associated with the natural mineral dust cycle.

Mercury (Hg)

Unlike other metals, mercury (Hg) in the atmosphere exists to a significant degree in gaseous form and undergoes reactions leading to a variety of both gaseous and particulate forms of Hg. Atmospheric input of Hg to the global ocean is much more important than riverine input. The current atmospheric loading of Hg is three to five times pre-industrial levels and the surface ocean loading roughly twice pre-industrial values (Amos et al. 2013). Mercury measurements have improved significantly in quantity and quality in the last five years and a global mercury monitoring network has been established. Studies of the atmospheric oxidation of Hg and its cycling and methylation in the ocean have provided a link between deposition, methylation, entry into the food web and bioaccumulation. It is *likely* that the loading of mercury to the sub-surface ocean, where mercury is methylated and enters the food web, will continue even if anthropogenic emissions remain constant due to cycling of legacy Hg. If anthropogenic emissions do not decrease quite radically it is probable that methyl Hg concentrations in pelagic piscivorous fish will continue to increase. GESAMP considers it imperative that atmospheric monitoring continues and that campaigns to measure Hg compounds in the open ocean water column are continued in the future, particularly in major fisheries (Pirrone et al. 2013).

Noise

By the 1960s, the average ambient noise level in the deep ocean had increased 10-100 fold in frequencies important for whales, fish and invertebrates since pre-industrial times. At some sites it is continuing to double in intensity every decade. Shipping is the largest anthropogenic source of low-frequency sound; most of the noise comes from propellers (Frisk 2012). There are additional, more localized impacts from offshore and coastal developments, including intense sounds from oil and gas exploration and naval sonar. Baleen whales, most acoustically sensitive invertebrates and fish are sensitive to low sound frequencies, which can travel long distances in seawater, and are most *likely* to be affected by long-term increases in low frequency ambient noise. Noise may disrupt animals that use sound on ocean reefs. There are significant gaps in the scientific literature concerning the impacts of anthropogenic noise on marine ecosystems (Parks et al. 2013). The resulting uncertainty makes it difficult to balance the need for precaution in protecting marine ecosystems against the potentially large costs to socially important activities such as commercial shipping, offshore energy, and military readiness. In the view of GESAMP, a monitoring program for noise should be incorporated into planned global ocean observation programmes. There is also an urgent need for expanded research on the impact of anthropogenic noise on marine life. Particular attention must be paid not only to cumulative long-term effects, but also to synergy between noise and other anthropogenic pressures on marine ecosystems. For example, ocean acidification is increasing sound propagation; the extent of this effect on ocean noise is just beginning to be addressed. Numerous measures have been recommended for mitigation of noise, but there are no systematic programs to assess or monitor actual noise levels in the ocean at scales useful for predicting impacts on marine life.

CO_2 and acidification

Ocean uptake of CO_2 emissions by human activity is the dominant cause of observed changes in surface ocean pH and carbonate chemistry. Acidification of the global surface ocean is a pervasive threat to all marine life (Whittmann and Pörtner, 2013, and already described in this Report, Chapters 4.4 and 5.6). It will promote large changes in marine ecosystems globally and may already be doing so. Ocean acidification will have wide-ranging consequences by changing biogeochemical cycles, metal speciation[37] and the production of climatically active gases. The strength and impact of acidification are a direct function of CO_2 emissions by human activity and resulting ocean CO_2 uptake. Global average surface ocean pH is expected to decrease from a pre-industrial value of 8.2 to pH of 7.8 to 7.9 by 2100, if CO_2 emissions continue to be high or to a pH of 7.9 to 8.0 by 2100 (Ciais et al. 2013), if CO_2 emissions are mitigated. The response of organisms and ecosystems to acidification is uncertain but there will be both winners and losers. Some non-calcifying taxa may experience a positive effect, such as an increase in growth and photosynthesis. Calcifying species are particularly vulnerable (as described in Sections 4 and 5). Corals, echinoderms and molluscs show *medium* sensitivity and crustaceans low sensitivity. Initial results indicate that fish may have a strongly negative response to ocean acidification, possibly as a result of a high sensitivity of their larvae. The global, pervasive threat of ocean acidification creates an urgent need for long-term, global monitoring of the impact of ocean acidification on marine organisms and ecosystems. Volcanic CO_2 vent systems provide valuable natural analogues of possible ecosystem responses and adaptation to ocean acidification.

Persistent Organic Pollutants (POPs)

Since 2009, there has been progress in monitoring POPs (as defined by the Stockholm Convention), PBTs (other Persistent Bioaccumulating and Toxic chemicals) and CFCs (chlorofluorocarbons, commonly used as a refrigerant and propellent), in the marine environment, mainly in the Northern hemisphere. Predatory species frequenting different oceanic regions can provide unique insights into the fate of chemicals of concern. Such an approach may provide vital information for marine environmental assessment in the future. Distinct differences exist in body burdens of POPs between geographic locations, notably *high* levels in Monk seals, swordfish and killer whales close to industrial and population centres such as the Eastern Mediterranean and off California. Species in remote locations and with open ocean life-histories, such as the relatively low trophic-status leatherback turtle, generally have low POP levels, although by no means negligible. Downward trends in many POPs reported in Atlantic cod and British Columbia harbour seals are encouraging, although concentrations in some populations of killer whale remain *high* (Law et al 2012). In general, contaminant levels in open ocean biota appear lower in comparison to equivalent species inhabiting the coastline. Confounding factors are the paucity of information on the diet and migratory patterns leading to POP exposures for many populations examined. In addition to atmospheric deposition and various biological factors, local pollution sources can strongly influence observed body burdens, even in remote areas. The Arctic shows strong indications of decreasing tissue levels of PCBs, DDT and many of the 11 original POPs listed in the Stockholm Convention (Hung et al. 2010). On the other hand, levels of some more recently developed and used chemicals such as perfluorocarbons (PFCs, used as a refrigerant and solvent) decabromodiphenyl ether (BDE-209, a

37 Referring to different chemical forms of metal such as organic, inorganic and oxides

flame retardant), and hexabromocyclodecane (HBCDD, another flame retardant), show significant increases in some Arctic biota (Houde et al. 2011; Law et al. 2014). Reports of POPs body burdens being associated with health effects are, in general, tenuous and non-specific, even for marine mammals. Concentrations of POPs absorbed onto or within microplastics close to pollution sources are *very high* in comparison with those from remote areas and open seas; they can be of the same order of magnitude as those found in sediments in those areas.

Marine debris

Debris from both land- and sea-based activities can be found floating, drifting and on the seabed throughout the marine environment and, in the view of GESAMP, is a matter of special concern. Shipping remains a significant source along busy shipping lanes and fishing-related debris is common wherever commercial fishing takes place. Floating plastics are transported by ocean circulation and have been found in the most remote parts of the ocean (Barnes et al. 2010). Plastics fragment through exposure to UV and fragments can remain in the marine environment for substantial periods of time. Surveys on remote shores and mid-ocean islands are particularly useful at demonstrating long-distance transport and potential effects. Debris is widespread across the shelf (Sanchez et al. 2013), and may be concentrated in deep-water canyons (Schlining et al. 2013) and mid-ocean gyres (Morét-Ferguson et al. 2010). The effects of macro-scale debris, by ingestion or entanglement, have been clearly demonstrated for a wide variety of fauna (for example: birds, fish, reptiles, marine mammals). Some species may already be affected at population level; examples are the Northern Right Whale, (*Eubalaena glacialis*) by entanglement, or vulnerable species such as the leatherback sea turtle (*Dermochelys coriacea*) by ingestion of plastic. Floating durable debris can provide an effective vector for transporting organisms, from viruses to macro-fauna such as molluscs and brown algae (Phaeophyceae); this may be responsible for introductions of non-indigenous and problem species. Plastics may contain a variety of chemicals introduced to achieve particular properties, some with known toxicological properties, and many organic contaminants already in the environment (for example: PCBs, DDT, flame-retardants) are absorbed into the polymer matrix if present in the surrounding seawater. Small plastic fragments, or 'microplastics', can be ingested by a great variety of organisms, and contaminants may pass the gut barrier, with potential for toxicological effects. Whether or not this represents a significant risk is unclear (GESAMP 2015b). The most cost-effective way of reducing anthropogenic debris in the marine environment is to prevent its introduction. This will require a multi-faceted approach, involving industrial sectors and public education in addition to regulatory action. This is being pursued on national, regional and global scales, with the GPML[38], led by UNEP, being the most ambitious to date. Further discussion on floating plastics is provided in Chapter 7.2 of this Report and the Governance discussion in Section 3.

Radioactivity

The accident at the Fukushima Dai-ichi nuclear power plant on 11th March 2011, caused by the Tōhoku earthquake and tsunami, resulted in an unprecedented release of radioactivity to the ocean from a single point source, both by direct release to the ocean and from atmospheric deposition. The predominant radionuclides released were isotopes of caesium (Cs) and iodine (I), together with substantial quantities of strontium (^{90}Sr) and lesser quantities of plutonium and short-lived radionuclides (Buesseler 2014). There is evidence that contaminated groundwater (Maderich et al. 2014) and run-off via rivers (Nagao et al. 2011) continued to act as a source to the ocean long after the accident. Marine sediments contaminated by Fukushima ^{137}Cs appear to be an additional continuing source of caesium to the overlying biota and to benthic and demersal organisms. Rapid atmospheric transport resulted in widespread dispersion of Fukushima radionuclides in the northern hemisphere, including the short-lived ^{131}I (half-life 8 days) (Masson et al. 2013). Dispersion in surface waters was dominated by the Kuroshio Current (Aoyama et al. 2012), with transport to the north-western coast of the United States, estimated to have occurred by early 2014. Despite the relatively *high* levels of contamination, and uptake by a wide variety of biota, the radiological consequences of the accident in the marine environment, and then human consumption of seafood, have been rather low.

38 Global Partnership on Marine Litter (http://gpa.unep.org/index.php/global-partnership-on-marine-litter

Discussion

Assessments of the open ocean must take account of the highly varied hydrography, climatic conditions, habitats and patterns of resource exploitation across the major ocean basins, as well as pollution resulting from human activities both on land and at sea. Accordingly, this review of recent scientific knowledge on ocean pollution addresses just one of the many forms of pressure on ocean ecosystems and should be considered in the light of other pressures and changes affecting the marine environment. A feature of pollution in the open ocean, as opposed to coastal waters, is that the major sources of potentially polluting substances are the atmosphere and commercial shipping. GESAMP emphasizes that for many (but not all) substances introduced to the ocean through human activity, there is presently no clear evidence of harmful effects, for example: a criterion of pollution. Nevertheless, the possibility of cumulative effects due to multiple stressors cannot be discounted.

Sources

Shipping and the atmosphere are the two primary sources of ocean pollution. Commercial shipping tends to be concentrated around the major shipping lanes, such as the Straits of Hormuz and Malacca. Ships are significant sources of oil, CO_2 and oxides of sulphur and nitrogen along such busy shipping lanes. Losses of deck cargo and poor waste management practices aboard vessels also add to the ubiquitous problem of ocean litter and debris. New shipping lanes may extend the areas impacted. For example, based on climate forecasts for 2040-2059, it is possible that during summer months, when the extent of sea ice is at a minimum, some ships may be able to transit directly across the Arctic Ocean. This route is 20 per cent shorter than today's busiest Arctic shipping lane, the Northern Sea Route, which follows the coast of Russia (IPCC 1997). This will also open up the region to natural resource extraction, including minerals, oil, gas, and methane hydrates, as well as commercial fishing. The sources of atmospheric contaminants are, of course, much broader than just shipping and include emissions from land-based power generation, industry, traffic and agriculture; such emissions can be widely dispersed and transported long distances before deposition in the ocean.

Multiple stressors

When interpreting data on environmental conditions and on contaminants in particular, it is important to bear in mind that biological effects may occur gradually over time and that, in conjunction with natural variation, the effects of chronic exposures may go unnoticed. Whereas the assessment of effects from individual contaminants in the open ocean can be problematic, assessing the combined effects of many different forms of contaminant is even more complex. Populations and communities of marine organisms occupying a variety of ocean ecosystems and habitats, are subject to a multiplicity of changes[39] ranging from physical (for example: temperature, noise, pH) to chemical (for example: POPs in tissues) to biological (for example: food supply). Although a minor change in any one variable may be harmless, at some level all changes will impose a stress that can interfere with growth, reproduction or behaviour and thereby jeopardize populations and the communities of which they are part.

At present, methodologies for estimating the combined effects of different forms of stressor do not exist. Yet, drawing on principles from toxicology, it is conceivable that the effects of certain stressors acting in combination could be either additive or even synergistic. There is already speculation that cumulative stresses, for example tissue contaminants, noise and changes in food supply, may already be responsible for changes in reproduction, behaviour, and perhaps even the viability, of some top predators such as marine mammals. Such negative changes undoubtedly constitute pollution and, in the opinion of GESAMP, new and improved measures to reduce known stresses on living components of ocean ecosystems warrant detailed consideration at international level. The proposed new instrument to protect ocean biodiversity (outlined in UNESCO-IOC et al. 2011) is one such initiative and should help to dispel any impression that the ocean is somehow less vulnerable than the shelf seas.

39 See also Table 2

Matters of special concern

An important aim of this review was to identify issues affecting the open ocean that represent significant risks to ocean ecosystems, both now and in future. These are changes, directly or indirectly associated with human activities, threatening the integrity, biodiversity, productivity or sustainability of ocean sectors on large spatial scales.

Numerous human activities impinge on the marine environment, either because they mobilize materials that are readily transported seawards either in water or through the atmosphere, or because they exploit marine resources for food, industry or recreation. The effects of some activities are small-scale and localized, with minimal impact at ecosystem level, while others are far more extensive and pervasive, causing insidious changes that have potential to disrupt ecosystem function. Many (but not all) of the substances reviewed in this report fall into the latter category and, in deciding on issues that warrant 'special concern', the most important criteria are those that have potential to disrupt ecosystem function. Clearly, another criterion is a sense that the issue has yet to receive the attention it deserves at the international level.

It is clear that practices with the greatest potential to adversely affect the open ocean are those that occur at many different locations around the world and that release large amounts of biologically active substances, either directly to the sea or atmosphere. However, due to the substances they utilise or release, their complexity or the physical conditions under which they operate, certain technologies are more hazardous than others. These include nuclear facilities and a range of operations engaged in the extraction, bulk storage and transport of crude oils. Here, attention is drawn to three issues which, from a scientific perspective, are of special concern:

Inputs of carbon dioxide (CO_2): Previously, GESAMP (2009) highlighted the issue of carbon capture and storage as a matter of special concern due to the unknown consequences of artificial fertilization of the ocean with nutrients, such as iron (Fe) and nitrogen (N), in order to draw down CO_2 from the atmosphere. GESAMP reiterates its view that proposals to apply this technology at the massive scales needed to significantly reduce levels of CO_2 in the atmosphere require very careful consideration with regard to environmental effects and sustainability. Likewise, the risks associated with the use of sub-seabed geological formations for long-term storage of CO_2, in particular the effects of leakage, require further research and assessment.

Since GESAMP's last report on ocean pollution (2009), new data on CO_2 in the atmosphere and its effects on the ocean have added considerable weight to arguments for greater control of anthropogenic CO_2 emissions to the atmosphere (see Sections 4 and 5). There is strong evidence that uptake of CO_2 from the atmosphere into the upper layers of the ocean is responsible for declining pH levels in seawater which has serious implications for marine life. Calcifying species are particularly vulnerable to ocean acidification, for example corals, echinoderms, molluscs and crustaceans and there are preliminary indications that fish may have a negative response to acidification. Amongst the many different responses to declining pH levels are alterations in growth, survival, behaviour, the ability to detect prey and to avoid predators. Such effects could have implications at both population and community levels as well as for commercial fisheries. The global, pervasive impact of ocean acidification creates an urgent need for long-term, global monitoring of its impact on marine organisms and ecosystems and for a drastic reduction of anthropogenic CO_2 emissions, as already discussed in Chapter 5.6.

Inputs of nitrogen (N) and iron (Fe): It is clear from research that there is a major perturbation in the natural cycle of nitrogen which has potentially significant impacts on marine ecosystems, especially in waters with low ambient nutrient concentrations. Modelling predicts that nitrogen fluxes to the ocean will increase in the years up to 2100. There are observable impacts of N deposition on the biochemistry of the ocean downwind of the intense N emission regions of East Asia. Because Fe plays an essential role in several key enzymes of photosynthetic organisms, including those associated with N uptake by phytoplankton, the effect of anthropogenic emissions in increasing the flux of soluble Fe (from combustion sources, or through enhancing solubility of Fe from mineral dust) to the ocean also warrants attention. The collection of time-series datasets on atmospheric fluxes of nitrogen and iron at island stations in each of the north and south basins of the Atlantic, Pacific and Indian Oceans is a minimum requirement for the identification and assessment of trends.

Deep-water extraction of seabed (benthic) resources: As conventional sources of fossil fuels and minerals become depleted, extraction industries have turned their attention to the considerable reserves that exist on and beneath the seabed at deep-water locations. Very large reserves of oil are known to exist beneath salt layers buried 2-3 km beneath the seabed in deep water (c.2000 m and more) off Brazil, Angola and in the Gulf of Mexico; exploration is *likely* to reveal other such deposits. The technology to open wells at these deep-water sites already exists and continues to be developed. But despite stringent efforts by the industry to improve safety standards and contingency measures, operating under such extreme conditions presents significant risks for the marine environment. High pressures and temperatures at sub-sea wellheads present risks of explosions and, as shown by the recent *Deepwater Horizon* incident in the Gulf of Mexico, response times may not be sufficiently rapid to prevent substantial losses of oil. The long-term environmental costs of major oil leakages at deep-sea locations, their implications for ecosystem viability and associated ecosystem services, warrant further scientific analysis supported by modelling of different scenarios.

Deep sea mining for valuable metals is also on the increase. Ocean mining sites are usually around large areas of polymetallic nodules or active and extinct hydrothermal vents at about 1,400 - 3,700 metres below the ocean's surface. The vents create sulfide deposits, which contain precious metals such as silver, gold, copper, manganese, cobalt, and zinc. As with all mining operations, deep sea mining raises questions about environmental damage to the surrounding areas. With deep sea mining being a relatively new field, the environmental impacts are largely unknown. There are concerns that removal of parts of the sea floor might result in disturbances to the benthic layer, toxic levels of contaminants in the water column and sediment plumes from tailings. Further research into the environmental implications of seabed mining technologies, the nature and scale of impacts, is essential to better understand the significance of these operations for ocean ecosystems. In the interim, a code of best practice for deep-sea mining operations[40], preferably developed by the industry in conjunction with the International Seabed Authority which regulates the exploitation of seabed resources, would be beneficial.

Litter and debris: GESAMP's 2009 report also drew attention to the ubiquitous occurrence of litter and debris in the ocean derived from shipping, mariculture, discarding, land run-off, shoreline littering and flooding (for example: tsunamis) and the hazards these present to marine life, navigation and recreation. More recent reports fail to show any degree of improvement in the range and abundance of marine debris; the problem persists and the open ocean is not exempt. There is further evidence of POPs absorbed into microplastics, providing vectors for the distribution of these contaminants and their transfer to marine organisms. Debris is widespread in deep water canyons and in the mid-ocean (for example: Fram Strait, North Atlantic). The effects of macro-scale debris, through ingestion or entanglement, have been clearly demonstrated for a wide variety of fauna (for example: birds, fish, reptiles, marine mammals; CBD 2012, Wright et al. 2013). For some vulnerable or endangered species this additional stressor may have an impact at population level. The production of plastics worldwide has risen approximately exponentially since the 1950s (Plastics Europe 2013). The marine environment has become a repository for a significant fraction of plastic waste and better controls over the sources of this waste are urgently needed, such as a global code of practice for plastics disposal. Despite increased opportunities for recycling, the percentage of plastics recycled remains low; 80 per cent of the 30 billion plastic water bottles sold in the US, for example, go to landfill. GESAMP would firmly support initiatives to raise the profile of plastic wastes as potential hazards to the marine environment and coordinated international action to reduce losses of plastic materials to the ocean.

Syntheses

As a means of comparing current levels of scientific knowledge on each of the contaminant categories reviewed in the report, Table 7.1 gives a subjective assessment of the degree of human input and whether or not there is clear evidence of effects. It also provides an indication of trends in environmental levels or loads of the contaminants and GESAMP's perspective regarding their relative, overall environmental significance. The fact that living components of the marine environment are subject to multiple stressors, many at low levels but nevertheless acting in consort, is recognized throughout the report.

40 Recommendations on impact assessment for exploration already exist (ISBA/16/LTC/7, 2010)

Table 7.1 Current scientific knowledge of open ocean contaminants: synthesis and assessment

Topic	Natural occurrence	Human input	Demonstrable effects (from human input)	Trend/Load	High status as a hazard?
Oil	Y	Y ++	Y	→	Y
Debris	N	Y ++	Y	↗	Y
Radioactivity	Y	Y +	N	→	N
Carbon					
CO_2/ocean acidification	Y	Y +++	Y	↗	Y
POPs/PBTs	N	Y +++	Y	↗	Y
DDE	N	Y +++	Y	↓	N
Nutrients/metals					
N	Y	Y +++	Y	↗	Y
P	Y	Y +	N	↗	N
Fe (soluble)	Y	Y ++	N	↗	N
Pb	Y	Y ++	N	↘	N
Cu	Y	Y ++	Y	↗	Y
Mercury	Y	Y +++	Y	↗	Y
Noise	Y	Y+++	Y	↗	Y

Yes/No + Low ++ Moderate +++ High

To illustrate the potential for combined effects on various taxonomic groups including humans, Table 7.2 contrasts the ranges of impacts from different contaminants and, in particular, highlights the broad scale of effects that may arise from unmitigated ocean acidification. In general, the net effect of multiple stressors on individual groups of organisms is unknown.

Table 7.2 Recognizing multiple stressors: taxonomic groups considered most impacted by open-ocean contaminants reviewed

	Humans	Marine mammals	Reptiles	Seabirds	Fish	Invertebrates	Corals	Phytoplankton
Oil	+	++	+	+++	++	+	+	+
Debris	+	+++	+++	++	+	+	+	
Radioactivity	+							
Carbon/CO_2	+	++		++	++	+++	+++	+++
POPs	+	+++		+++	+			
Nutrients							+	+
Mercury	+++	+++		+	++			
Noise		+++			++			

(Empty cells reflect that impacts, should they exist, are judged to be relatively minor)

Conclusions

GESAMP's updated review of pollution in the deep ocean shows that, in 2014, all of the human-induced inputs of polluting substances, materials and noise identified its 2009 report on this topic (Reports & Studies No.79) continued to impact marine ecosystems. In particular, GESAMP draws attention to elevated atmospheric inputs of CO_2 and nitrogen, as well as the extent of solid debris in the water column and on the seabed. Despite inevitable gaps in knowledge, in most cases there is sufficient scientific evidence to conclude that, without intervention, the contaminant inputs examined present significant risks for marine resources and/or processes that sustain ecosystem function. Another, rapidly emerging, threat is the exploration and extraction of minerals and hydrocarbons on or within the deep ocean seabed. Whereas levels of contaminants show wide regional variation, the changes they exert and the management solutions needed to combat these changes, are clearly *trans-boundary* in nature. In some instances (for example: CO_2, plastic debris), the extent and rate of change constitute a strong argument for early, coordinated and more effective measures to offset widespread, possibly irrevocable, damage to marine life.

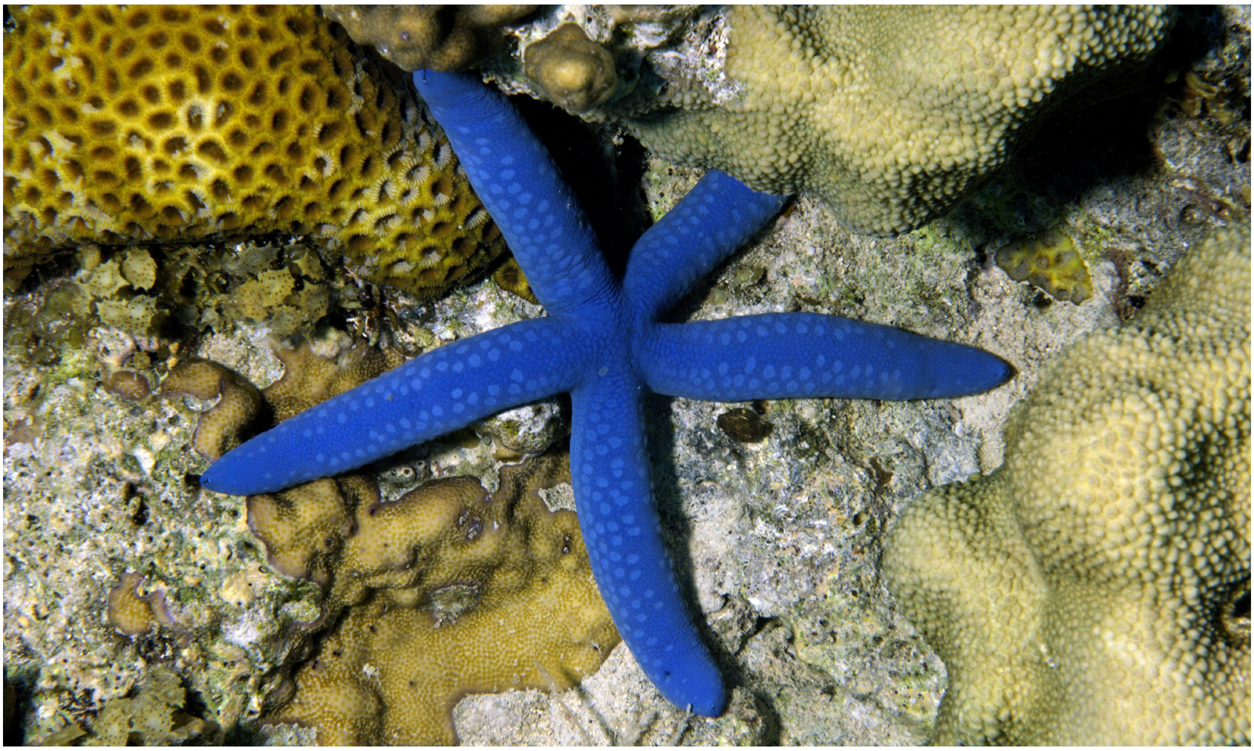
The deep ocean, occupying about 65% of the Earth's surface, is significantly contaminated with the by-products of human activities; all major ocean basins are affected. Substantial quantities of contaminants are introduced from land, through shipping, and via the atmosphere. Scientific knowledge of pollution in the open ocean is steadily improving and some important advances have been made in the past five years. No early decline in the bio-availability of mercury is predicted and without mitigation atmospheric inputs of CO_2 will increase acidification of surface waters. Inputs of the nutrient nitrogen, which are already significantly elevated downwind of industrialized regions, are predicted to increase to the end of the century. In the Arctic, environmental levels of some recently-manufactured POPs are on the increase. Various taxonomic groups are adversely affected by noise generated by shipping, sonar devices and seismic surveys. The high incidence of marine debris, such as nets on the seabed that cause entanglement, and plastic fragments that that are ingested by many different species, is increasingly apparent.

7.1.3 Notes on Methods

The scope of scientific literature reviewed embraces thematic reviews and assessments, including those by international organizations and governments agencies, and research papers published in the wider scientific literature. The review focuses on publications post 2009, with the addition of a few important papers that had been overlooked in the previous review. In summarizing the status of particular contaminants in the open ocean, efforts have been made to identify recent changes in knowledge and scientific understanding of importance to policy-makers, environmental regulators and managers, as well as the research community.

Pollution monitoring by coastal states tends to concentrate on the shallower shelf sea areas which are often most affected by contamination from land-based sources. Consequently, the amount of scientific information relating to conditions in the open ocean is small in comparison to near-shore areas. There are no fixed criteria of marine pollution and, consequently, the studies reviewed employ a diverse range of techniques for the sampling and analysis of marine media. Pollution indicators to a great extent are determined by the available scientific methodologies. For the most part, they consist of measurements of particular substances in samples of water, sediment, biological issues and atmospheric deposition. Substances routinely monitored are those with hazardous properties, known to arise from human activities, for which analytical methods exist (for example: they can be accurately detected and quantified). However, the mere presence of a substance introduced by human activity is not always harmful and does not necessarily constitute *pollution*. Environmental concentrations that approach or exceed those known to be harmful (effect levels) are important indicators but such levels are seldom found in the open ocean. An obvious indicator of pollution is evidence of biological effects but to date the techniques and opportunities available for recording biological impacts in the open ocean are limited. A very useful indicator is a trend in either input of contaminants or their environmental concentrations; trend monitoring requires repetitive measurements over long periods of time. In the case of the open ocean, trend monitoring of inputs is restricted to atmospheric deposition (for example: measurements at island stations and on ships).

The geographical scope of the review was defined as areas 'where the water depth exceeds 200m around the boundaries of the major continental land masses' as well as all waters surrounding archipelagos regardless of depth. The inclusion of archipelagos was necessary because measurements at island stations are frequently used to represent conditions in the surrounding seas, particularly air-borne contaminants and marine debris distributed by ocean currents. In keeping with the relative scarcity of data compared to those for coastal areas, as well as outputs from modelling, summaries of atmospheric inputs in the previous review tended to be summarised on the basis of the major ocean basins, for example: Atlantic, Pacific and Indian. The present report (GESAMP 2015a) adopted a similar approach but its geographical scope was extended slightly to include deep-water (>200m) areas of the Mediterranean and Arctic. Further information is available in the full report available at http://onesharedocean.org/open_ocean/pollution



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Chapter 7.2 Open Ocean Pollution – Floating Plastics

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7.2 Open Ocean Pollution – Floating Plastics

7.2.1 Summary and Key Messages

Plastic enters the marine environment from a wide variety of land and sea-based activities, including directly into the open ocean, but there are no reliable or accurate estimates of the nature and quantities of material involved. The majority of the floating plastic in the open ocean is *likely* to have originated from activities within Large Marine Ecosystems (LMEs) and on land.

Once plastic enters the ocean it can become widely dispersed by ocean currents and winds. The overall distribution of floating plastics in the open ocean is dominated by the influence of the general surface water circulation, with relatively high abundances confined to sub-tropical gyres, large-scale systems of rotating ocean currents. An unknown proportion sinks to the seabed as a result of fragmentation or biofouling.

Larger items of plastic debris have a significant impact on many species of marine organisms (for example: invertebrates, fish, birds, reptiles and mammals), due to entanglement and ingestion. Plastic can also cause significant economic loss and may pose a threat to navigation and human safety, and this may occur at a considerable distance from the point(s) of entry.

Plastics fragment as a result of several factors, especially UV irradiation, but retain their original properties. Very little is known of the actual effects of microplastics on marine organisms but a separate assessment of potential effects has been carried out, in parallel, by a GESAMP Working Group (GESAMP 2015).

There is a general lack of reliable and consistent observational monitoring data on floating plastics in the open ocean. This prevents reliable quantitative estimates of the amount of micro- (<5 mm in diameter) and macro- (>5 mm in diameter) plastics in both space and time, especially where the size of particles effectively sampled is unknown and where differences exist in the sampling methods used. Even where good time-series datasets exist, the significant inherent heterogeneity in distribution, at a range of space- and time-scales, has prevented the detection of trends over time, within a defined ocean region, such as a sub-tropical gyre.

The complex nature of multiple sources and effects poses difficulties in designing and implementing cost-effective measures to reduce inputs. In most cases, solutions will need to be multi-agency, multi-sector, regional and international, and require a significant change in public perceptions and attitudes, to be fully effective.

7.2.2 Main Findings, Discussion and Conclusions

Plastics (for example: petroleum-based polymers) started to be produced and used on a large scale in the 1950s. Since, there has been an almost exponential increase in use, as plastics have replaced traditional materials, such as metal, glass and wood, and aided the development of completely new products, such as computers. The most characteristic property of plastic is its durability. This, combined with lightness, excellent barrier properties and low cost, has led to the rapid expansion in use. There are six main polymers in production, but their properties are expanded by the inclusion of a range of additive substances, for example to improve UV resistance, plasticity, colour, impact-resistance and fire retardation.

There has been much discussion about the quantities of marine debris in the environment, where this material originates from and the route by which it reaches the ocean (Ryan et al. 2009, Cozar et al. 2014, Eriksen et al. 2014). Part of the difficulty in ascribing origin to marine plastic is that a significant proportion may be fragmented and difficult to identify. The ability to develop and implement targeted and effective mitigation and adaptation strategies, to reduce the quantities of litter entering the marine environment, will be severely compromised if key sources cannot be identified. In beach surveys, 'consumer waste' often makes up the greatest number of items identified. While consumer waste is undoubtedly a major source of marine litter, including plastic, it would be a mistake to underestimate the importance of other categories (for example: shipping, fisheries and aquaculture) that may represent an equal or greater risk to the marine environment in many regions.

Because of the difficulty and expense of data collection there are generally far fewer observations of floating litter, compared with shoreline litter, and even fewer observations of water column and seabed litter. However, away from the beach, the categories and relative proportions of marine litter tend to be quite different. For example, in those offshore studies that have been reported there tends to be a higher proportion of fishing-related debris, especially on the seabed (Pham et al. 2014).

Plastics fragment when exposed to UV irradiation, especially at higher temperatures and oxygen levels (Andrady 2011). This is greatest on tropical beaches but decreases rapidly at depth in the water column.

Sources can be described as predominantly land-based or sea-based. Some of the most important sources can be categorised as follows:

Land-based

- Coastal tourism/recreation
- Population centres
- Poorly controlled/illegal waste sites
- Industrial sites
- Agriculture
- Natural catastrophes (storms, floods and tsunamis)Sea-based
- Merchant shipping
- Cruise ships
- Fisheries/aquaculture
- Recreational boating
- Offshore oil & gas platforms

Land-based plastic may be transported to the ocean by water and wind. The same sources of litter tend to recur globally, but the relative importance of each source shows significant regional differences, corresponding to the degree of infrastructure development, the principle maritime or coastal industries and the extent of coastal tourism. Along busy shipping lanes, such as the southern North Sea and the Mediterranean, shipping-related debris is more prevalent. Equally, regions subject to intensive aquaculture or fisheries have a proportionately higher incidence of litter directly related to those activities. For example, fragments of expanded polystyrene from floatation blocks are common in the coastal waters of Korea, Japan and Chile where aquaculture is abundant. Cultural differences can influence the input of certain types of litter, such as the readiness to flush sanitary items with domestic sewage waste.

Once in the sea, floating litter is transported by ocean currents and rapidly becomes a transboundary issue. An unknown proportion sinks to the seabed either due to the inherent density of the plastic, once air has been excluded or due to an increase in density caused by biofouling (Holmström, 1975). The economic model used over the second half of the 20th century has been largely linear: raw materials –> manufacture –> use –> disposal. This is unsustainable in the longer term. It also relies on very effective systems for dealing with waste. Unfortunately, these are inadequate in many parts of the world. Poor waste management, combined with inappropriate use, unhelpful public attitudes and irresponsible behaviour, is the principal reason why plastic enters the marine environment.

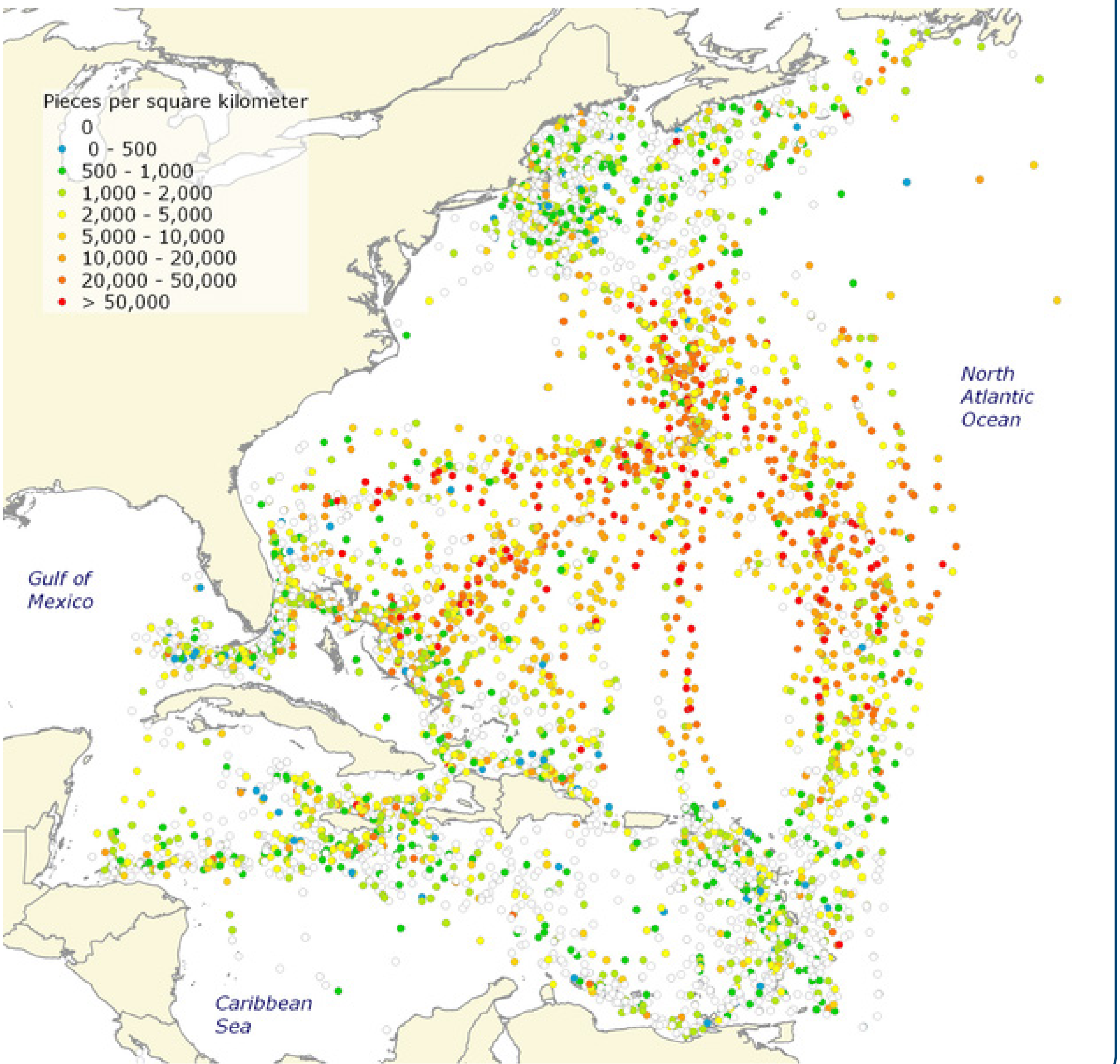
Floating plastics occur across a very wide size spectrum, from items several metres in diameter to nano-sized particles (<0.1 mm). There has been increasing interest in the occurrence of microplastics within the past decade. The term 'microplastics' was coined quite recently, in the mid-2000s (Thompson et al. 2004) and is now used extensively. However, there is a lack of consensus on the size of particles this refers to. Polymer spheres and irregular-shaped particles in the nano- to micro- size ranges are used in a wide variety of applications, including printer inks, spray paint, injection mouldings and personal health products such as toothpaste. Plastic resin pellets are produced as the basis for that part of the industry that converts these basic polymers into the enormous variety of goods on which modern society depends. These are typically spherical or cylindrical 1-5 mm in diameter, and there have been many reported incidents of accidental release on land and at sea. Efforts by industry to improve the handling of plastic pellets have brought about a decrease in the quantity of pellets in the environment (Ryan 2008).

Plastics have been shown to injure or kill many species of marine organisms (fish, birds, reptiles, mammals, invertebrates) by ingestion or entanglement. Floating plastic can cause significant loss of income to some social groups, such as fishers, and pose a hazard to navigation (for example: by blocking cooling water intakes on ships and fouling propellers).

Findings

The Sea Education Association (SEA) has collected zooplankton using towed nets in the western North Atlantic for many years. References to floating plastic micro-litter appeared in cruise reports from the early 1990s, although there are published records from the 1970s by other workers. The SEA began to systematically re-analyse archived zooplankton samples for the presence of microplastics and published a 20-year summary in 2010 (Morét-Ferguson

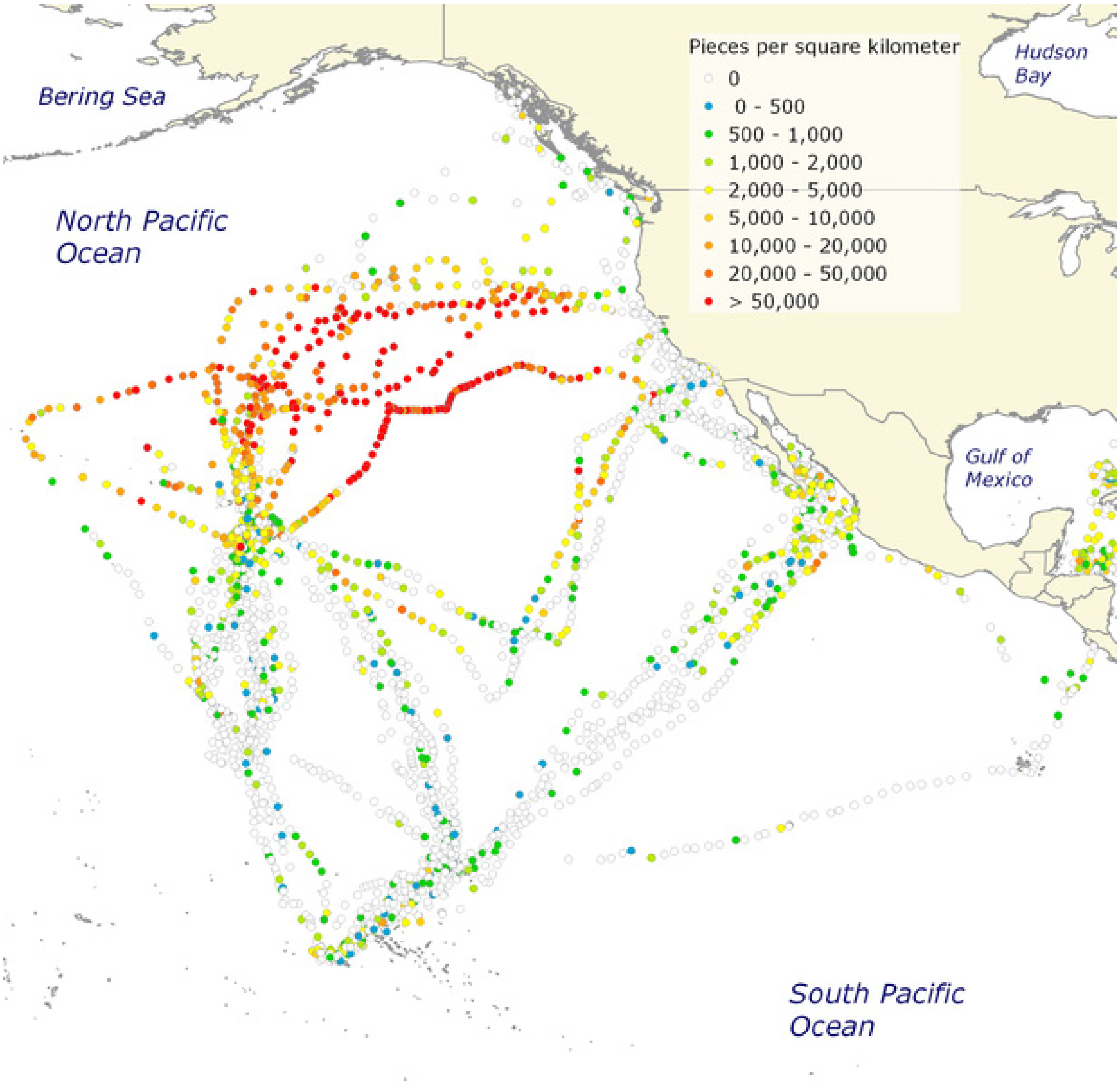
Figure 7.1. Density of floating microplastics (pieces km^{-2}) per year , from Sea Education Association expeditions to the western North Atlantic, 1986-2008 (see http://onesharedocean.org/open_ocean/pollution/floating_plastics)



et al. 2010). This represents the most comprehensive spatial and temporal survey in the global ocean, and clearly showed the overwhelming influence of the North Atlantic Gyre circulation. Most of the Atlantic and Pacific data are available for download (http://www.marine-geo.org/tools/search/entry.php?id=Pacific_Law).

The SEA has also been active in the eastern North Pacific and a similar 11-year dataset of microplastic abundance was published recently (Law et al. 2014). The influence of the sub-tropical gyre is again striking. However, a careful analysis of the data revealed significant differences in recorded abundance due to meso-scale eddies, wind-induced linear convergence zones or 'windrows' (due to Langmuir circulation) and similar features due to internal waves. Repeated year-on-year sampling at the same location failed to reveal a significant trend in abundance, presumably due to the spatial heterogeneity created by this physical forcing. An analysis by other researchers, comparing microplastic data from the period 1972–1987 with 1999 –2010 in the eastern North Pacific, did appear to show an increase in concentration of two orders of magnitude (Goldstein et al. 2012). However, uncertainties remain about the magnitude of the increase due to differences in sampling techniques and sampling strategy.

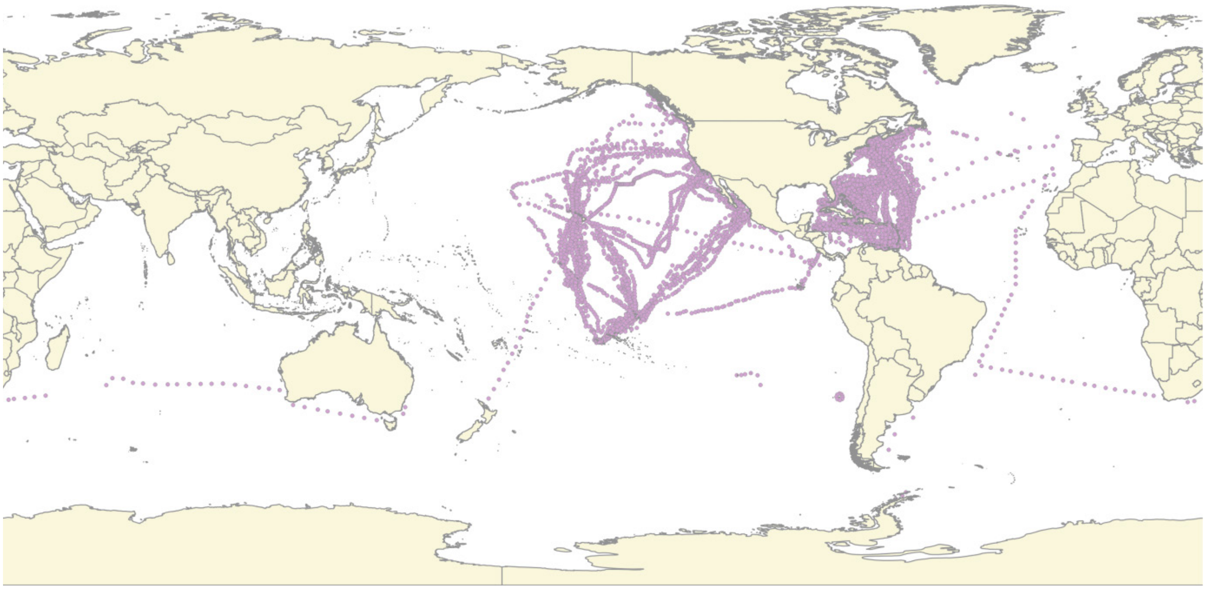
Figure 7.2. Density of floating microplastics (pieces km-2) per year, from SEA expeditions to the western North Pacific, (see http://onesharedocean.org/open_ocean/pollution/floating_plastics)



The 5 Gyres organisation, an NGO, has conducted a number of sailing expeditions in the South Pacific, North and South Atlantic and Indian Oceans (Eriksen et al. 2013; Eriksen et al.2014). These usually provide single transects but this still represents a valuable source of information from ocean regions that may not be visited regularly by more conventional research vessels. The Algalita Marine Science Association has helped raise awareness of marine litter, organising a number of expeditions in the eastern North Pacific to sample for microplastics. Algalita promoted the term 'North Pacific Garbage Patch' to describe the accumulation of plastic debris in the North Pacific Gyre. This had the unintended consequence of being translated in the media and public conscience to mean a floating island of waste material, variously described as being the size of Texas, or some other arbitrary unit of area depending on the national origins of the writer. This is far from reality.

A collation of the most comprehensive datasets was compiled by the TWAP group to produce a five-year 'synoptic' overview of the current status of the open ocean with respect to floating microplastics in surface waters (for example: plastic debris collected in a 330 µm towed net). A similar analysis of floating micro- and macro-debris, largely utilising previously unpublished data from 24 expeditions, was published in December 2014 (Eriksen et al. 2014),

Figure 7.3. Sampling locations for floating microplastics, compiled from published sources



Debris has been found washed ashore in the remote islands of the Pacific, Atlantic, Indian and Southern Oceans. This includes fishing gear, household items and microplastics. Such data provide the most reliable source of information about sources and trends, although they are not readily translated into '*items km*$^{-2}$' of the ocean surface. Observations of macro- and micro-plastics have been made in the Southern Ocean, despite the remoteness and difficulty of sampling in this environment (Barnes et al. 2010). These have included sea-based and shoreline observations, including the effects on local fauna (Ivar do Sol et al. 2011).

One of the consequences of catastrophic natural events, such as hurricanes and tropical storms (for example: Katrina, USA, 2005; Sandy, USA, 2012; Haiyan/Yolanda, Philippines, 2013), river basin flooding (for example: Bangkok, Thailand, 2011) and tsunamis due to seismic activity (for example Sumatra-Andaman earthquake & Indian Ocean tsunami, 2004), is that large quantities of debris can suddenly be introduced in coastal waters. This includes anthropogenic materials such as plastics, and the issue has come to prominence following the enormous devastation and human tragedy of the great Tohoku tsunami along the east coast of Japan on 11 March 2011. The Japanese government estimated that 5 million tons of debris entered the ocean, of which 70 per cent is thought to be lying on the seabed, leaving 1.5 million tons of floating material. This varies enormously in size and composition, ranging from floating docks and ships to household artefacts and the smallest items of litter. An unknown proportion will be composed of plastic. Monitoring using a mix of satellite, over-flight, ships' sightings and beach observations has helped to track the progress of the debris field. The distribution of floating plastic from this single event will continue to evolve for many decades to come.

Model simulations have proved to be very useful in predicting the transport pathways and transit times of debris fields from accidental releases and catastrophic events (Lebreton and Borroro, 2013). These range from plotting the distribution of cargo from individual stricken vessels, to large-scale events such as tsunamis. This can assist in evaluating potential navigation hazards as well as predicting when material can be expected to be start appearing on beaches (http://marinedebris.noaa.gov/tsunamidebris/). The HYCOM/NCODA model (Hybrid Coordinate Ocean Model/Navy Coupled Ocean Data Assimilation) was also used to provide an estimate on the global quantity of floating plastic based on the observed distribution of micro and macroplastic. It was estimated that there were more than 5 x 10^{12} pieces of floating litter, with a mass of 250,000 tonnes (Eriksen et al. 2014).

Modelling has also been used to simulate the input and transport of plastics from a number of sources. A group based in Australia and the USA combined the HYCOM/NCODA ocean circulation modelling system with the particle tracking dispersal model PoL3DD (Lebreton et al. 2012). Instead of assuming a uniform starting condition, as adopted by previous efforts (IPRC 2008), the team used three particle input scenarios: i) an impervious watershed, as a proxy for the input of debris as it relates to the degree of urbanisation and runoff; ii) coastal population density; and iii) shipping density. In year one, 100 000 particles were released and this was increased linearly, with 9.6 million particles being released over the 30 year simulation.

This revealed an apparently similar relative distribution of particles for each scenario, with higher quantities in the northern hemisphere due to the higher intensity of human population and shipping pressures. However, a more detailed examination of the data indicated significant differences in the relative importance of the three pressures represented by the scenarios chosen, in different accumulation zones.

Once plastic enters the sea the surface is rapidly colonised with biofilms (Zettler et al. 2013) and larger sessile organisms may become established. In time a new microcosm is created and this may be utilised by other organisms as a refuge, for feeding or reproduction (Barnes and Milner 2005; Goldstein et al. 2012). Rafting of organisms on floating debris is a natural phenomenon, but the increase in the number of floating items, combined with the durability of plastic, may represent a vector for the transport of non-indigenous species. This has been of particular concern in the USA and western Canada in the aftermath of the Tohoku tsunami.

Discussion and Conclusions

The social, economic and ecological impacts of macro-scale debris, especially plastic litter, have been clearly demonstrated, although it is difficult to quantify this in terms of monetary value or ecological significance. Plastic litter can have a direct impact on shipping as a navigation hazard, for example by cooling water intakes becoming blocked or propellers fouled. Many species have been shown to suffer injury and death from both entanglement and ingestion of larger debris, although it has proved more difficult to demonstrate this for microplastics.

Studies have shown that micro-particles can be ingested by filter-feeding organisms, and these have been observed to cross the gut wall and induce a reaction within the tissue. This is described in more detail in a separate assessment carried out by GESAMP (GESAMP 2015, www.gesamp.org). At a different scale, baleen whales, such as the endangered North Atlantic right whale (*Eubalaena glacialis*), feed on copepods and other small invertebrates by filtering enormous volumes of seawater. It is not known whether the presence of microplastics presents a potential additional stressor by clogging the baleen.

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Debris acts as vector for the transport of non-indigenous species (NIS). Because plastic does not degrade readily, unlike natural debris such as plant material, the potential distance over which NIS may be transported could be much greater.

Providing a clearer picture of the spatial distribution of macro- and micro-sized plastics, and the physical processes responsible for their transport, will allow potential management measures to be more clearly targeted. For example, this approach has been applied in the design of conservation measures to protect turtle populations off the coast of northern Australia from derelict fishing gear (Wilcox et al. 2014).

Some plastics contain additives to achieve certain properties (for example: flexibility, UV resistance, flame retardation), which have potential eco-toxicological impacts. What is not known with enough certainty is the degree to which this represents a potential exposure pathway. Even if there is some transfer from a particle into an organism, is this at a level that will result in a significant impact?

Seawater is contaminated with a wide variety of organic and inorganic pollutants. Many plastics absorb organic contaminants, such as PCBs (polychlorinated biphenols) and the pesticide DDT (dichlorodiphenyltrichloroethane), to a high degree. These compounds can cause chronic effects such as endocrine disruption, mutagenicity and carcinogenicity. They penetrate the structure of the plastic and it can take tens to hundreds of days to reach equilibrium with the surrounding seawater. Once ingested, the compounds may start to leach out, but the rate and direction of transfer will depend on the chemical environment in the organism's gut and the existing levels of those compounds in the tissue. Organisms become contaminated by contact with their environment and by ingesting contaminated food. Separating the potential additional contaminant burden due to microplastics remains extremely problematic.

Recommendations

As a result of discussions during the preparation of this report the contributors agreed a series of recommendations to improve the effectiveness of future assessments, including to:

- Encourage the harmonisation of sampling and analysis protocols to allow data on marine litter to be compiled more readily, including the use of automated systems;
- Examine ways of introducing sampling for marine litter as a routine operation on both research vessels and ships of opportunity, especially on regular cruise, ferry or commercial routes;
- Encourage the reporting of observations of marine litter in the water column and on the seabed from commercial fishing activities using towed nets, and from research organisations using nets, Remotely Operated Vessels (ROVs) and other sampling techniques;
- Promote closer working between international bodies (for example: FAO, IMO, UNESCO-IOC, IWC, CBD, ICES, PICES), regional organisations (for example: OSPAR, HELCOM, NOWPAP, MED-POL, Regional Fisheries Management Organisations (RFMOs), European Commission) and commercial bodies (for example: shipping companies), to encourage greater awareness, cooperation and data sharing;
- Maintain the OneSharedOcean.org website to allow the research and wider community make use of this as a continuing data repository and resource; and
- Promote the use of the improved evidence base to encourage the reduction in plastic litter entering the ocean, recognising that effective solutions will need to be supported multi-agency, multi-sector, regional and international efforts.

7.2.3 Notes on Methods

A small group of experts was assembled to examine and review published data on the occurrence of floating macro and microplastics in the ocean. The aim was to collate reliable data to establish spatial and temporal trends. It soon became evident that there was an overall paucity of data for many ocean regions. The first reports of floating litter were published in the early 1970s (Carpenter et al. 1972), but it proved to be very difficult to locate the originators of the study and the current data holders. In addition, there was a lack of detailed information on sampling positions and sampling methodologies.

Data of floating plastic debris have been collected for many decades, but the spatial extent and resolution of observations have increased significantly since 2000. This includes routine monitoring programmes set up at governmental level and ad-hoc surveys, as performed by NGOs. Of these the NOAA Marine Debris Programme (http://marinedebris.noaa.gov /) and the SEA (http://www.sea.edu/plastics/) have produced the most comprehensive datasets, with the North Pacific and North Atlantic sub-tropical gyres being the most studied.

Data on floating plastics are obtained by two main approaches: direct observation of larger items from ships (Ryan 2013); and, sample collection of smaller items using towed nets (Morét-Ferguson et al. 2010). A recent trend has been to try to utilise image recognition software to analyse camera images of larger items floating on the sea surface or of microplastics from on-line water sampling, but these techniques are at an early stage of development. Aircraft and satellite observations have also been used to track debris fields from catastrophic events, such as the great Tohoku tsunami in 2011.

Each method requires certain assumptions to be made about sampling efficiency and representativeness of the observations. This can impose limitations on the degree to which data from different sources can be combined reliably. Recommendations for more harmonised sampling, monitoring and assessment strategies have begun to be published (for example: Lippiat et al. 2013) which should improve the value and reliability of future monitoring data. Shoreline observations provide an additional data source, and are particularly useful in monitoring trends in litter accumulation in regions remote from the input sources, such as mid-ocean islands and at high latitudes (Barnes et al. 2010), although the results are sensitive to the frequency of sampling (Ryan et al. 2014).

Fragments of plastic cover a huge range of sizes, and defining what is and is not a ‘microplastic’ is a matter of debate. Many researchers now use the arbitrary upper size limit of 5 mm; a size that could be considered to be easily ingested by organisms such as fish and smaller seabirds, although for filter-feeding bivalves the size limit tends to be < 1 mm. The quantity of microplastics reported will depend on the size definition and the sampling methods used. The main message is that it is important to state the definition being used in every study.

Microplastics are usually collected using a neuston net or manta trawl, developed for zooplankton sampling, often using a 330 µm mesh and towing in the upper few centimetres. Nets with coarser mesh sizes have been used in some older surveys (for example: 505 µm, Goldstein et al. 2012). In addition, some results are reported by number and some by mass of particles, illustrating the need to re-analyse data from different sources are combined or compared. In addition, wave action can cause floating microplastics to be mixed to depths of several metres, lowering the observed surface concentrations by up to an order of magnitude. Observations of sea state should be made at the time of sampling to help in data interpretation, but this does not appear to have been a routine practice on some sampling campaigns. Such differences in sampling and reporting mean present difficulties when combining or comparing data.

Direct ship-based observations of floating litter have been by several researchers, usually from research vessels or ships of opportunity, and there have been attempts to collate the metadata about some of these published sources. For example, data from ship observations has been collated and compared with recent observations from the Bay of Bengal and Straits of Malacca (Ryan, 2013).

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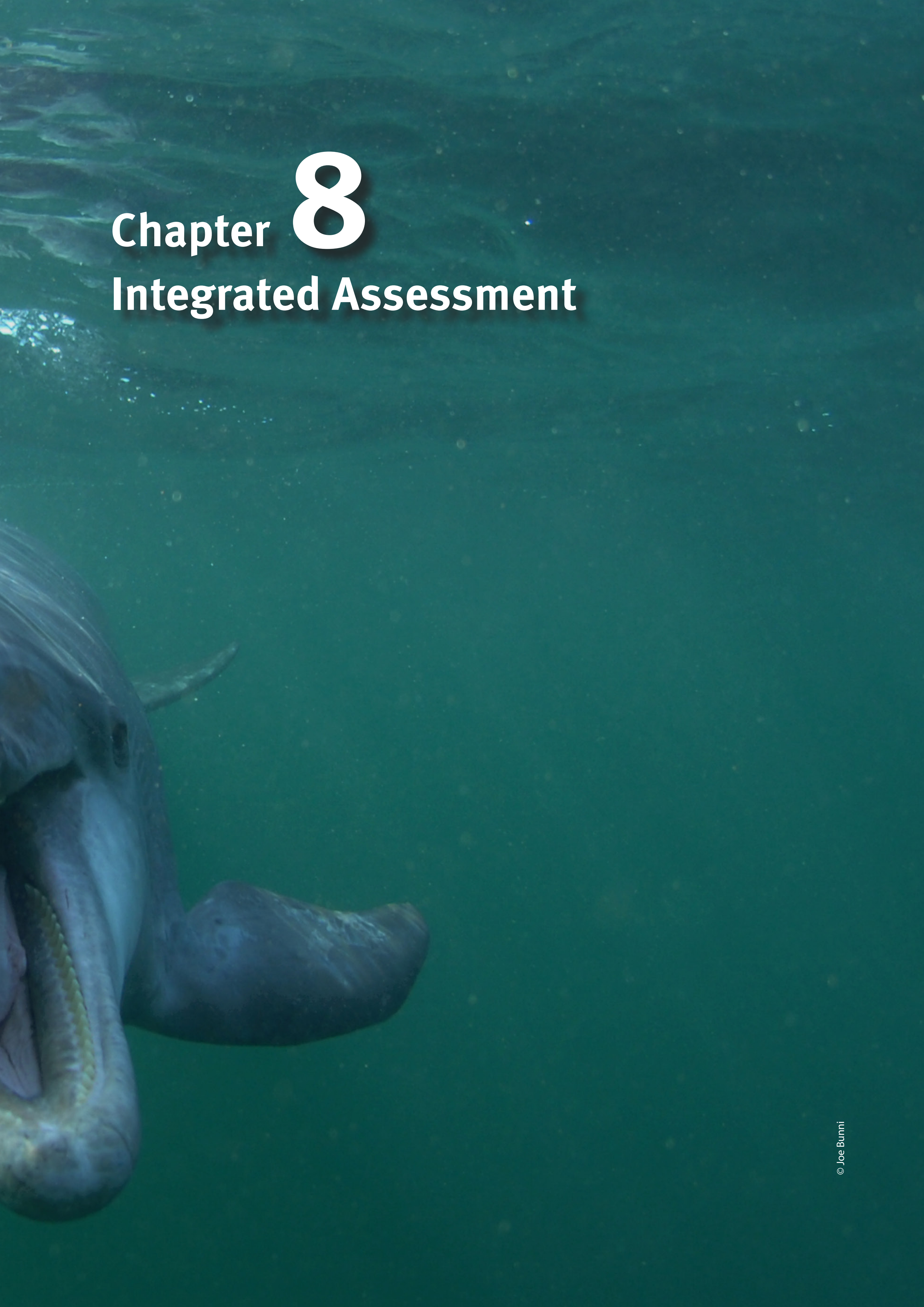
Chapter 8
Integrated Assessment



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Chapter 8.1 Cumulative Human Impacts in the Open Ocean

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Integrated Assessment

8.1 Cumulative Human Impacts in the Open Ocean

8.1.1 Summary and Key Messages

Marine ecosystems experience a wide range of stressors associated with human activities. These multiple stressors cumulatively impact systems in ways not always known, but their combined impact is always greater than the individual stressors. Recognition of the ubiquitous role of multiple stressors in marine ecosystems motivates management to focus on ecosystem-based management and marine spatial planning.

Assessing and mapping the cumulative impact of human activities on marine ecosystems provides a unique perspective and understanding of the condition of marine regions, and of the relative contribution of different human stressors to creating that condition. By focusing on the combined impact of multiple stressors within a common assessment framework, one that allows direct comparison among stressors and regions, cumulative human impact (CHI) assessments can feed directly into a wide range of possible policy decisions. In fact, the same approach has been applied to the Large Marine Ecosystem (LME) theme of the Transboundary Water Assessment Programme (TWAP), allowing for direct comparison between the LME and Open Ocean Assessment themes. CHI assessments can, for example, inform policy that aims to identify stressors with the greatest impact, rank regions most or least impacted, or highlight stressors that originate from one location but have key impacts in another region.

Stressors affecting the open ocean (also called high seas) regions largely fall into three main categories: climate change, commercial fishing, and commercial activity (such as shipping). A fourth category – land-based pollution – has essentially no effect on the high seas via watershed processes due to the large distance between land and the high seas, although may have impacts via atmospheric deposition of pollutants. To understand the relative importance of each stressor to a location, CHI assessments draw on data and information that map the location and intensity of stressors associated with human activities and the unique vulnerability of each habitat type to each stressor. The global assessment (which includes LMEs) draws on data for 19 stressors and 20 marine habitats from a variety of sources that provide globally-consistent outputs, with most data reported in 2011 or 2012 for inclusion in analyses of impact scores for the reporting year 2013. In the high seas, only 11 stressors and four habitats are present and thus relevant for the assessment.

Averaged across the area within each of 18 high seas regions (defined by FAO reporting regions), a relatively modest range of cumulative impact scores exists. In general, northern hemisphere high seas regions have higher impact scores, while polar regions tend to have lower scores. Several key results and messages emerge from the global analysis of cumulative human impact to high seas regions:

Key Messages

1. The most heavily impacted high seas regions are northern and central Atlantic and the northwest and western central Pacific, regions in closest proximity to Europe and China, where LME scores are also the highest (see the TWAP LME Technical Assessment Report, Chapter 7.2.4.);

2. The least impacted high seas region is the Arctic. Because this indicator does not project into the future, these results do not reflect any of the changes in condition that are expected to occur in the near future that will heavily impact these regions;
3. Stressors associated with climate change, most notably ocean acidification and increasing frequency of anomalously high sea surface temperatures, are the top stressors for nearly every high seas region. In part, this result emerges from the scale of assessment. At smaller scales, other stressors, such as commercial fishing, play a dominant role;
4. Commercial shipping and demersal commercial fishing that use gear on the seafloor (demersal fishing) are the other two main stressors at the scale of the high seas region. Stressors associated with these activities tend to affect different parts of the ecosystem, such that where they overlap in space, cumulative impacts are *likely* to directly affect the entire food web; and
5. Estimates of impact are *likely* conservative, as many stressors exhibit synergistic interactions with each other, where the total impact is greater than the sum of the individual impacts.

Efforts to manage marine ecosystems at the scale of high seas regions will require global coordination among countries, not only because the high seas are beyond the jurisdictions of national Exclusive Economic Zones (EEZs) but also because the key stressors are global in nature. Coordination among sectors will also be key to successful management because, the cumulative impacts on the system are much greater than what can be identified and addressed through single-sector management. Cumulative human impact (CHI) assessments provide a tool for transparently and quantitatively informing such policy processes and decisions.

8.1.2 Main Findings, Discussion and Conclusions

For millennia, humans have used the oceans for a wide range of purposes, including obtaining food through fisheries, getting rid of wastes, and navigating the planet. In the last century, due to rapid human population growth and the industrial revolution, these uses have become much more intense, widespread, and overlapping. We now live on a planet where no single patch of ocean remains untouched by human activities (Halpern et al. 2008), and a vast majority of marine ecosystems experience the impacts of multiple human uses simultaneously.

Even though high seas regions of the ocean are far from land and human populations, these regions still experience stressors related to commercial fishing, climate change, commercial shipping, and likely others. To understand the condition of high seas regions, one must therefore address the cumulative impacts of multiple stressors – any single-issue indicator, by default, will give an incomplete picture of the overall condition.

Managing for multiple stressors is inherently a transboundary challenge, as most stressors cross boundaries, including atmospheric pollutants produced by one nation and deposited elsewhere, fishing that targets fish stocks outside EEZ boundaries; and the global nature of commerce that connects patches of ocean to countries far away. The transboundary nature of multiple stressors is amplified in the high seas, where no country has jurisdiction of the regions and thus no responsibility or authority to manage any individual stressor let alone all of them. High sea regions thus provide a valuable lens through which to view these challenges and identify key opportunities for conservation and mitigation solutions.

Cumulative human impact (CHI) assessments track the change in intensity of human drivers and their associated stressors and model the expected change in ecosystem condition in response to these stressors. As such, CHI assessments capture stages 2-4 in the Conceptual Framework (see Section 2), spanning both the human and natural system. In combination with the Ocean Health Index (see the following Chapter 8.2 for more detail), measures of ecosystem service valuation, and governance assessments, a complete picture of high seas condition emerges.

Results

Most of the high seas regions have similar CHI scores, with all but one within one standard deviation of the average score (3.265). The highest scores are in the northern and central Atlantic and the northwest and western central Pacific, regions in closest proximity to Europe and China (See Figure 8.1), where LME scores are also the highest (see the TWAP LME Technical Assessment Report, Chapter 7.2.4). The lower range of scores included the three Antarctic (southern) Ocean regions and the southeast and eastern central Pacific. Only the Arctic has a relatively *low* average CHI score (0.743). This is not surprising as most of the Arctic high seas region has been under permanent sea ice until very recently, and even now it is generally too risky for most human use and exploration of the region.

Three stressors related to climate change – ocean acidification, changing sea surface temperature (SST), and increasing UV radiation – contributed most to the cumulative impact score for each high seas region (Table 8.1). In fact, these three stressors accounted for >80% of cumulative impact for all regions, and in over half of the regions accounted for >95% of cumulative impact.

The other main stressors in the high seas are shipping and ocean-based pollution, which are derived from the same input data source (commercial shipping traffic). Global shipping routes that pass through the high seas primarily occur in the northern hemisphere, connecting Europe and North America and Asia and North America. Thus, shipping impacts are primarily concentrated in the northern Atlantic and northern Pacific regions.

Commercial fishing has relatively *low* impact scores for nearly all high seas regions. The one exception is the western central Pacific high seas region, where demersal non-destructive (both high and *low* bycatch) and pelagic *low* bycatch fishing have significant impact. Although commercial fishing in the high seas can be intense in certain locations, only six nations actively fish the high seas (White & Costello 2014) and catch is relatively *low* compared to coastal areas within EEZs.

Figure 8.1. Map of open ocean regions (by FAO fishing area) and their average cumulative impact score

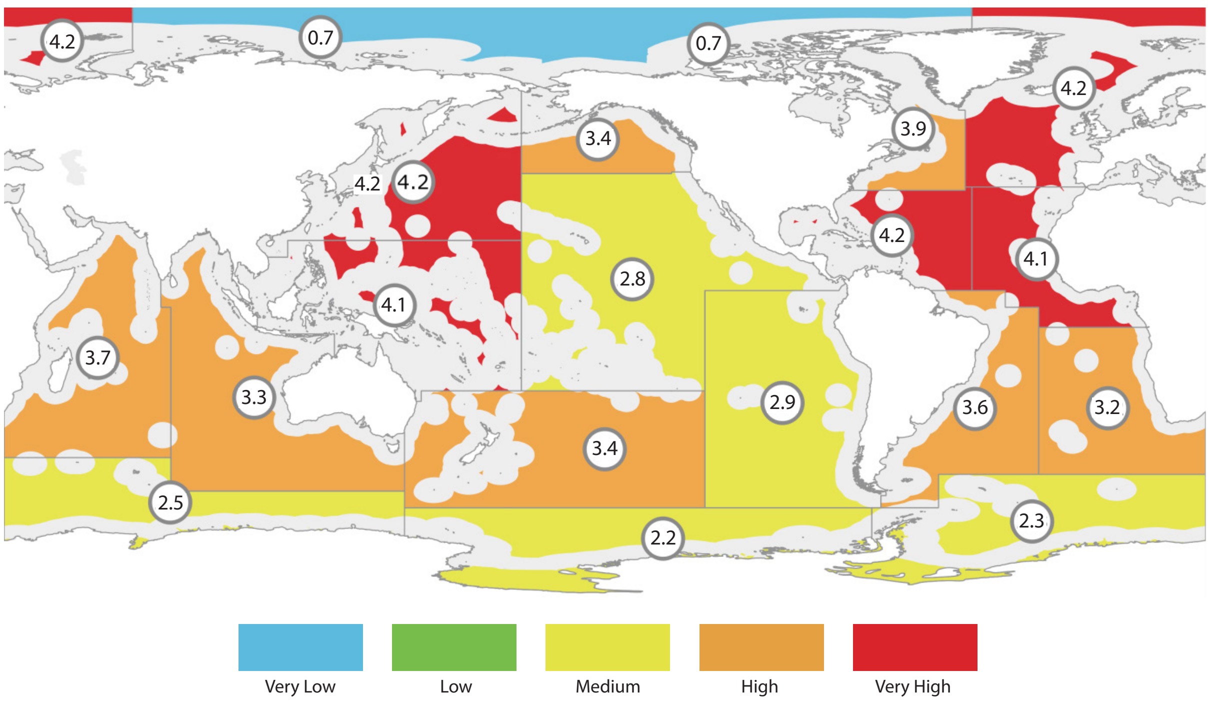

Table 8.1 Full results of CHI and individual stressor impact scores for each high seas region. True zero values are indicated by zeros without decimal points; zero values with decimal points are extremely low but non-zero scores.

FAO region	Name	CHI	Climate Change				Industry		Commercial Fishing				
			SST	UV	Ocean Acidification	SLR	Ocean-based pollution	Shipping	Demersal Destructive Fishing	Demersal Non-destructive High Bycatch Fishing	Demersal Non-destructive Low Bycatch Fishing	Pelagic High Bycatch Fishing	Pelagic Low Bycatch Fishing
18	Arctic Sea	0.743	0.017	0.015	0.708	0.000	0.001	0.001	0.000	0.000	0	0	0
21	Atlantic, Northwest	3.887	1.351	0.818	1.138	0.002	0.344	0.210	0.017	0.004	0.002	0	0.001
27	Atlantic, Northeast	4.200	1.817	0.730	1.126	0.000	0.310	0.196	0.017	0.001	0.003	0	0.001
31	Atlantic, Western-Central	4.217	1.799	0.743	1.251	0	0.250	0.147	0.003	0.003	0.009	0.005	0.005
34	Atlantic, Eastern Central	4.104	1.911	0.742	1.168	0.000	0.149	0.086	0.001	0.001	0.018	0.004	0.024
41	Atlantic, Southwest	3.634	1.633	0.795	1.092	0.000	0.058	0.032	0.010	0.004	0.003	0.005	0.003
47	Atlantic, Southeast	3.237	1.306	0.789	1.030	0.000	0.069	0.038	0.000	0.000	0.003	0.000	0.002
48	Atlantic, Antarctic	2.274	0.788	0.720	0.736	0	0.015	0.008	0.001	0.000	0.005	0	0.000
51	Indian Ocean, Western	3.689	1.601	0.743	1.146	0.000	0.087	0.049	0.010	0.008	0.017	0.002	0.024
57	Indian Ocean, Eastern	3.265	1.296	0.787	1.043	0.000	0.057	0.031	0.004	0.014	0.013	0.006	0.015
58	Indian Ocean, Antarctic & Southern	2.452	0.907	0.799	0.721	0.000	0.016	0.009	0.001	0.000	0.000	0.000	0.000
61	Pacific, Northwest	4.177	1.720	0.777	1.090	0	0.276	0.160	0.013	0.064	0.060	0.000	0.016
67	Pacific, Northeast	3.420	1.113	0.836	0.929	0	0.335	0.197	0.002	0.002	0.003	0	0.003
71	Pacific, Western Central	4.118	1.602	0.694	1.148	0.000	0.133	0.075	0.020	0.103	0.146	0.000	0.198
77	Pacific, Eastern Central	2.813	0.727	0.732	1.083	0	0.152	0.086	0.001	0.006	0.009	0.005	0.012
81	Pacific, Southwest	3.440	1.532	0.815	1.018	0.000	0.044	0.024	0.002	0.002	0.001	0.000	0.001
87	Pacific, Southeast	2.916	1.028	0.773	0.961	0.000	0.045	0.024	0.003	0.031	0.037	0.001	0.012
88	Pacific, Antarctic	2.186	0.710	0.750	0.703	0.000	0.011	0.006	0.002	0	0.000	0	0.003

Note: Eight of 19 stressors included in the CHI assessment are coastal and thus do not affect open ocean systems. They all had zero impact on all FAO high seas regions; they include: artisanal fishing, nutrient pollution, organic pollution, inorganic pollution, light pollution, oil rigs, invasive species, and direct human impacts

Discussion and Conclusions

Nearly all high seas regions are experiencing *moderate* to *high* levels of cumulative impact, primarily due to impacts from climate change. Therefore, managing the high seas and mitigating human pressures by necessity requires addressing climate change. Climate change stressors are the only ones that are truly global, and thus have the potential to impact every square kilometre of the high seas. This global scale contributes to climate change consistently being the highest scoring stressor. The addition of information on stressors that currently do not have global data, in particular atmospheric deposition of key pollutants and marine debris, would increase the cumulative impact for at least some of the high seas regions, but would unlikely change the result that climate change stressors are the dominant impact to high seas regions.

The issue of scale of assessment has important implications for how results presented here can inform policy and management actions. For actions at the scale of entire high seas regions (or entire ocean basins), such as allocating funding among different oceanic regions, these results are useful for identifying high seas regions most in need of conservation and mitigation resources. Within a high seas region, however, these results will have more limited relevance, and decisions would benefit from a regional analysis focused on smaller scale outputs. For example, decisions about where or how to allocate funds to particular locations within a high seas region, or which stressors to mitigate first for particular locations, would all require finer-scale analyses.

The only high seas region to have relatively *low* scores was the Arctic, where sea ice has covered nearly the entire area until very recently. As climate change stressors continue to alter the Arctic, in particular by melting the sea ice, this region's cumulative impact score is *likely* to jump much higher. Careful and strategic management of shipping, fishing and other uses of the area will be important to help prevent overall cumulative impact from getting too high for the region.

The social and economic implications of these results are challenging. Most of the main stressors at the scale of entire high seas region are driven primarily by global forces that are external to the region. Climate change is fueled by global emissions, and commercial shipping by global trade and trade routes. To mitigate these stressors requires truly global efforts. This global need is even more pronounced in the high seas where countries lack jurisdictional authority.

Results from CHI assessments only capture half of what needs to be known and understood for measuring the condition of high seas regions. CHI assessments measure and indicate human activities, their associated stressors, and the expected impact on ecosystems. Missing from these assessments is how the change in ecosystem condition affects the delivery of services to people and how that in turn affects governance and management decisions. Connecting CHI assessments to the scale and location of service delivery (instead of the entire high seas region) would *likely* produce very different results and potentially be much more informative.

Cumulative human impact (CHI) assessments were also done for LME systems, providing an opportunity to directly compare all regions of the world's ocean with the same indicator. Similar CHI assessments have been done for river systems (Vorsmarty et al. 2010). As such, CHI assessments within LMEs provide a powerful tool for linking the assessment of these three water systems in TWAP.

Cross-system comparisons are made possible by the fact that CHI assessments are quantitative and measured in the same, universal metric of impact to ecosystems. Because CHI assessments are fully transparent in their methods and process, they can easily be repeated (to check results or to update with new data) and they are more amenable to policy and management decisions. Transparency and repeatability are hallmarks not only of the scientific process but are also essential for decision-making if it is to be trusted by all involved and effected.

All indicators rely on the underlying data that informs them. Uncertainty in CHI assessments is thus dependent on the quality and certainty of all of the input data, including information on habitat extent and the location and intensity of human stressors. Uncertainty is highest at the finest resolution of assessments permitted by these data (1km^2), with resulting '*medium* certainty' in cumulative impact scores at this resolution. At larger scales, in particular at the scale of an entire high seas region, certainty is '*high*' for overall scores, and especially for the relative quantitative difference in scores among regions. A full discussion of assumptions and caveats to CHI assessments is provided elsewhere (Halpern and Fujita 2013).

Recommendations

Much of the area far offshore but still within EEZs is essentially identical to the high seas in terms of component ecosystems and the pressures and impacts to those ecosystems. Managing high seas regions will benefit greatly from coordination with surrounding countries. Because relatively few human activities occur in the high seas, the dominant stressors to the regions result from climate change, although the remoteness of the high seas means they are poorly monitored, limiting our understanding of the location and types of habitats and the extent and intensity of key stressors such as atmospheric pollution and commercial fishing. Meaningful management and stressor mitigation in the high seas must focus on global approaches to reducing carbon emissions, and will also benefit from improved monitoring and assessment.

8.1.3 Notes on Methods

Full details on data sources and processing are provided in extensive supplementary information provided in Halpern et al. (2015). In summary, data layers were developed as follows. Sea surface temperature (SST) and UV layers were based on satellite time series data, and both were processed to assess the number of values that exceeded one standard deviation above the long term average. Ocean acidification and sea level rise (SLR) were both modeled globally and processed as the difference between current and historic values. The five commercial fishing layers were based on spatially-allocated FAO catch data assigned to one of the five fishing gear types. Commercial shipping was based on voluntary monitoring data from ships and processed into shipping tracks across the ocean. Annex A summarizes key attributes of each data layer. Key stressors missing from the analysis include atmospheric pollution and marine litter, and high resolution data on the location and types of habitats in the high seas remain limited.

Intensity values for each stressor and presence/absence for each habitat layer are processed to be at 1km^2 resolution, requiring down-scaling for some layers (for example: finer resolution is modeled for data at coarser native resolution). All stressor layers are normalized to their reference, or maximum, value to allow direct comparison of stressors measured in very different units. Finally, normalized stressor intensity values are multiplied by the habitat vulnerability weight unique for each stressor-habitat combination to create a modeled impact score, and these impact scores are summed by habitat type to create a per-habitat cumulative impact score and averaged across habitats to create a final per-pixel cumulative impact score.

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Annex A

Summary of data layers used to calculate CHI. Only layers relevant to the high seas are included.

Data Type	Layer	Native resolution	Source
Stressors			
Fishing	Demersal, destructive	half-degree	Sea Around Us
	Demersal, non-destructive, high-bycatch	half-degree	Sea Around Us
	Demersal, non-destructive, low-bycatch	half-degree	Sea Around Us
	Pelagic, high-bycatch	half-degree	Sea Around Us
	Pelagic, low-bycatch	half-degree	Sea Around Us
Climate Change	SST	~16km^2	NOAA
	UV	half-degree	NOAA
	Ocean acidification	half-degree	Halpern et al. 2008
	Sea Level Rise	quarter-degree	Nicholls & Cazenave 2010
Ocean-based	Shipping	~25km^2	VMS AIS data
	ocean-based pollution	1km^2 (modeled)	Shipping + port volume
Habitats			
Offshore	Seamounts	1km^2 (modeled)	Halpern et al. 2008
	Hard shelf (60-200m)	1km^2 (modeled)	Halpern et al. 2008
	Soft shelf (60-200m)	1km^2 (modeled)	Halpern et al. 2008
	Hard slope (200-2000m)	1km^2 (modeled)	Halpern et al. 2008
	Soft slope (200-2000m)	1km^2 (modeled)	Halpern et al. 2008
	Hard deep (>2000m)	1km^2 (modeled)	Halpern et al. 2008
	Soft deep (>2000m)	1km^2 (modeled)	Halpern et al. 2008
	Pelagic surface (0-60m)	1km^2	Halpern et al. 2008
	Deep pelagic (>60m)	1km^2	Halpern et al. 2008

Chapter 8.2 Ocean Health Index for the Open Ocean

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8.2 Ocean Health Index for the Open Ocean

8.2.1 Summary and Key Messages

One of the greatest challenges for resource management is to comprehensively understand the condition of coupled human-natural systems, and make informed decisions about how best to improve them. Too often monitoring, assessments, indicators, and decisions are made within a single sector or with a single objective in mind, without full consideration of the broader implications of those actions. Both ecosystem-based management and marine spatial planning aim to overcome these management barriers, but relatively few tools exist to directly inform and support such comprehensive management approaches. Without a tool to measure overall ecosystem health and track progress towards improving it, we cannot effectively manage towards multiple integrated objectives. We need a transparent and quantitative means to make such assessments. In the marine environment, this challenge particularly persists in areas beyond national jurisdictions (ABNJ), beyond 200 nm from the coast: the high seas.

The Ocean Health Index (OHI) was developed in part to address this need. Using a common framework, the Index measures the performance of ten widely-held public goals for a healthy ocean, including food provision, carbon storage, coastal livelihoods and economies, and biodiversity (Table 8.1). Each goal is assessed against an ideal state, defined as the optimal, sustainable level that can be achieved for the goal. Global datasets spanning ecological, social, economic, and governance measures are used for the assessments. To date, three annual assessments have been completed at the global scale for the years 2012 through 2014 for each of 221 coastal countries or territories (exclusive economic zones; EEZs). In the most recent assessment, the Index was calculated for the high seas regions of 15 Food and Agriculture Organization (FAO) marine major fishing areas. Because many of the ten goals in the Index are driven by direct human interaction with the ocean (for example: coastal livelihoods) or benefits from the ocean (for example: coastal protection), the high seas are assessed on the subset of goals that are relevant to ocean health in these remote areas. Here we focus on these high seas results.

Ocean Health Index (OHI) scores for the 15 high seas regions ranged from 53 to 79 out of 100 (average per-region score, 66), with all high seas regions together scoring 67. The lowest scoring high seas regions were in each of the main ocean basins (Arctic, Pacific, Indian and Atlantic), as were the highest scoring regions (excluding the Arctic). Very few goals from the Index framework are relevant to high seas, so high seas scores were primarily driven by the status of biodiversity and wild-caught fisheries. Data deficiencies for both of these goals create some uncertainty in overall scores.

Key Messages

Four key results and messages emerge from this assessment of overall ocean health in the high seas:

1. On average, the high seas scored lower according to the OHI than coastal regions, confirming the need for coordinated international action to better manage these areas beyond national jurisdiction;
2. For all regions, there remains substantial opportunity to improve the sustainability of harvest of wild caught fisheries. Achieving this outcome could benefit global food security;
3. Biodiversity in the high seas is at slightly less risk of extinction than in most coastal waters, although the subset of species iconic to people are proportionally faring much worse in the high seas, particularly in the Arctic; and
4. Many aspects of ocean health in the high seas remain poorly monitored, hindering our ability to comprehensively assess ocean health across space. Improving data reporting standards from all UN member states, especially for fisheries catch and better monitoring of deep-sea habitats, would significantly aid assessments of ocean health and decision making based on those assessments.

Management of the high seas should ideally be comprehensive and span the ecological, economic and social aspects of how people interact with ocean ecosystems. Such management is challenged when faced with disparate data and information focused on different aspects of the human and natural system; integration is left to the individual and is often *ad hoc*. The OHI provides a framework for combining this disparate information into a single, comparable, quantitative and transparent measure of ocean health and its many component factors. The Index highlights the relative performance of different human values and goals for the ocean, and with repeated calculations can help elucidate where and why tradeoffs among goals may occur under different management actions.

8.2.2 Main Findings, Discussion and Conclusions

People value ocean ecosystems for the food they provide, the aesthetic beauty they carry, the livelihoods they support, and the existence and vast diversity of species within them. Even though the relative importance of each of these benefits varies from person to person, their value is nearly universal. The ocean enriches our lives in many ways, but the sustainable delivery of these benefits is jeopardized when ocean health is compromised. Although the high seas are rarely visited by people, they support key goals people have for the ocean, most notably food provision through wild-caught fisheries and the iconic and existence value of species. To fairly assess the condition, or health, of the high seas, one must measure the status of all relevant goals achieved from high seas ecosystems.

Managing for ocean health is inherently a transboundary challenge, as many processes that produce and support the values we have for ocean ecosystems cross national boundaries, including: provision of seafood from fish stocks straddling boundaries or largely unregulated in the high seas, existence value of the many migratory species making up the ocean's rich marine biodiversity, and the cultural and spiritual value of iconic species through which we relate to the ocean. Exploring how these goals are faring in the high seas provides a valuable lens through which to view these issues and the challenges they represent, and through that lens we can identify key opportunities to enhance their sustainable delivery to people, conserve and protect the underlying processes supporting the values, and mitigate threats to them.

The OHI tracks the current status and expected future condition of these human values for ocean ecosystems. It does this by assessing the cumulative stressors on ecosystem services and tracking the resulting status of the sustainable delivery of services to people. It also incorporates measures of governance as a means of quantifying the potential resilience of the system. As such, the Index directly captures stages 4-6 in the Conceptual Framework (see Section 2) and indirectly stages 1a and 3, thus spanning both the human and natural systems. In combination with cumulative human impact (CHI) assessments, which directly measure the connection between stages 3 and 4, ecosystem service valuations, and more comprehensive governance assessments, a complete picture of high seas condition emerges.

Table 8.2 Name, abbreviation (in parentheses) and definition of each goal and sub-goal of the Ocean Health Index. Only those goals and sub-goals marked with an * were assessed for the high seas.

Goal	Sub-goal	Definition
*Food provision (FP)	*Fisheries (FIS)	Harvest of sustainably caught wild seafood
	Mariculture (MAR)	Production of sustainably cultured seafood
Artisanal fishing opportunity (AO)		Opportunity to engage in artisanal-scale fishing for subsistence and/or recreation
Natural products (NP)		Sustainable harvest of natural products, such as shells, algae, and fish oil used for reasons other than food provision
Carbon storage (CS)		Conservation status of natural habitats affording long-lasting carbon storage
Coastal protection (CP)		Conservation status of natural habitats affording protection of the coast from inundation and erosion
Tourism & recreation (TR)		Opportunity to enjoy coastal areas for recreation and tourism
Coastal livelihoods & economies (LE)	Coastal livelihoods (LIV)	Jobs and wages from marine-related sectors
	Coastal economies (ECO)	Revenues from marine-related sectors
*Sense of place (SP)	*Iconic species (ICO)	Cultural, spiritual, or aesthetic connection to the environment afforded by iconic species
	Lasting special places (LSP)	Cultural, spiritual, or aesthetic connection to the environment afforded by coastal and marine places of significance
Clean waters (CW)		Clean waters that are free of nutrient and chemical pollution, marine debris and pathogens
*Biodiversity (BD)	Habitats (HAB)	The existence value of biodiversity measured through the conservation status of habitats
	*Species (SPP)	The existence value of biodiversity measured through the conservation status of marine-associated species

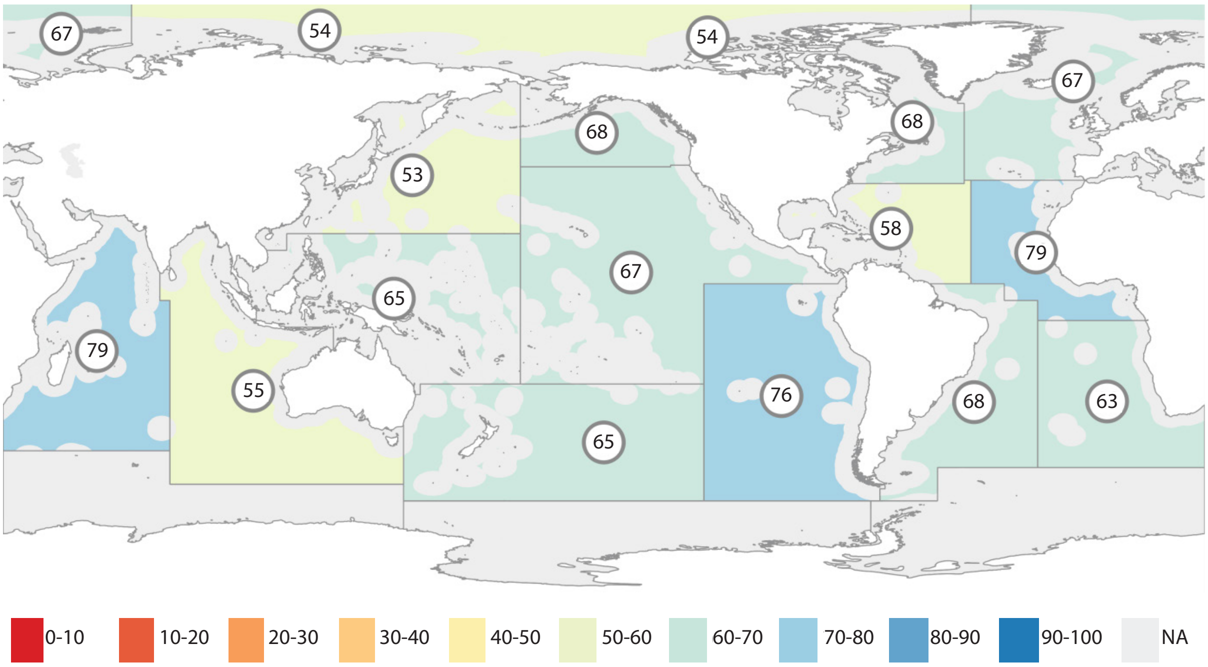
Results

Overall Index scores varied from 53 to 79, with an average regional score of 66 and an area-weighted total high seas score of 67 (Figure 8.2). The highest scoring regions were the Western Indian Ocean (79), the Eastern Central Atlantic (79) and the Southeast Pacific (76), while the lowest scoring regions were the Pacific Northwest (53), Arctic Sea (54), and Eastern Indian Ocean (55; see Table 8.3). These scores suggest a lot of room for improvement in ocean health – substantial room in the lowest scoring regions – but also that some dimensions of ocean health are faring better (described below). In general, high seas regions scored lower than EEZ regions globally, except for species biodiversity, which scored slightly higher in the high seas (Table 8.3).

Overall Index scores were largely driven by differences in the scores for the fisheries sub-goal. Scores for the fisheries sub-goal were much more variable, and were sensitive to the underlying stock assessment models used and the composition of stocks (for which catch data were reported) in each region. The highest scoring regions on the fisheries sub-goal were the Eastern Central Atlantic (81) and the Western Indian Ocean (80), but both had catch dominated by three tuna species that data-limited assessment models predict are currently sustainably fished. The lowest scoring regions were the Pacific Northwest (6), Eastern Indian Ocean (8) and Western Central Atlantic (11).

High seas regions differed very little in the species biodiversity scores, with all regions except the Arctic scoring between 79 and 84 (see Table 8.3). On average, these scores are similar to those in coastal (EEZ and Large Marine Ecosystem (LME)) waters (see the TWAP LME Technical Assessment Report Chapter 7.2.5), indicating that biodiversity (that has been assessed) may be at similar risk in the high seas. The Arctic scored significantly lower than other high seas regions for biodiversity (66), largely due to having relatively few assessed species for the region and a much higher proportion of those at risk of extinction. Similar patterns are seen for the iconic species sub-goal, which is

Figure 8.2. Map of Ocean Health Index (OHI) scores per FAO high seas region.



based on a subset of species that are culturally important to people. The same set of species was considered iconic for all regions of the high seas (their differential distribution determined the different scores for this sub-goal). Most high seas regions scored between 71 and 81 for the iconic species sub-goal, with the Western Central Pacific scoring higher (85) and the Northwest Atlantic, Northeast Atlantic, and Arctic all scoring lower (63, 61, and 41, respectively).

Table 8.3 Full results of Ocean Health Index (OHI) scores and component goal scores for each high seas region. Only three sub-goals were assessed for the high seas; the goal scores are thus determined solely by the sub-goals. See Table 1 for goal and sub-goal abbreviations.

High Seas Region	Index	FP (FIS)	SP (ICO)	BD (SPP)
All high seas	67	45	75	80
Pacific, Northwest	53	6	71	81
Arctic Sea	54		41	66
Indian Ocean, Eastern	55	8	78	80
Atlantic, Western-Central	58	11	81	83
Atlantic, Southeast	63	34	77	80
Pacific, Southwest	65	43	75	79
Pacific, Western Central	65	30	85	82
Pacific, Eastern Central	67	47	74	79
Atlantic, Northeast	67	61	61	81
Pacific, Northeast	68	48	71	84
Atlantic, Southwest	68	45	79	80
Atlantic, Northwest	68	63	63	79
Pacific, Southeast	76	74	74	79
Atlantic, Eastern Central	79	81	74	83
Indian Ocean, Western	79	80	76	81
All EEZs	67	59	60	83

Discussion and Conclusions

Overall, the high seas scored lower on the OHI than waters within EEZs, primarily due to the limited number of goals that are relevant and assessable in the high seas and the relatively poor performance of those goals. The range of scores was smaller in the high seas than EEZ regions, with the former ranging 53-79 (Table 8.3) and the latter ranging 45-94 (Halpern et al. 2015). This is *likely* due to the larger size of high seas regions (goal scores tend to be less extreme when averaged over larger areas) and the fewer number of reporting regions (15 high seas regions versus 220 coastal regions).

No ocean-basin scale patterns in Index scores emerged. The highest scoring and lowest scoring high seas regions were found in each of the main ocean basins (Table 8.3). These patterns were largely driven by the scores for fisheries, as this goal had the largest range of values (and was one of just three goals that could be assessed). Given the large role that fisheries play in determining overall ocean health in the high seas, improving the taxonomic and spatial resolution of catch data being reported to FAO, as well as further improvement of models used to assess data-limited stocks, would go a long way towards improving the accuracy, and thus utility, of assessments of the health of the high seas. Assessment, and ultimately management, of high seas fisheries is compounded by the fact that most stocks straddle EEZ boundaries (often multiple EEZs), requiring multilateral as well as global efforts to address fisheries management.

Scores for species biodiversity and iconic species represent the average of the status of all (assessed) species that overlap a reporting area; regardless of the amount of area each species potentially occupies (Halpern et al. 2012). Because of the very large size of each high seas region, more smaller-range species are *likely* to overlap with the region than might be expected in smaller areas, such that these species have a stronger influence on scores. Smaller-range species tend to have higher extinction risk (Gaston 1998). These patterns in biodiversity scores in turn influence overall OHI scores. For example, the poor performance of ocean health in the Arctic high seas region is solely due to the high level of extinction risk to the species in that region, given that no other goals, including fisheries, were relevant or measurable in the region. In particular, a large proportion of iconic species in the Arctic are faring poorly, most notably the fin whale (*Balaenoptera physalus*) and the polar bear (*Ursus maritimus*). Ocean health in the Arctic high seas would benefit from strong measures to protect and restore biodiversity. See Section 3 for more details on governance.

The high seas represent nearly two-thirds of the world's ocean, yet this large area is divided into only 15 separate regions that were assessed here (due to FAO delineations and data resolution constraints), compared to 220 EEZ regions (summarized for 66 LMEs in the TWAP LME Technical Assessment Report Chapter 7.2.5). The ability to monitor and manage the high seas is challenged by the huge scale of these regions. The condition and location of the goals being delivered by these regions is almost certainly highly variable spatially across each region; informed decision-making would thus benefit from higher resolution assessments, which depends on higher resolution monitoring and reporting data.

Cross-system comparisons are made possible by the fact that OHI assessments are quantitative and measured in directly-comparable metric. Because Index assessments are fully transparent in their methods and process, they can easily be repeated (to check results or to update with new data) and they are more amenable to policy and management decisions. For example, OHI assessments were also done for LMEs, providing an opportunity to directly compare all regions of the world's ocean with the same indicator. Transparency and repeatability are hallmarks not only of the scientific process but are also essential for decision making if it is to be trusted by all involved and effected. All indicators rely on the underlying data that informs them. Uncertainty in OHI assessments is thus dependent on the quality and certainty of all of the input data. This concern is particularly true for assessment of fisheries in the high seas. Furthermore, key gaps remain for assessment of certain goals of the Index in the high seas (in particular pollution and its influence on the clean waters goal and the location and condition of habitats and the influence of that on the biodiversity goal), leading to higher uncertainty in assessments of overall ocean health than was possible for the LMEs. Most notably missing from this assessment is the status of deep-sea habitats. Although physical maps of these habitats exist, almost no information exists on their condition relative to historical, undisturbed baselines.

Results from OHI assessments capture most of the dimensions of the Conceptual Framework (see Section 2) that defines what needs to be known and understood for measuring the condition of high seas regions. Missing from these assessments is direct measure of how human pressures affect ecosystem state (although this is indirectly captured in the Index), and how changes in the components of the Index may (or should) affect governance and management decisions. In particular, climate change and its associated pressures on the ocean (increasing temperatures and acidification, and potential deoxygenation) are not directly transparent in the Index (although they are captured in the CHI assessment; see Chapter 8.1), and their future impact on the ocean is expected to be particularly large (Harley et al. 2006 and also see Sections 4 and 5 of this Report) but is not part of the Index beyond near (5 year) timeframe.

Connecting Index assessments to the scale and location of service delivery (instead of the entire high seas region) would *likely* produce very different results and potentially be much more informative. In particular, although it is possible to achieve a perfect score on all goals in the Index simultaneously, most actions and changes in the system result in tradeoffs among goals. For example, patches of the high seas that are highly productive and thus heavily fished may offer high levels of food provision but at cost to the status of iconic species that feed in that region. Improved and higher-resolution maps of where such tradeoffs *likely* occur would allow for much more informed decision-making regarding strategies to mitigate impacts and improve ocean health.

Managing the high seas is challenged by at least two broad issues: lack of comprehensive assessment and lack of strong governance institutions. The assessment reported here helps address the first of these; the latter is an active topic of research and discussion (for example: Berkman and Young 2009). As future assessments help refine our understanding of the spatial pattern of the health of the high seas and new institutions are developed or existing ones strengthened, the tools will be in place to significantly improve ocean health in the open ocean.

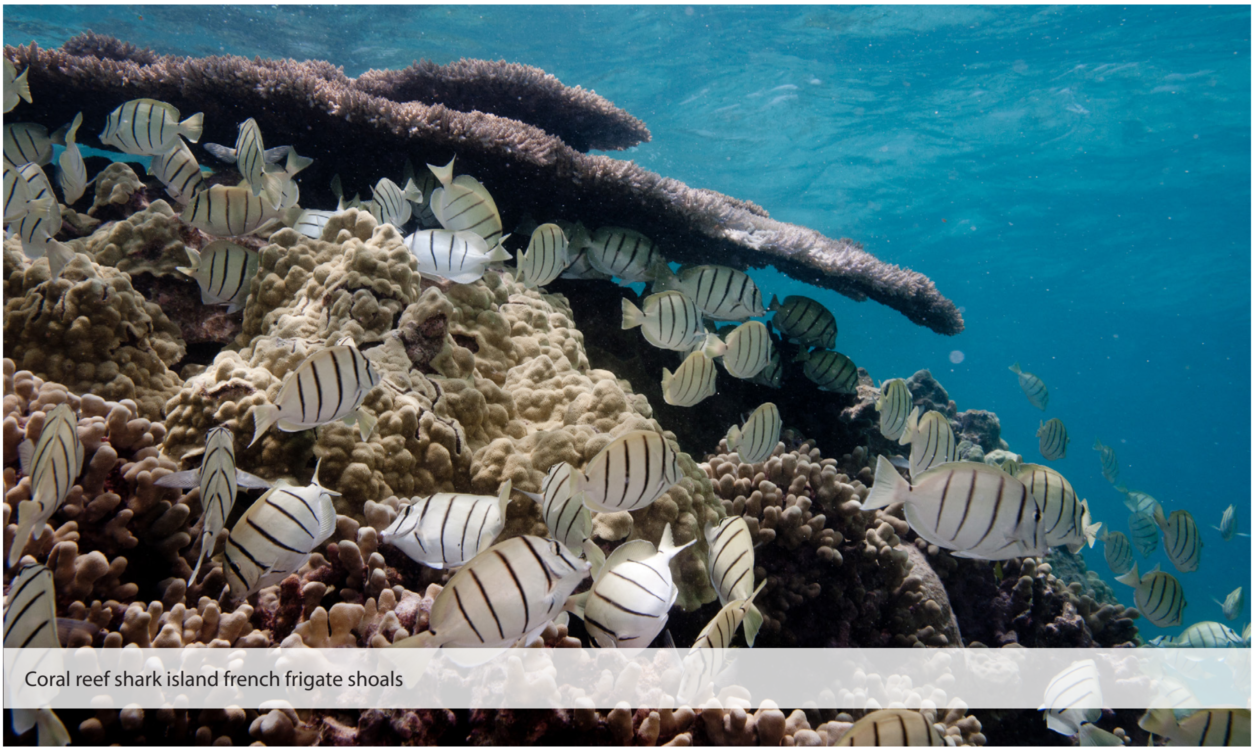
Recommendations

Managing high seas regions will benefit greatly from coordination with surrounding countries. For many issues, this will require agreements by UN member states on how to regulate areas beyond national jurisdiction (ABNJ). Because relatively few goals are relevant to or can be assessed in the high seas, the status of fisheries and biodiversity drive Index scores in these regions. As such, meaningful management aimed to improve overall ocean health needs to focus on improving fisheries management, particularly for migratory and wide-ranging stocks that influence fisheries scores for multiple high seas regions, and mitigating threats to biodiversity, in particular climate change. There is also urgent need to increase and improve monitoring of the high seas so that future assessments will be more comprehensive.

8.2.3 Notes on Methods

The OHI measures, on a scale from 0-100, the sustainable delivery now and in the future of 10 different goals for healthy oceans (Table 8.2). The current status of each goal is assessed against a reference point (see Samhouri et al. 2012; Halpern et al. 2012) that defines the maximum or optimal sustainable value of the goal, and the overall goal score is determined by combining the current status, recent trend, existing negative cumulative impacts on the goal, and governance and resilience measures in place (Halpern et al. 2012). Extensive details on how each goal is measured and which data are used to calculate the goal scores are provided elsewhere (Halpern et al. 2012, 2015; www.ohi-science.org).

Of the ten goals in the Index, only a subset is relevant to the high seas and has available data for an assessment. Goals and sub-goals that are currently not relevant and thus are not assessed include: mariculture (sub-goal of food provision), artisanal fishing opportunities, coastal protection, tourism and recreation, and coastal livelihoods and economies. Goals and sub-goals that could be relevant but do not currently have sufficient data to assess them globally include: natural products, lasting special places (sub-goal of sense of place), habitats (sub-goal of



Coral reef shark island french frigate shoals

biodiversity), and clean waters. For the clean waters goal, we had expected data to be available, but global marine debris data do not exist (although some regional data are available), human pathogens data is *likely* zero in the high seas but this is unknown (for example: ships *likely* dispose of waste in the high seas), and the spatial distribution of organic pollution is currently too coarse to be applicable to our assessments. Spatial data on atmospheric deposition of nitrogen do exist (GESAMP 2012) but we felt it was not appropriate to assess the clean waters goal (which is comprised of these 4 types of pollution) based on a single type of pollution. Emerging global data on pollution in the high seas should allow this goal to be included in future assessments. We considered including carbon storage in the assessment, but ultimately excluded the goal because pelagic carbon sequestration is currently not something that management can affect in any meaningful way, so its assessment would provide no policy value. Thus the assessment focused only on fisheries (sub-goal of food provision), iconic species (sub-goal of sense of place), and species diversity (sub-goal of biodiversity).

To assess the current condition of fisheries resources, we used data on all commercially exploited species whose catch was reported to the FAO. Many of these species are not monitored through formal stock assessments, so we calculated their status using a simplified assessment model based on the best currently available science in the field of 'data-limited' fisheries (described in detail in Halpern et al. 2015). Tests of various data-limited models using simulated data showed a modified catch- (MSY[41]) model, based on Martell and Froese (2012), as the most appropriate. The model was modified from its original formulation to obtain estimates of current population biomass relative to the biomass that yields maximum sustainable yield (B/B_{MSY}[42]; see Rosenberg et al. 2014).

41 Maximum Sustainable Yield

42 Where 'B' is current biomass, and 'B_{MSY}' is biomass at MSY. The ratio of these two values can indicate the status (sustainability) of the fishery.

One of the model parameters, the distribution of the prior (a value used to seed and constrain parameter space) for final population biomass, included a constraint based on historical peak to account for the fact that in many unregulated fisheries historical catch declines are due to overexploitation. Explorations suggested that this constraint caused the model to predict a decline in population biomass in several cases when the decline in catch was due to regulatory measures. For this reason, in cases where it could be reasonably assumed that the stock was being managed (for example: there was a Regional Fisheries Management Organization (RFMO), operating in the area that was formally charged to manage that stock) we replaced the prior on final biomass biomass (which includes constraints as a default) was replaced with a uniform distribution.

Iconic species and species biodiversity sub-goals were assessed using IUCN's Red List data on species' risk of extinction (Mace et al. 2008). The Red List categorizes species along a spectrum of extinction risk, from least concern (zero risk) to extinct, and includes assessments for 6080 species across a range of taxa. Of these species, 1820 are present in the high seas somewhere and 52 are iconic in at least one region.

The Index was calculated for the high seas portion of 15 different FAO major fishing areas (the three Antarctica FAO regions that include high seas areas were assessed together with coastal Antarctica as a single region, and the Mediterranean FAO region is completely subsumed within EEZ boundaries and so assessed for those EEZs). Because data and the best available science improved since development of the initial methodology (Halpern et al. 2012), methods for calculating several goals and the data used for them were updated (Halpern et al. 2015). For this high seas assessment, this only affected calculation of the fisheries sub-goal. Because this is the first time the high seas have been assessed, it was not possible to evaluate emerging trends in high seas scores across multiple years.

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The water systems of the world – aquifers, lakes, rivers, Large Marine Ecosystems (LMEs), and the open ocean – sustain the biosphere and underpin the health and socioeconomic wellbeing of the world's population. Many of these systems are shared by two or more nations. The transboundary waters, which stretch over 71% of the planet's surface, in addition to the transboundary subsurface aquifers, and the water systems entirely within the boundaries of the individual countries, comprise humanity's water heritage.

Recognizing the value of transboundary water systems, and the reality that many of them continue to be overexploited and degraded, and managed in fragmented ways, the Global Environment Facility (GEF) initiated the Transboundary Waters Assessment Programme (TWAP) Full Size Project in 2012. The Programme aims to provide a baseline assessment to identify and evaluate changes in these water systems caused by human activities and natural processes, as well as the possible consequences of these changes for the human populations that depend on them. The institutional partnerships forged in this assessment are expected to seed future transboundary assessments.

The final results of the GEF TWAP are presented in six volumes:

Volume 1 – ***Transboundary Aquifers and Groundwater Systems of Small Island Developing States: Status and Trends***
Volume 2 – ***Transboundary Lakes and Reservoirs: Status and Trends***
Volume 3 – ***Transboundary River Basins: Status and Trends***
Volume 4 – ***Large Marine Ecosystems: Status and Trends***
Volume 5 – ***The Open Ocean: Status and Trends***
Volume 6 – ***Transboundary Water Systems: Crosscutting Status and Trends***

A Summary for Policy Makers accompanies each volume.

This document – Volume 5 – presents the results of a baseline review of issues linking human well-being with the status of the open ocean, examining aspects of governance, climate, ecosystems, fisheries, and pollution. The open ocean is the largest transboundary water space, and the common heritage of mankind.

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