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

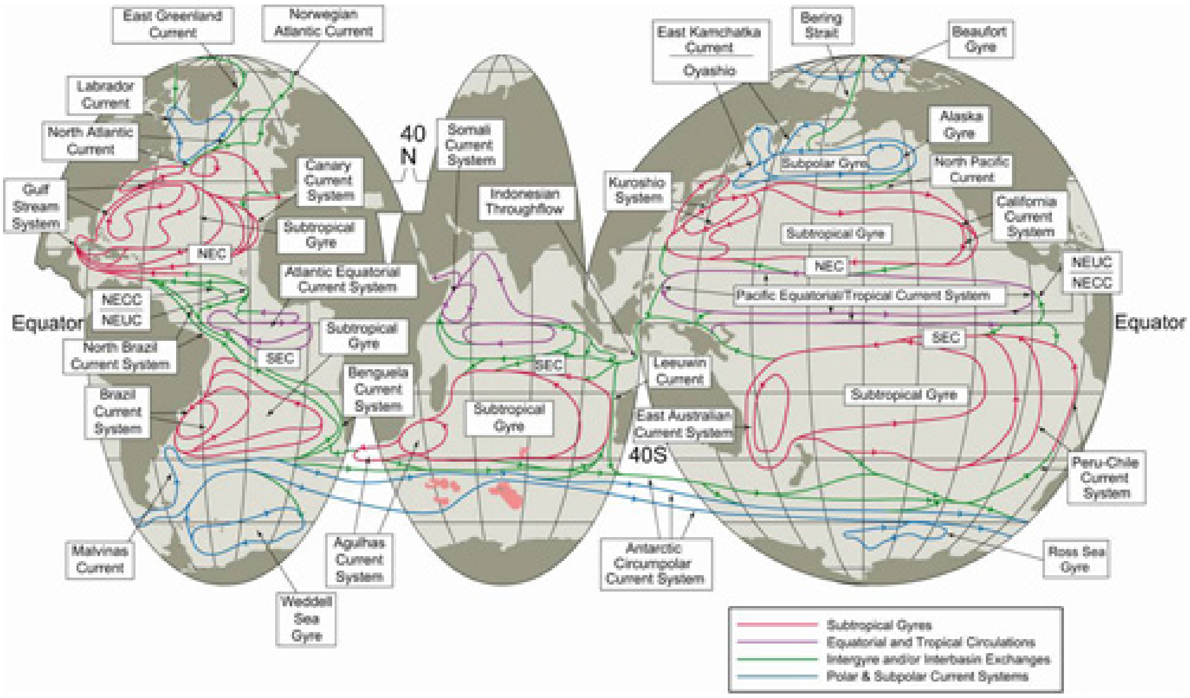
- Ocean warming has dominated the energy stored in the climate system in the last 40-50 years, accounting for approximately 93 per cent of the energy accumulated between 1971 and 2010, according to IPCC AR5;
- Changes in sea-surface salinity are observed in response to changes in precipitation, evaporation 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

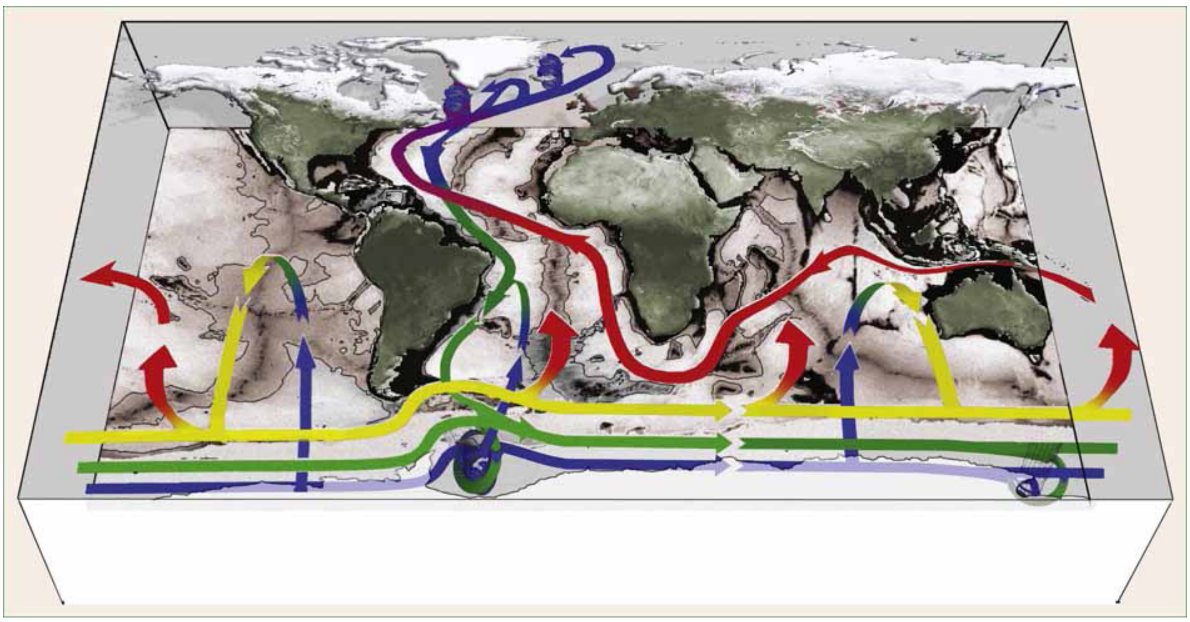
Figure 4.1. Surface circulation schematic.



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)

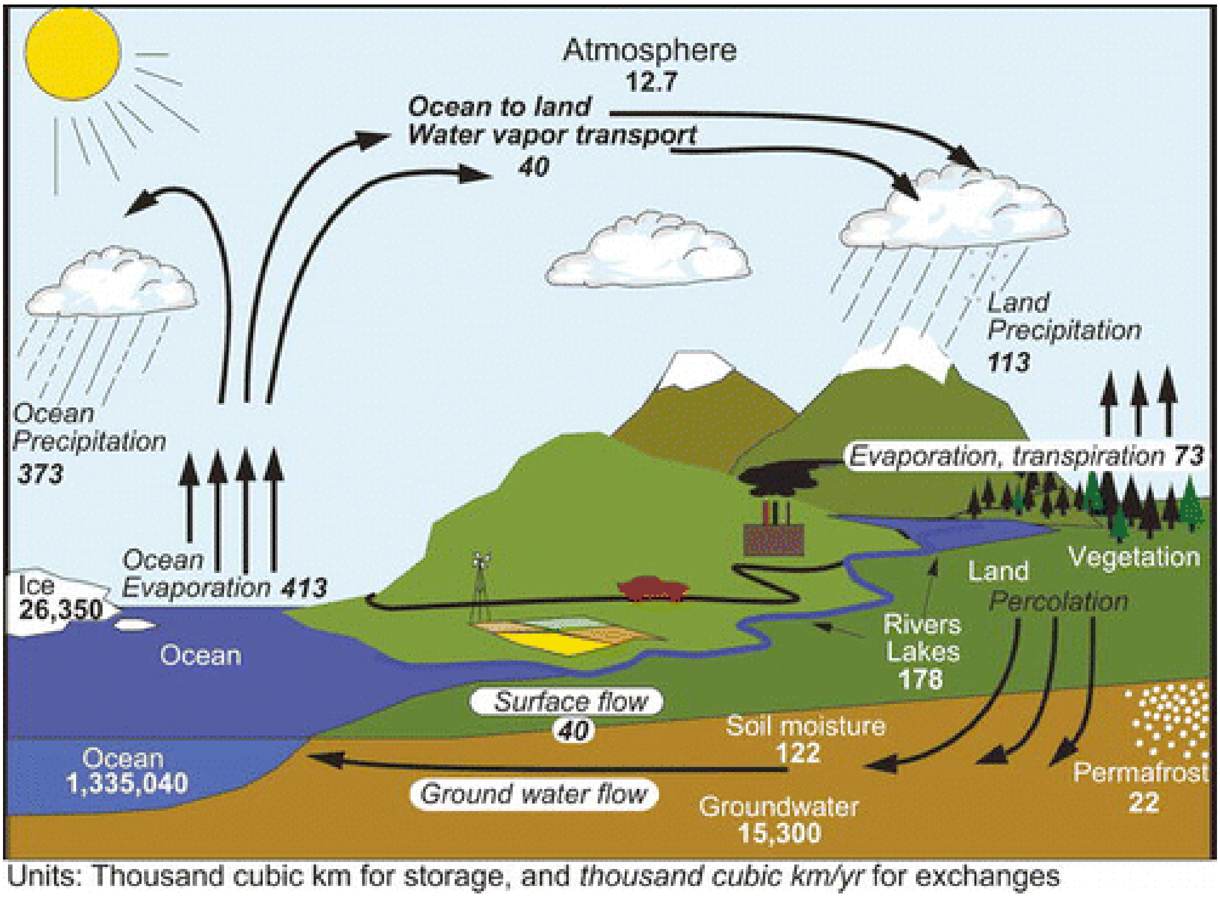


Source: Box 1 in Marshall and Speer (2012)

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)

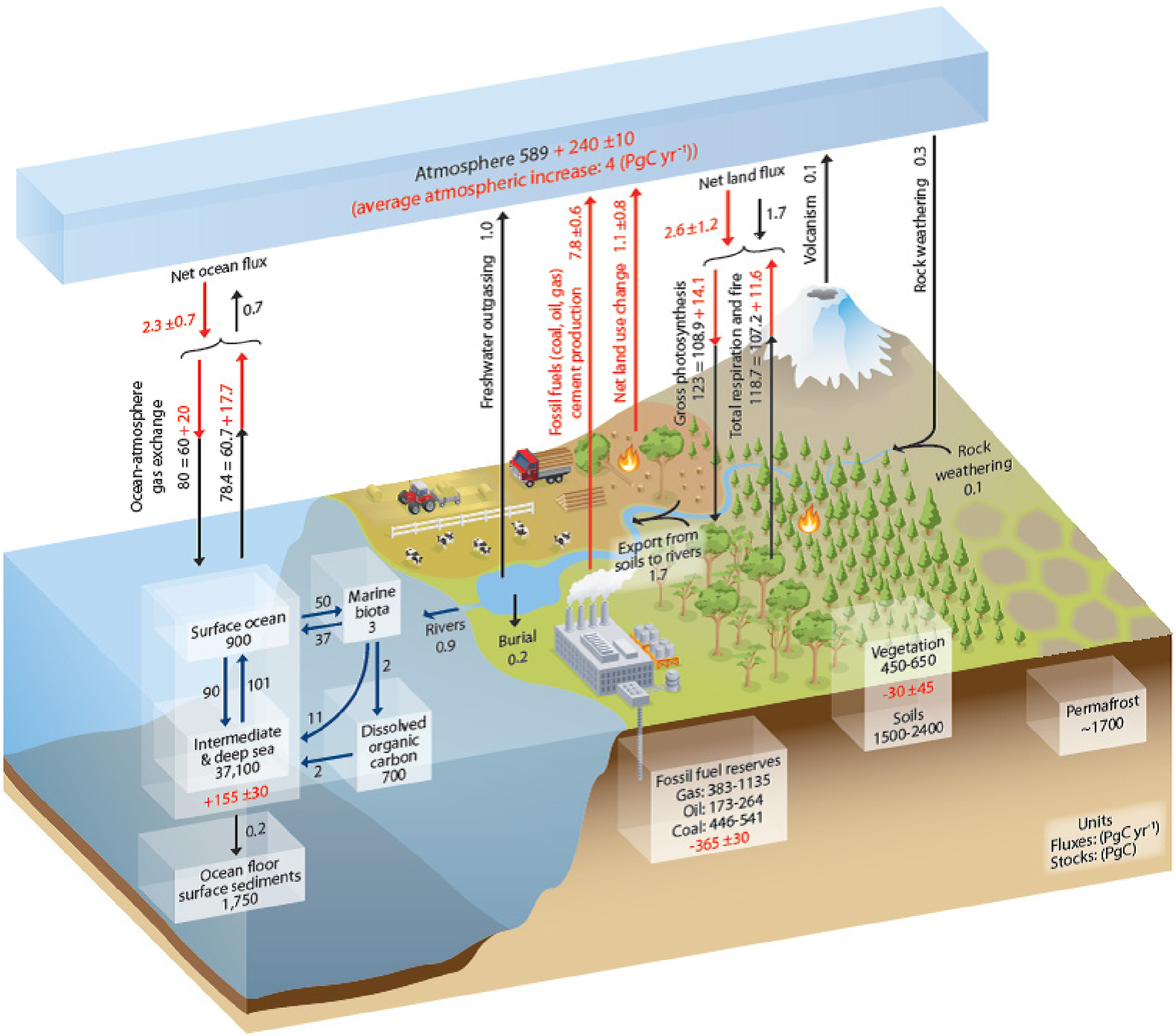


Source: Trenberth et al. (2007)

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

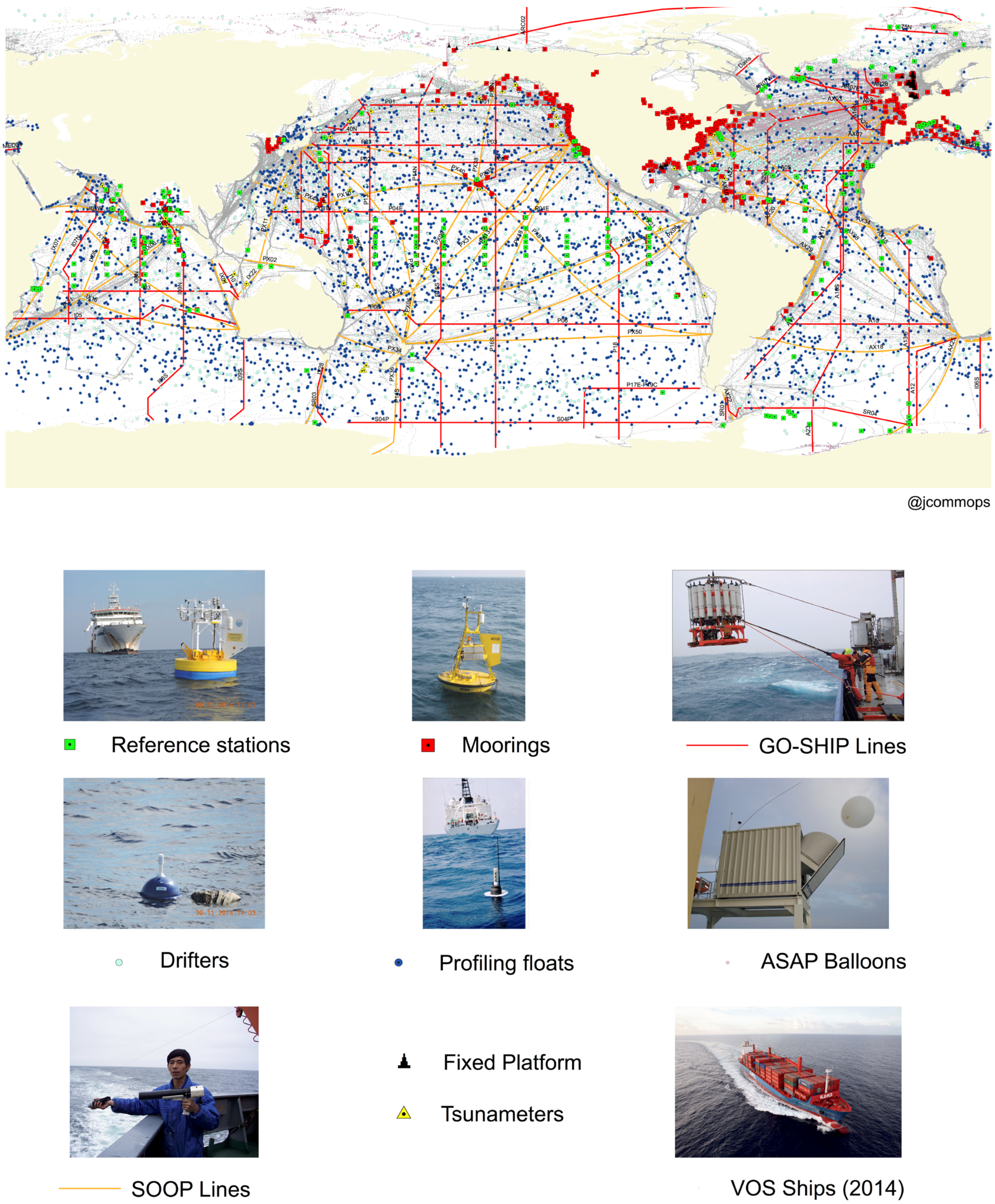
Climate information from the ocean is dependent on the in situ observation network and on the capacities for satellite remote sensing.

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 19th 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.

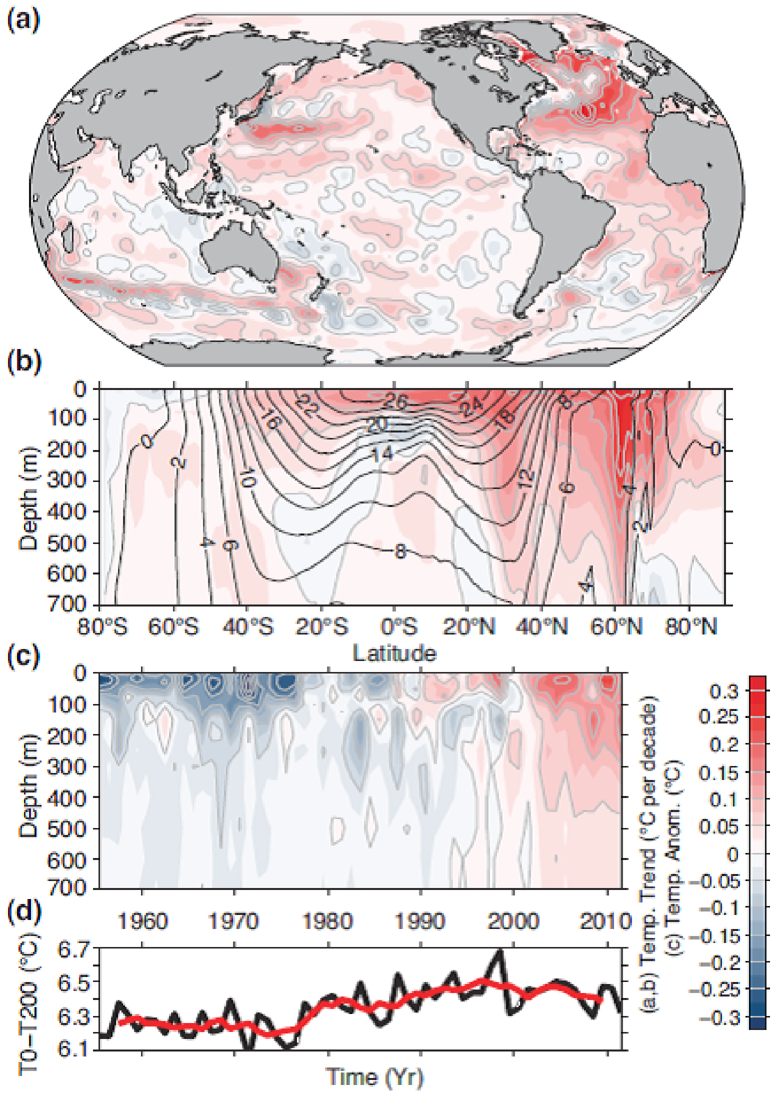
Ocean warming is the most obvious feature in line with lower atmospheric warming and the net influx of additional energy in the climate system. In fact ocean warming dominates the increase in energy stored in the climate system, accounting for approximately 93 per cent of the energy accumulated between 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).

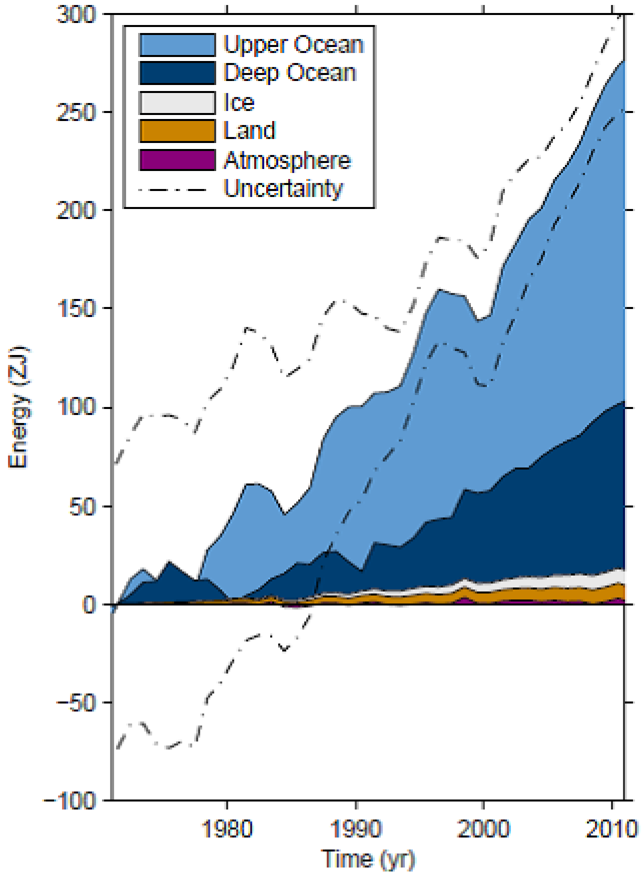


Source: Figure.3.1 from AR5 WGI

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).

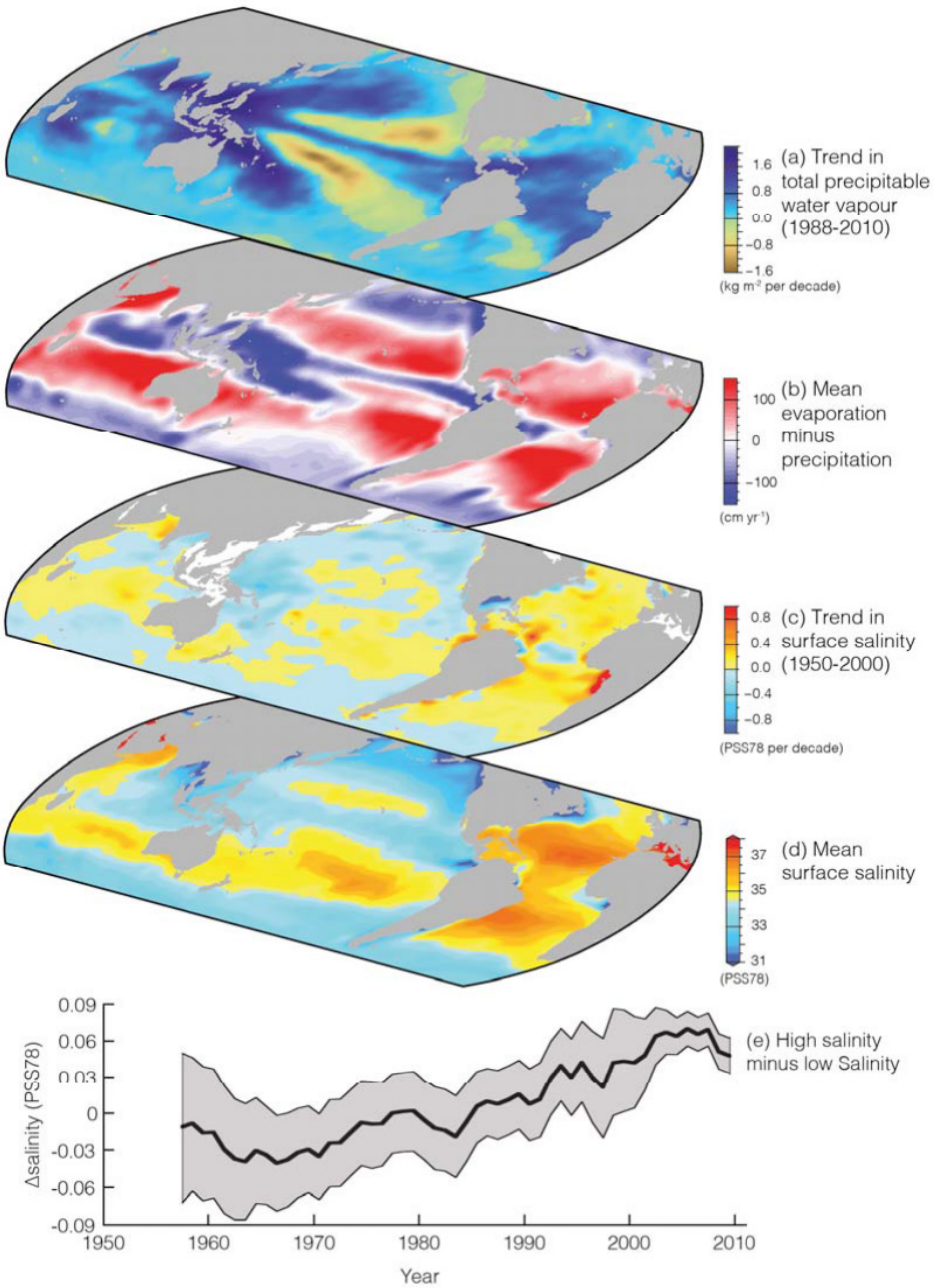


Source: Figure 1 Box 3.1 from AR5 WG I

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 x 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.

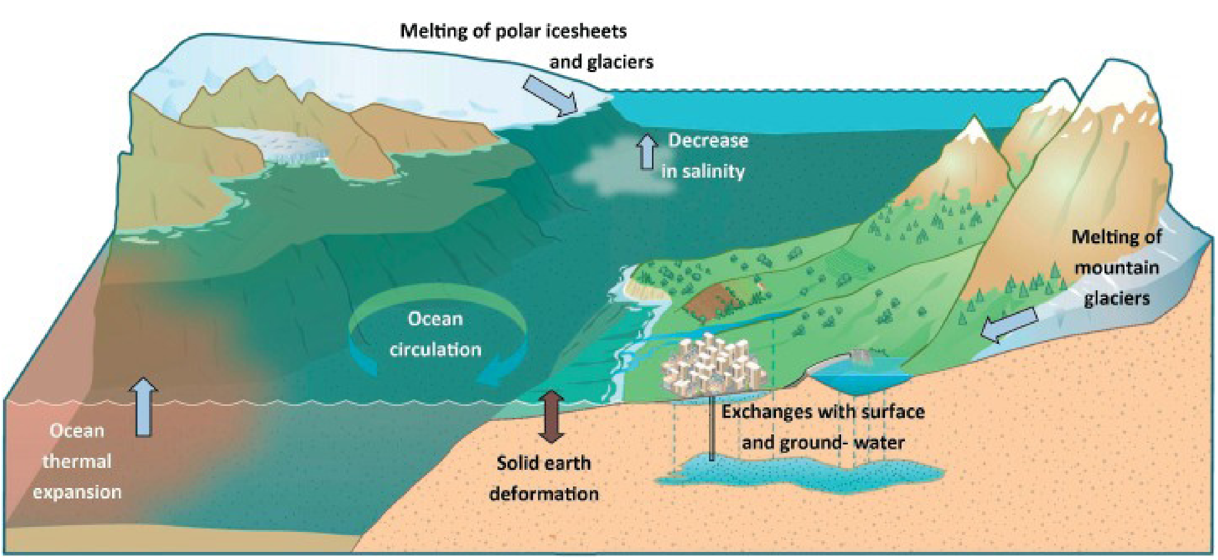
Sea-level change

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)

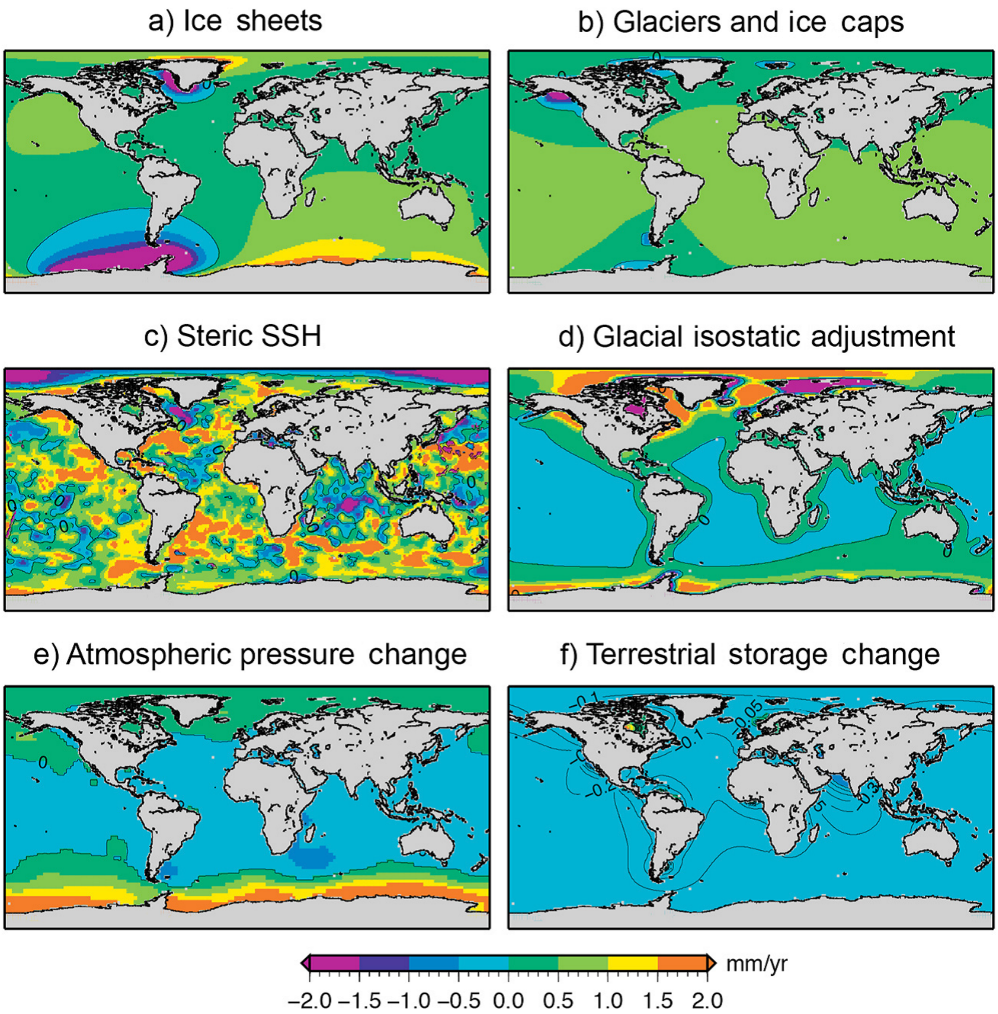
Global absolute mean sea level changes occur mostly at decadal and longer time scales, and result from two major factors (mostly related to recent climate change) that alter the volume of water in the global ocean:

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.

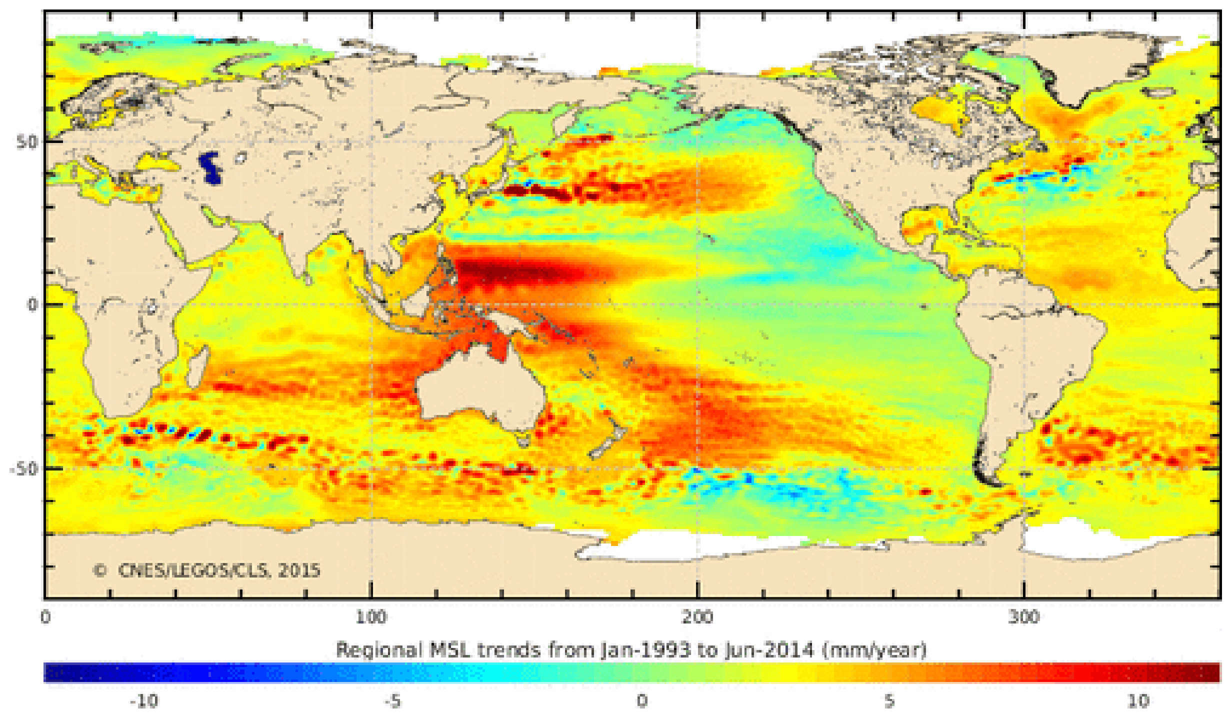
Figure 4.10. Regional sea-level trends (mm yr−1) over the period 1961–2003 for the following contributions; (a) ice sheets, (b) glaciers and ice caps, (c) steric change, (d) glacial isostatic adjustment, (e) atmospheric pressure loading, and (f) terrestrial water storage change from groundwater extraction 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.

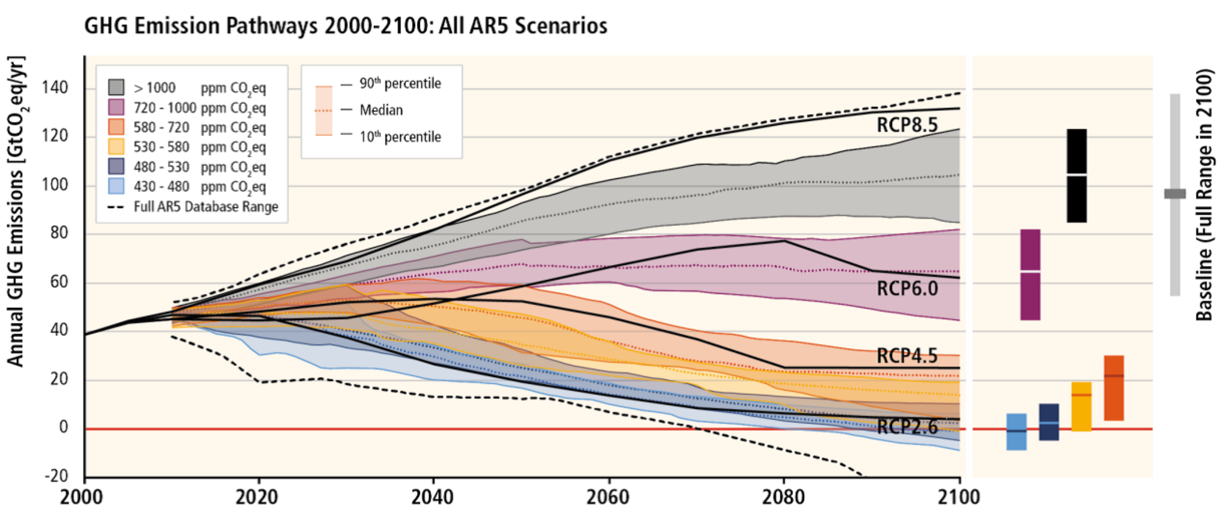
Future anthropogenic emissions of greenhouse gases, aerosol particles and other "forcing agents" for climate, such as land-use changes, are dependent on socio-economic factors, including demography, patterns of economic development and potential global geopolitical agreements designed to control emissions. 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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