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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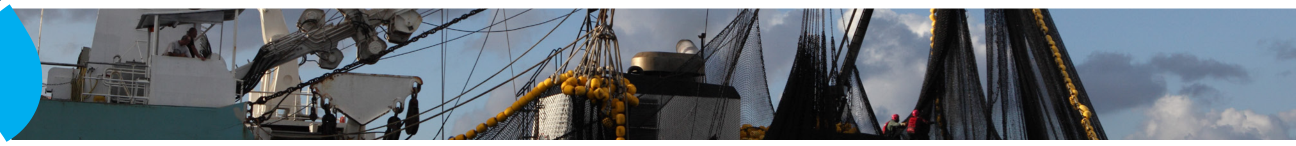
Pollution



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.

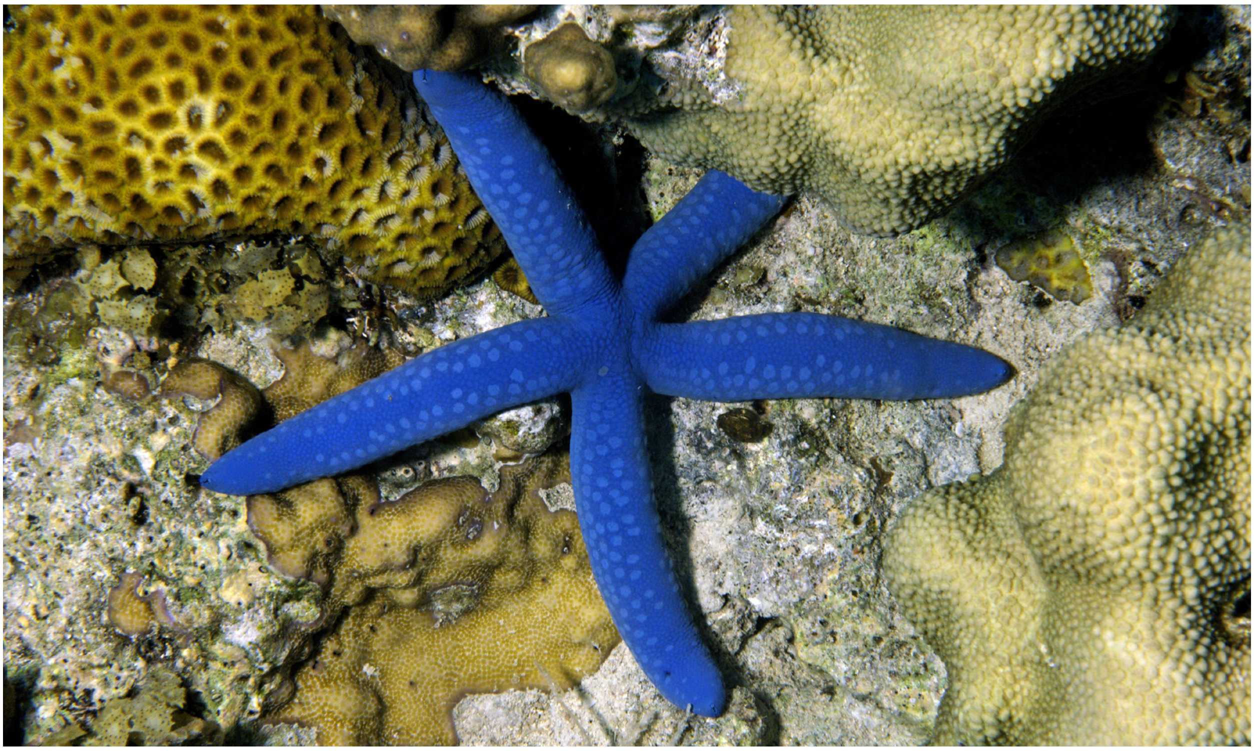
The deep ocean, occupying about 65% of the Earth's surface, is significantly contaminated with the by-products of human activities; all major ocean basins are affected. Substantial quantities of contaminants are introduced from land, through shipping, and via the atmosphere. Scientific knowledge of pollution 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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