Chapter 11
Changes in liquid and atmospheric inputs to the marine environment from land (including through groundwater), ships and offshore installations

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Keynote points

Persistent organic pollutants

- Persistent organic pollutants (POPs) continue to be a global issue, persisting at concentrations likely to cause biological effects.
- POPs are detected in remote locations far from their source of production, which includes the deepest parts of the ocean and the polar regions.
- The number of POPs continues to increase and thus the mixtures to which biota are exposed become more complex, making the determination of the likelihood of individual or population effects ever more challenging.

Metals

- There is a critical need to develop and expand coastal metal time series globally.
- Trends in metal concentrations vary regionally, although most show levelling of dissolved metals and a slight increase in higher trophic organisms.

Radioactivity

- There have been no significant nuclear accidents affecting the oceans since the first World Ocean Assessment (United Nations, 2017c).
- The generation of electricity from nuclear power plants continues to increase, with an increase of about 5 per cent globally between 2013 and 2018. Improved technology may be reducing discharges of many radionuclides, but those of tritium are probably increasing in line with electricity generation. Tritium is, however, only weakly radioactive.
- Published information on recent discharges of radioactive substances to the ocean from nuclear power plants and nuclear reprocessing plants is not available except for the North-East Atlantic and its adjacent seas. In that area, discharges to the ocean of radioactive substances from nuclear power plants and nuclear reprocessing plants continue to decline.
- On the basis of the information available, there is no reason to think that adverse impacts of radioactivity on the ocean have become significantly worse since the situation was reported in the first Assessment.

Pharmaceuticals and personal care products

- Hundreds of pharmaceuticals and personal care products (PPCPs) have been detected in the ocean, including in the Arctic and Antarctic.
- Novel analytical techniques have been developed for non-target analysis of PPCPs and their transformation products in the marine environment.
- A “watch list” of PPCPs should be formulated and incorporated into long-term international, national and regional monitoring programmes to serve as a scientific data basis for assessing the status of PPCPs in the ocean.

Shipping

- There is a globally decreasing trend regarding shipping accidents leading to oil spills (over 7 tons), and regionally improved surveillance and action capabilities indicate increased awareness leading to fewer spills.
- There is a general knowledge gap on the nature and impact of liquid input from ships, and the discharge of water from exhaust gas cleaning systems (scrubbers) is an emerging source of metals and polycyclic aromatic hydrocarbons.
Hydrocarbons

- Produced water from oil and gas exploration containing both hydrocarbons and metals is known to affect the marine environment, but knowledge gaps exist on the long-term impact of produced water discharges.

- There is a need for further studies at the community and population levels to advance the current knowledge on single species toxicity data.

- An increased rate of offshore platform decommissioning poses a challenge for the marine environment.

1. Introduction

Chemical production has continued to increase and change since 2003. The potential geographic impact of the chemical industry continued to change from the Atlantic Ocean to the Pacific Ocean, where almost 70 per cent of the industry is expected to operate by 2030, while new products are continually being developed, thus adding to the mixture of chemicals to which biota in the ocean is being exposed.

Different lists of hazardous substances have been identified by international organizations, although there is still no agreed single global list of substances that are of concern. The present chapter contains an assessment of the changes since the first Assessment in water and airborne inputs to the marine environment from land (including groundwater), ships and offshore installations. In addition, the information in the present chapter builds upon the assessment of the list of hazardous substances used in the first Assessment, namely, POPs, metals, hydrocarbons and radioactive substances. It includes new information on rare earth elements, PPCPs and airborne inputs of nitrogen oxides and sulfur oxides that were not included in the first Assessment.

2. Situation recorded in the first World Ocean Assessment

Chapter 20 of the first Assessment (United Nations, 2017b) contained the sources, main uses, production and related development, movements and impact of different hazardous substances included in the so-called black or grey lists of substances of concern that had been identified at the national level and by international organizations. Those lists evolved into a list of “priority substances” based on their toxicity, tendency to bioaccumulate and persistence in the ocean. Therefore, the hazardous substances included in the first Assessment were selected based on those for which action had been taken in all or some parts of the world ocean and included: metals (mercury, lead, cadmium), organometallic compounds (tributyltin), POPs (for example, halogenated hydrocarbons), polycyclic aromatic hydrocarbons and radioactive substances. Other substances, including pharmaceutical compounds (both human and veterinary) and cosmetic ingredients (e.g., musk xylene) that have been identified as emerging contaminants of concern are included in the present evaluation. Land-based point sources (wastewater treatment plants or industrial plants discharging into the ocean directly or through rivers), diffuse sources (run-off from land, seepage of groundwater directly to the ocean, accidental land-based or sea-based emissions of discharges) and atmospheric deposition (wet and dry deposition and emissions from sewage and from several industrial processes) that can reach and affect the ocean and their impact in several areas were identified.
The international commitment at the United Nations and the obligation at the regional level to take measures to reduce the impact of recognized emerging substances was also highlighted. From the data available at that time, it was difficult to make meaningful comparisons between areas and set priorities, not least because the data on hazardous substances in water, biota or sediments were expressed in different units. Methodological differences further complicated the picture, and the need to control sampling procedures and analytical methods was highlighted. For that reason, no detailed figures on concentrations of contaminants were included in the first Assessment.

The selected hazardous substances were found in all parts of the ocean, and those from waterborne origins were concentrated in coastal areas, whereas contaminants were transported much further out to the ocean. In the first Assessment, it was not possible to develop a general assessment of the relative impacts of those hazardous substances, but it was possible to identify the slow progress made to reduce their concentrations in some parts of the world ocean. It was also pointed out that there was increasing evidence of the significance of airborne inputs of metals and other hazardous substances to the ocean.

3. Persistent organic pollutants, including run-off from the use of agricultural pesticides

3.1. Introduction

Persistent organic pollutants represent a complex group of (often halogenated) substances that, as their name suggests, endure in the environment. Although the production of such compounds as polychlorinated biphenyls (PCBs) is no longer allowed under the Stockholm Convention on Persistent Organic Pollutants, the Convention allows for equipment containing PCBs to continue to be used until 2025, thereby providing for a possible small, but new, source of PCBs. Movement through trophic levels and environmental recirculation of PCBs mean that they continue to be present in marine systems at concentrations likely to affect marine biota. As other halogenated hydrocarbons have been developed, they have added to the mixture of POPs to which marine biota is exposed. The mixtures, and their respective components, have very different physico-chemical characteristics. The consequence of that is that they exhibit different distributions in environmental compartments, distribution equilibria and analytical requirements.

Once in the environment, POPs recirculate and, through both atmospheric transport and transport by ocean currents, are translocated to locations far from their source. It is for that reason that POPs remain of concern in both the Arctic and Antarctic, as well as throughout the ocean.

3.2. Situation recorded in the first World Ocean Assessment

New substances are constantly being developed, and international organizations have prepared lists of chemicals presenting hazardous characteristics, including organohalogenes and pesticides and/or biocides. Many of them are covered under the Stockholm Convention but others are not. Knowledge of the extent of the presence of those hazardous substances in the marine environment was patchy. The main observations in the first Assessment were:

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(a) POPs are a global issue, however, concentrations in the open ocean were generally low, but detectable, with polybrominated diphenyl ethers (PBDEs) identified in tissues;

(b) Concentrations of POPs were often associated with urbanization and densely populated regions, such as densely populated coastal areas around the Mediterranean and in Africa, South America and the South Pacific, where there was also significant industrial activity;

(c) Some coastal areas were being affected by pesticides;

(d) POPs were found in the Arctic and concentrations, although decreasing, were likely to cause biological effects in some seabirds and polar bears;

(e) Biological effects of POPs were likely to be detected in coastal areas of the North-East Atlantic;

(f) Concentrations of POPs in the North-West Atlantic and the North-East Pacific were quite low, with a decreasing trend in concentration;

(g) Reductions in the concentrations of POPs were observed, but they tended to be localized;

(h) POPs were measurably present in most coastal areas of the East Asian seas;

(i) An area of concern was the exposure of the Great Barrier Reef to pesticides associated with intensive agriculture along the north-eastern coast of Australia;

(j) There was a dominance of comprehensive studies or time series in the northern Atlantic, Arctic, Baltic and northern Mediterranean areas.

3.3. Description of the environmental changes between 2010 and 2020

POPs continue to be a cause for concern in the marine environment, especially in top predators, such as cetaceans, which have been found to have mean blubber PCB concentrations likely to cause population declines and suppress population recovery (Jepson and others, 2016). In addition to the “legacy POPs”, new POPs that represent a threat to the marine environment, including pesticides, industrial chemicals and by-products, have been regularly added to the Stockholm Convention (Stockholm Convention, 2018).

Many studies continue to focus on the legacy chemicals, including PCBs and dichlorodiphenyltrichloroethane (DDT) (and its metabolites DDD and DDE). PBDEs were not, however, among the initial 12 POPs covered by the Stockholm Convention and are still grouped with the emerging contaminants, despite having been monitored in marine systems for many years. PBDEs are among the 16 “new” POPs to have been incorporated in the Convention since 2009. They include pentachlorobenzene, polychlorinated naphthalenes, short-chain chlorinated paraffins (SCCPs), perfluorooctane sulfonic acid (PFOS) and its salts, and perfluorooctane sulfonyl fluoride (PFOSF). Chemicals recommended for listing include dicofol and pentadecafluorooctanoic acid (PFOA, perfluorooctanoic acid), its salts and PFOA-related compounds. Chemicals under review by the Persistent Organic Pollutants Review Committee are perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS-related compounds. The inclusion of additional chlorinated molecules, as well as

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2 Twelve POPs, namely aldrin, chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, polychlorinated biphenyls (PCBs) hexachlorobenzene, and polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/PCDF) are recognized as causing adverse effects.


4 The Persistent Organic Pollutants Review Committee is a subsidiary body under the Stockholm Convention established for reviewing chemicals proposed for listing in the annexes to the Convention.
both brominated and fluorinated compounds, means that the breadth of contaminants covered by the term "POPs" has greatly increased, resulting in new challenges for environmental analytical laboratories. Short-chain chlorinated paraffins were detected in the Firth of Clyde, but the concentrations were method specific (Hussy and others, 2012), most likely owing to the presence of significant concentrations of medium- and long-chain chlorinated paraffins.

In the recent draft report on progress towards the elimination of PCBs (Stockholm Convention, 2018), it was highlighted that, for many countries, little, if any, relevant quantitative information was available. Extensive analytical work continues to be undertaken in some regions of the world, and it shows evidence of high concentrations of PCBs in some top predators, with the possibility of population consequences (Desforges and others, 2018) or altered adipose function in seal pups (Robinson and others, 2018). Both of those examples come from the North-East Atlantic. Recent data for the Arctic, based on long-term time series of PCBs in marine mammals and fish, show that concentrations are generally decreasing (Carlsson and others, 2018), although the rate of decrease has slowed in recent years (Arctic Monitoring and Assessment Programme (AMAP), 2016; Boitsov and others, 2019). Hexachlorobenzene (HCB) in fish liver decreased less with time compared with PCBs, DDT and its metabolites, trans-nonachlors and PBDEs (Boitsov and others, 2019). Exceptions exist, however, which are associated with changes in diet or a change in environmental processes that affect run-off and re-emissions (AMAP, 2016). For example, significant increasing trends for the concentration of a group of 10 PCBs have been observed in blue mussels from Iceland and juvenile polar bears from the east of Greenland and for two blue mussel time series from Iceland (AMAP, 2016).

There is some evidence that the presence of POPs, such as PCBs, peaked in ocean water in the 1970s and has been declining since (Wagner and others, 2019). In line with declining atmospheric concentrations, the Arctic Ocean has started to export those legacy POPs back into the atmosphere and through currents into the Atlantic Ocean (Ma and others, 2018).

The concentration of PCBs in fishes and shellfish in the North-East Atlantic has decreased, although local problems continue. Of the seven PCBs identified by the International Council for the Exploration of the Sea, only PCB118 is found at a concentration in fishes and shellfish likely to cause biological effects (Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), 2017b). The other six PCBs are generally above background assessment concentrations, although in 4 of the 11 contaminant assessment areas defined by the Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission), PCB28 is at the background assessment concentration level. Furthermore, in 9 of 10 contaminant assessment areas where a temporal trend could be determined, the trend is downward. A similar state was described for PBDEs in fish, mussels and oysters in the majority of assessment areas of the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), with declining concentrations being noted in all but the Skagerrak and Kattegat, where no change in concentration has been observed (OSPAR, 2017b).

PCBs were detected in fish from depths of between 600 and 1,800 m on the European continental slope to the west of Scotland, United Kingdom (Webster and others, 2014). Concentrations of the seven PCBs identified by the International Council for the Exploration of the Sea in the liver of three fish species were highly variable, ranging from 58.7 nanograms

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per gram (ng/g) lipid weight in black scabbard to 3,587 ng/g lipid weight in roundnose grenadier. Concentrations were mainly less than 500 ng/g lipid weight (or <1,250 ng/g lipid weight for the sum of 28 PCBs), a value used by some researchers as an indicator of concern. A total of 23 of the 95 fish livers collected between 2009 and 2012, inclusive, had PCB concentrations of more than 500 ng/g lipid weight for the seven PCBs identified by the Council. PCB118 was at a concentration at which biological effects are likely to be observed for all three fish species. Although there were species differences with respect to concentration, there were no temporal trends between 2006 and 2012, nor were there any differences detected with depth. Concentrations of PCBs were also examined in prey species (including lanternfish and Bean’s bigscale) and were significantly lower compared with the concentrations found in predators. PBDEs were also detected in the predators, but at much lower concentrations than the PCBs.

Mean concentrations of PCBs in sediments in the Greater North Sea and the Celtic Seas are generally significantly above the congener’s background assessment concentration, but below the environmental assessment criteria (OSPAR, 2017b). Sediments in both the northern North Sea and the Irish Sea were found to contain PBDEs, although most of the measured concentrations of PBDEs in sediments were low and often below detection levels. However, the lack of assessment criteria for PBDEs in sediments means that it is not possible to determine the environmental significance of the observed PBDE concentrations (OSPAR, 2017b).

Inputs of hazardous substances to the Baltic Sea are defined, on the basis of the Baltic Sea Impact Index (Baltic Marine Environment Protection Commission (HELCOM), 2018a), as the second most widely distributed pressure (HELCOM, 2018a, 2018b). In terms of POPs, PCBs, dioxins and furans do not appear to be a major driver of the integrated assessment status for the period 2011–2016. Atmospheric deposition of PCBs and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF) shows a steady decrease owing to the increased efficiency of various combustion and chlorination processes (HELCOM, 2018b). Hexachlorocyclohexane (γ-HCH, lindane), and DDT and its metabolites (DDD, DDE) are no longer considered of significant concern in the Baltic. The improved breeding success in the white-tailed sea eagle is attributed to such reductions (HELCOM, 2018c). However, elevated concentrations of PBDEs in fishes are a major contributor to the current impeded overall status of the Baltic Sea. Similarly, undue inputs of PCBs contaminating the food web in the Lagos Lagoon in Nigeria had been reported from activities on land (Alo and others, 2014).

Even if the deposition of PCDD/PCDF in the Baltic Sea is decreasing, atmospheric deposition has been found to be the major external source, and there is still noticeable elevated deposition in coastal areas of the North-East Atlantic and in the Baltic, the Mediterranean and the Caspian Sea (Wiberg and others, 2013). The atmospheric deposition of PCDD/PCDF and HCB is quite high in coastal areas of the North-East Atlantic and in the Baltic, the Mediterranean and the Caspian Sea, although there has been no intentional global production of HCB for decades (e.g., Wang and others, 2010), and emissions of PCDD/PCDF are supposed to cease in 2018 (Josefsson and Apler, 2019).

It is clear that various POPs continue to be present in the atmosphere (figure I), with a hotspot for PCB153 over Western Europe (figure I.B). High atmospheric concentrations of PCDD/PCDF have also been detected over Europe (figure I.A).
PBDEs have been used as flame retardants for many years and have become widespread across marine systems. As with other POP mixtures (e.g., PCBs), concentrations are based on a small number of the possible congeners. The lipophilic nature of PBDEs means that they, in the same way as PCBs, can be trapped in sediments. A review of PBDE concentrations on a worldwide basis for which the samples were collected prior to 2010 concluded that, in the majority of open ocean sediments, concentrations do not vary that much and are approximately 1 ng/g (Zhang and others, 2016). That contrasts with sediment concentrations close to the source of contamination, which were in excess of 7,000 ng/g. However, PBDEs were detected in amphipods from both the Mariana Trench and the Kermadec Trench, with the deepest sample collected at 10,250 m. The concentration for the sum of seven congeners ranged from 9.33 ng/g lipid weight to 318.71 ng/g lipid weight. PCBs were also detected in those samples, with concentrations, again for the sum of seven congeners, ranging from 62.02 ng/g lipid weight to 1,866.25 ng/g lipid weight (Jamieson and others, 2017). Although there is a scarcity of POPs data from the open ocean, the data available strongly indicate that those chemicals continue to be universally present in marine components far from their source. Concentrations of PBDE47 and PBDE99 in water to the west of Los Angeles, United States, were found to be in excess of 12,500 picograms per litre (pg/l) in 2012. In subsequent water samples, collected from progressively more westerly sites (towards Honolulu, United States), concentrations were very much lower (< 20 pg/l) but PBDEs were evident at all sites (Sun, 2015). Further studies show the presence of organophosphate flame retardants and PBDEs in the atmosphere, sediments, and surface and deeper waters of the Arctic Ocean and the North Atlantic Ocean (Li and others, 2017; Ma and others, 2018).
At present, atmospheric transport is presumed to be dominating over other modes of long-range transport for organophosphate flame retardants and PBDEs (Sühring and others, 2016; Vorkamp and others, 2019). Therefore, monitoring of those compounds needs to continue.

Fishes from around the South China Sea were found to contain PBDEs, PCBs and DDT and its metabolites, but concentrations in muscle (PBDEs, sum of eight congeners, and PCBs, sum of 19 congeners, < 200 ng/g lipid weight) were at the lower end of the global range and related to feeding habits among the various fish species (Sun and others, 2014). Staying in the South China Sea, more recent data from a range of species (xanthid crab, whippomor octopus, striated cone, Bower’s parrotfish, bigeye scad and pike conger) from the Xuande Atoll illustrated that PCBs, PBDEs and DDT and its metabolites occur in the various components of that marine ecosystem; the PCB (17 congeners) concentrations ranged from 8.8 ng/g lipid weight in the whippomor octopus to 117.9 ng/g lipid weight in the pike conger (Sun and others, 2017).

Sediments carried from the Bering Sea through the Bering Strait, and from the Chukchi Sea, the Canada Basin and the Fram Basin to the Iceland Stations (central Arctic Ocean) contained organochlorine pesticides, PCBs and PBDEs. In depths below 500 m, the top 5 cm of sediments contained 286 ± 265 pg/g dry weight (d.w.) of PCBs (47 congeners), which was greater than concentrations from deeper sediments (149 ± 102 pg/g d.w.). There is also some evidence of increasing sediment concentrations of HCB, at least in the Baltic Sea (Josefsson, 2018), while in some environmental compartments in China, there is minimal change in the concentrations of HCB detected in the blubber of finless porpoises from the South China Sea. There were minimal differences between 1990, when the range of concentrations for HCB was 140–230 ng/g lipid weight, and 2000/2001, when the range was 87–250 ng/g lipid weight (Wang and others, 2010). The lack of reducing or even increasing HCB levels might be attributable to the unintentional production of HCB as a by-product in various combustion and chlorination processes (Josefsson and Apler, 2019).

There is no doubt that, in addition to widespread contamination of the marine environment by POPs, there are localized hotspots associated with urban proliferation and industrial establishments. A complex mix of POPs has been discharged into Lagos Lagoon on a daily basis. In addition to direct discharges, sawdust and other inland domestic wastes are ready sources of contaminants. POPs of interest were organochlorine pesticides since, in Nigeria and other developing countries, such pesticides, including DDT and lindane, are still used for pest control and as insecticides.

The Mediterranean has also been described as a hotspot area for POPs (Marsili and others, 2018 and references within table 7.1). The mean concentrations of PCBs in blubber from bottlenose dolphins in the Gulf of Ambrakia in 2013 were low (26,770 ng/g lipid weight; Gonzalvo and others, 2016) relative to the mean concentrations for the same species from the northern Adriatic Sea in 2011 (110,460 ng/g lipid weight; Jepson and others, 2016). However, the mean concentration for the northern Adriatic Sea was about 40,000 ng/g lipid weight higher than the mean obtained for bottlenose dolphins from Scotland, United Kingdom, that had been sampled over the period 2004–2012. Values for the Gulf of Mexico (Texas, United States); Hawaii, United States; and Reunion, France, were 47,700 (Balmer and others, 2015), 11,800 (Bachman and others, 2014) and 5,200 (Dirtu and others, 2016) ng/g lipid weight, respectively, with the animals all sampled around the period 2009–2012. Mean sperm whale blubber PCB concentrations in animals from the Corso-Ligurian Basin of the Mediterranean between 2006 and 2013 was 24,240 ng/g lipid weight and 16,880 g/g lipid weight for males and females, respectively (Marsili and others, 2018, table 7.2 and references within; Pinzone
and others, 2015). That was not as high as in the Ligurian Sea and the Gulf of Lion (107,810 ng/g lipid weight; Praca and others, 2011), sampled between 2006 and 2009, but it was very much greater than the means obtained from the waters around the Galapagos Islands (1,320 ng/g lipid weight) and Papua New Guinea (1,140 ng/g lipid weight) in 2000 and 2001, respectively (Godard-Codding and others, 2011).

Although decreasing, the change in concentration of dieldrin in Arctic biota is slow, which is consistent with the air observations, where the change was very small over the period between 1993 and 2016. Chlordane compounds were also shown to be decreasing in concentration in Arctic biota (AMAP, 2016). The story for other “legacy” POPs (e.g., α-HCH, β-HCH and γ-HCH, PCBs) tends to be similar for Arctic biota.

As highlighted earlier in the present chapter, there are a range of fluorinated compounds that are of increasing interest. At coastal sites in the eastern North Sea, concentrations of 3.8 nanograms per litre (ng/l) were observed for PFOA, and 1.8 ng/l for PFOS. The concentrations decreased further, to 0.13 ng/l and 0.09 ng/l for PFOA and PFOS, respectively, towards the open sea (Theobald and others, 2011). Perfluorinated compounds have been found in seabirds in the Baltic (Rubarth and others, 2011), fish caught around Charleston, South Carolina, United States (Fair and others, 2019), a range of seafood in the Republic of Korea (Jeong, and others, 2019) and the marine food web of the Arctic (Butt, and others, 2010), as well as in biota from the Antarctic, which illustrates that those POPs are as ubiquitous in the global environment as the original 12 POPs detailed in the Stockholm Convention.

The presence of per- and polyfluorinated alkyl substances was documented in the Arctic and the global ocean over the past decade (Ahrens and others, 2010; Benskin and others, 2012; Yeung and others, 2017). The phase-out of PFOA and PFOS from production in the United States and Europe will result in declining concentrations in the surface ocean (Zhang and others, 2017), while replacement per- and polyfluorinated alkyl substances are likely to increase. Observed high concentrations of PFOS in the South Atlantic could be attributable to the use of a precursor chemical as a pesticide in Brazil (González-Gaya and others, 2014).

The ultimate challenge remains insofar as human ingenuity has resulted in the production of a wide range of halogenated hydrocarbons that have brought significant benefit to mankind but have been identified in the abiotic and biotic environment at a global scale. The full impact of those compounds on marine biota, especially when there is biomagnification, remains unclear, in particular as monitoring programmes tend to focus on a subset of compounds rather than the full spectrum of fluorinated, chlorinated and brominated compounds that are known to be present in the marine environment and that contribute to the total contaminant loading of individual animals. A detailed study of each subgroup is necessary owing to the toxicity and bioavailability of each compound.

3.4. Economic and social consequences and/or other economic or social changes

Highly toxic compounds, such as γ-HCH and p,p’-DDT, pose potentially unacceptable risks to aquatic organisms. More widely, there are risks to animals at the pinnacle of the food web, including humans. The pesticide residues γ-HCH and p,p’-DDE were shown to be the most persistent of all the POPs assessed and extrapolated for the Gulf of Guinea. In addition, γ-HCH was found to have high potential for long-range transport. The fact that such compounds can exert dioxin-like toxicity on lagoon biota is an indication of likely health risks to biota and to humans (Rose and others, 2017).
As the climate changes on a global basis, marine plants and animals will be subjected to additional stress from increasing temperatures and ocean deoxygenation. A reduction in pH has the potential to cause further stress. The marine plants and animals that are already experiencing some form of stress owing to their contaminant loading may be more vulnerable. Research is required to provide an understanding of the implications of multiple stressors, not only from the perspective of biodiversity, but also in the context of the shellfish and finfish industries, should there be population-level impacts.

POP concentrations alone could cause adverse biological effects that might have an impact beyond the level of the individual marine plant or animal. Localized population effects, or instances in which contaminant concentrations exceed compliance concentrations, have the potential to affect local industries. In 2018, the European Food Safety Authority Panel on Contaminants in the Food Chain reduced the tolerable weekly intake for dioxins and dioxin-like PCBs in food to 2 pg per kg of body weight, a figure that is seven times lower than the previous European Union tolerable intake. That compares with the long-standing World Health Organization tolerable daily intake for dioxin-like PCBs of 1–4 pg toxic equivalent factor per kg of body weight. The United Nations Environment Programme (UNEP), which provides the secretariat for the PCB Elimination Network, has recently published a report (UNEP and United Nations Institute for Training and Research (UNITAR), 2018) detailing the progress made with respect to meeting the elimination deadline of 2028, as set out in the Stockholm Convention. Parties are not currently on track to achieve the 2028 goal. The consequence of that is that there is a need to continue to follow POP concentrations, both to understand the impact of an increasingly complex mixture of anthropogenic chemicals on marine systems and to assess the concentrations in seafood. Fishes and shellfish provide a valuable and nutritious source of protein, which must be safe to eat. That requires that emissions, discharges and losses of POPs are reduced and that concentrations in marine biota decline.

4. Metals

4.1. Introduction

Metals continue to be transported at elevated concentrations around the globe, with the potential to affect human life and the environment even in remote locations. Although metals occur naturally and are released into the environment from natural sources, anthropogenic emissions make important contributions to metal fluxes and even dominate fluxes for a number of metals. Highly toxic metals, such as mercury, cadmium and lead, along with tributyltin, which were assessed in the first Assessment, and rare earth elements are included in the present chapter.

4.2. Situation recorded in the first World Ocean Assessment

In the first Assessment, the sources, main uses, production and impact of metals (mercury, cadmium and lead) and tributyltin, an endocrine disruptor compound, were discussed; however, owing to the different analytical methods used and the fact that data were expressed in different units, the comparison was cumbersome. The main sectors contributing to mercury emissions to the air were found to be combustion plants, mainly burning coal, and artisanal, small-scale gold mining. The share of those sources was estimated by UNEP to be approximately

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50 per cent of total anthropogenic mercury emissions, based on 2010 data (UNEP, 2019).

4.3. Description of the environmental changes between 2010 and 2020

Observations of metal concentrations in the global ocean have improved over the past 10 years, primarily owing to integrated efforts, such as the international GEOTRACES programme. Coastal observations and assessments of trends are lacking for most regions, with the exception of the Baltic Marine Environment Protection Commission, Convention for the Protection of the Marine Environment of the North-East Atlantic and Arctic Monitoring and Assessment Programme regions, and are thus focused on the European coasts and the North Atlantic and Arctic regions. The currently established trends vary across regions and for the different metals. Generally, there appears to be a levelling off in water column concentrations in the cases of lead and cadmium. However, mercury concentrations in fishes and other biota appear to be increasing in the Arctic regions. Efforts to address the lack of time series data in key regions, including the South Atlantic and South Pacific, should be prioritized, in particular in the midst of changing global temperatures and the increased projected mobility of metals. Those efforts are of particular importance in regions where decreasing permafrost will mobilize metals and increase exposure across food chains. Global fish catch8 shows that all regions yield at least some higher trophic-level species that exceed recommended levels and, therefore, all ocean regions are affected. In summary, cadmium, mercury and lead can still be found at concentrations in biota above background levels, with both temporal and spatial differences. Top predators continue to be under pressure, with metal concentrations as a contributing factor.

According to the World Mineral Statistics archive (Brown and others, 2019), the annual world production of cadmium has been fairly constant at about 21,000–26,000 tons over the past decade, although production was at the higher end from 2014 to 2017. The mine production of lead has decreased almost 10 per cent since the peak production of 5,300,000 tons per year in the period 2013–2014. The production of refined lead has been fairly constant at around 11,000,000 tons during the same period. China alone is responsible for about half of the annual lead production. Annual mercury production doubled from 2010 to 2012 and reached 4,000,000 tons in 2017 (Brown and others, 2019). Also, during that period, the main producer, China, increased its share from about 75 per cent to almost 90 per cent.

Presently, based on 2015 data, UNEP estimates that stationary combustion of coal and artisanal gold mining are responsible for 60 per cent of total anthropogenic atmospheric mercury emissions (UNEP, 2019). However, it is not clear if the difference compared with 2010 is based on improved information or actual changes in emissions from those sectors. Overall, total anthropogenic emissions constitute about 30 per cent of the total mercury emissions to the air, whereas natural processes, such as the evaporation of mercury previously deposited to soils and water, are estimated to constitute 60 per cent, with the final 10 per cent coming from natural emissions from volcanoes (UNEP, 2019).

The global spatial distribution of mercury emissions to the air and atmospheric deposition reveals large hotspots in eastern and southern Asia, Central Africa and South America, as well as Central America and south-eastern North America (figure II). Subcontinental contributions to the global inventory in 2015 are very similar to those of 2010.

4.4. **Key region-specific changes and consequences**

4.4.1. **Arctic Ocean**

The Arctic is changing rapidly and is the subject of increased research and monitoring efforts. Permafrost thawing is projected to increase the transfer of terrestrial mercury and other metals to Arctic coastal environments (Fisher and others, 2012). Metals do not disappear over time but can be trapped in sediments. However, data on metals in sediments in the Arctic are limited. The mean cadmium concentration in biota from the Barents Sea (north-west coast of Norway) was above the OSPAR background assessment concentrations but significantly below the European Commission maximum level for food (OSPAR, 2017d). The mean concentrations for both mercury and lead were at the background assessment concentration. None of the metals showed upward trends in concentrations in the water column.

A review of mercury in the marine environment of the Canadian Arctic has shown that the understanding of the biogeochemical cycling of that metal has improved but needs further characterization. Total mercury concentrations in sediments from the Hudson Bay are lower (8–58 ng/g d.w.) than in other marine regions of the circumpolar Arctic Ocean (e.g., up to approximately 290 ng/g d.w., Greenland Coast, 2000) (Fisher and others, 2012).

The mercury reservoir in permafrost is poorly quantified, and surface soils in the Arctic likely contain some portion of legacy mercury. Current estimates of riverine mercury export to the coastal Arctic stem from limited data and models and vary widely, ranging from 13 to 80 megagrams per year (Dastoor and Dunford, 2014), while mercury export through coastal erosion is estimated at 15–30 megagrams per year (Soerensen and others, 2016). Riverine mercury concentrations can increase up to sixfold in coastal areas following scenarios projecting up to 30 per cent increased terrestrial run-off (Jonsson and others, 2017). Riverine transport also exports a significant amount of toxic mercury, namely, methylmercury. Present flux estimates cannot close the mercury budget in the Arctic and, thus, hypothesized major mercury processing occurs in coastal zones, with evasion of gaseous mercury species to the atmosphere (Heimbürger and others, 2015).

There remains significant spatial variation in the total mercury concentration in Arctic biota, including with respect to marine mammals...
and birds. In the latter (thick-billed murres), the total mercury concentration increased in birds breeding at a higher latitude. There was an increase in total mercury concentrations in the eggs of seabirds (various species) over the period 1975–2012. The reasons for the increase remain unclear but are likely to be multifactorial. Greenland sharks have been found to contain high total mercury concentrations in their muscle ($1.62 \pm 0.52 \mu g/g$ wet weight (w.w.)), which is consistent with their high trophic position in the Arctic marine food web.

The fourth Global Mercury Assessment (2018) (UNEP, 2019), a joint venture between UNEP and the Arctic Monitoring and Assessment Programme, highlights the following:

(a) Loss of sea ice in the Arctic owing to climate change allows greater exchange of mercury between the ocean and the atmosphere;

(b) Coastal Arctic sites in Norway have slightly elevated levels of atmospheric mercury compared with those in Greenland, which is associated with direct transportation from continental Europe, especially during winter and spring;

(c) The Arctic is predominantly influenced by the long-range transport of atmospheric mercury;

(d) Dry deposition of mercury may be important in inland Arctic tundra;

(e) The deposition of mercury to the Arctic will not diminish by 2035 under current policies;

(f) The impacts of climate change on marine ecosystems in the Arctic are occurring rapidly, which amplifies its significance for a global understanding of mercury trends;

(g) Arctic birds tend to be at moderate or low risk with respect to mercury;

(h) Some Arctic marine mammals are in a high-risk category as a result of the uptake of methylmercury through their diet, with the mercury concentration in the muscle of pilot whales at the higher end of the concentration spectrum for toothed whales;

(i) Mercury in ringed seals from the North American Arctic has increased;

(j) Changes in mercury concentration in marine mammals and seabirds are a result of changes in feeding patterns and in environmental conditions and of climate change, which means that the reasons for the observed changes in mercury concentration in marine mammals and seabirds are not necessarily identifiable;

(k) The consumption of fish and marine mammals by Arctic people continues to put them at high risk as a result of mercury exposure; however, exposures have dropped over the past two decades.

In summary, cadmium, mercury and lead can still be found in biota at concentrations above background levels, with both temporal and spatial differences. Top predators continue to be under pressure, with heavy metal concentrations as a contributing factor.

4.4.2. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

North Atlantic (including the OSPAR maritime area)

The Greater North Sea is the only OSPAR sea area that has sufficient waterborne metal input data to be used in an assessment. Mercury inputs via continental run-off have approximately halved between the period 1990–1995 and the period 2010–2014 (and atmospheric inputs have been reduced by approximately one third). Cadmium inputs through the atmosphere and run-off have both been reduced by two thirds. Advances in analytical methods resulting in improved (lowered) detection limits and higher precision mean that, while there is a downward trend in riverine inputs, the change is likely overestimated. However, it will
require longer-term observation to establish the significance of the change (OSPAR, 2017a). Lead inputs through continental run-off have more than halved, while atmospheric lead deposition is less than a third of the level it was at in 1990. Secondary atmospheric pollution from resuspended material and from sources outside the OSPAR maritime area are now the major sources of airborne pollution.

Cooperation is needed beyond the OSPAR area to manage those sources, in addition to the waterborne inputs. Analyses of lead isotopes in the tropical North Atlantic show that up to 30–50 per cent of natural lead detected came from North African mineral dust, which indicates successful global efforts to reduce anthropogenic lead emissions (Bridgestock and others, 2016). Concentrations of dissolved lead in surface waters of the Celtic Sea in the North-East Atlantic decreased fourfold over the past four decades to 8 ng/l (Rusiecka and others, 2018), which is still one or two orders of magnitude higher than background concentrations. Atmospheric lead inputs have been reduced, and benthic dissolved lead fluxes (5.6–8.5 µg lead/(m²/day)) now exceed the atmospheric lead fluxes (0.006–2.5 µg lead/(m²/day)) in the Celtic Sea, indicating the significance of sediments as a contemporary lead source (Rusiecka and others, 2018).

Mean concentrations of mercury, cadmium and lead in marine sediments are either decreasing or show no significant change in the majority of areas assessed. Nevertheless, concentrations in all areas are above natural background levels, and four of the six areas assessed are above levels where adverse ecological effects cannot be ruled out (OSPAR, 2017c). Following bans on tributyltin in antifouling paints, there has been a marked improvement in the reproductive condition of marine snails in the North-East Atlantic over the assessment period 2010–2015. Compared with an assessment in 2010, levels of imposex have markedly improved. In most assessment areas, imposex induced by tributyltin is at or below the level at which harmful effects are expected to occur, and there is also evidence of downward temporal trends in the severity of imposex in all areas assessed. Nevertheless, some areas are still subject to high imposex levels. Although levels of imposex are reducing, imposex remains above background levels in all of the areas assessed (OSPAR, 2017d).

Following the ban on tributyltin, mean concentrations in sediments have measurably reduced in the southern part of the Greater North Sea and are very low or undetectable elsewhere in the North-East Atlantic. Most countries in the area have stopped monitoring organotins in sediments, especially at offshore locations, because concentrations are now often so low that they are below the limit of detection. That means that a reliable assessment of organotins in sediments could be carried out only in the southern North Sea (OSPAR, 2017e).

In most areas assessed in the first Assessment, concentrations of mercury, cadmium and lead in mussels and fishes are higher than the estimated background assessment concentration levels (figure III). Nevertheless, all concentrations are below European Commission limits for foodstuff. Concentrations are decreasing or show no significant change in all areas assessed except for cadmium in a few Greater North Sea and Irish Sea locations (OSPAR, 2017b). European Commission maximum levels for metal concentrations in fish and shellfish are at least five times greater than background concentrations. In all OSPAR regions assessed since 2009, the average metal concentrations are below European Commission maximum levels.
Baltic Sea

There are large differences in the estimated total amounts of metals that enter the Baltic Sea every year, and their main route of entry is variable (Baltic Marine Environment Protection Commission (HELCOM), 2018a). It is estimated that the inputs of cadmium, mercury and lead to the Baltic Sea between 2012 and 2014 were in the range of 23–45, 4.8–5.6 and 443–565 tons per year, respectively (HELCOM, 2018a).

Mercury entering the Baltic Sea through atmospheric deposition constitutes about 70 per cent of the total, but levels decreased by 15 per cent from the 1990s to 2014.

Mercury concentrations in fish muscle (the most common species measured are herring and cod in open sea areas and flounder and perch in coastal areas) exceeded the established threshold level (20 µg/kg w.w.) in almost all monitored open sea sub-basins, indicating “not good” environmental status during the period 2011–2016 (HELCOM, 2018a). The threshold was also exceeded in some coastal areas and “good” status was achieved only in the Arkona Basin and in Danish and Swedish areas. There is no general trend for mercury in fish muscle for the investigated time series.

Riverine inputs of cadmium are dominant and make up 79 per cent of cadmium inputs to the Baltic Sea. Inputs through rivers with existing time series show large inter-annual variability that makes it hard to reveal any trend. Atmospheric cadmium deposition decreased by 60 per cent from the 1990s up to 2014.
For cadmium concentrations in seawater, biota (mussels) and sediments assessed by applying the “one-out-all-out” method, “good” status was achieved in only 35 per cent of open sea sub-basins assessed (HELCOM, 2018a) but no significant trends were observed in 89 per cent of the 38 trends evaluated, while there was a decreasing trend in 4 of 33 trends and only 1 showed an increasing trend. Threshold concentrations were 0.2 µg/l in water, 960 µg/kg d.w. (137.3 µg/kg w.w.) in mussel tissues and 2.3 mg/kg d.w. in sediments.

Riverine inputs of lead make up 64 per cent of the total input of lead to the Baltic Sea. The lead inputs of the existing time series show large inter-annual variability that makes it hard to reveal any tendencies. Atmospheric lead deposition has decreased by 80 per cent since the 1990s up to 2014.

Lead concentrations in biota (fishes and mussels) and sediments using the “one-out-all-out” approach indicate that “good” status was achieved only in four open sea sub-basins and in some coastal areas (HELCOM, 2018a). Furthermore, lead generally fails the established threshold value in biota (26 µg/kg w.w. in fish liver, and 1,300 µg/kg d.w. and 185.9 µg/kg w.w. in mussels). No consistent trend was observed.

In most areas, tributyltin is still a problem in water, sediments and biota (HELCOM, 2018b). For sediments, most of the sites failed the threshold level (1.6 µg/kg w.w.) and, even after two to three years of monitoring, no temporal trends could be assessed.

Levels of imposex measured for six or more years were found to be below the threshold value in the southern Kattegat and Skagerrak. In eight other sites, declining effects were observed, which is consistent with the findings in the North Sea area, where 48 per cent of the imposex sites showed decreasing trends.9

While the tributyltin situation is improving, levels of tributyltin in sediments and causal effects in marine gastropods indicate that historic pollution continues to affect the Baltic Sea. Uses of organotins other than in antifouling paints and their release from previously contaminated sediments should be investigated to ensure that decreasing trends continue.

**Mediterranean**

Metal contamination in the Mediterranean is the result of human activities (drivers and pressures) that take place all around the coastal and marine areas of the Mediterranean and cause imbalance to ecosystems from their natural steady-state conditions. Harmful contaminants enter the marine ecosystem through different routes, such as atmospheric deposition or inputs from land- and sea-based sources. Along the Mediterranean coast, small recreational marinas up to major commercial ports have created a number of different pressures in terms of chemical pollution. At present, there are still old threats and new pressures, although the trends and levels of metals have significantly decreased in most affected areas following the implementation of environmental measures (e.g., bans on leaded fuels and antifouling paints, mercury regulations), as observed in the western Mediterranean (UNEP/Mediterranean Action Plan (MAP)/Coordinated Mediterranean Pollution Monitoring and Research Programme (MED POL), 2011a), but Mar Menor is still highly affected by metals.

The latest available data sets of contaminants reported to the Coordinated Mediterranean Pollution Monitoring and Research Programme database continue to indicate lower levels of legacy pollutants and contaminants in the biota (mainly bivalves), despite known hotspots, as did the previous assessment reports (UNEP/MAP, 2009; UNEP/MAP/MED POL, 2011a; UNEP/MAP, 2012a, 2012b) and temporal

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trends reports (UNEP/MAP/MED POL, 2011b, 2016b), while also indicating the accumulation and persistence of chemicals in coastal sediments. The monitored chemical contaminants in bivalves (e.g., mussels, clams), fishes and sediments and their assessment against background assessment concentrations, environmental concentrations and effects range-low criteria also point to that conclusion. For biota (bivalves and fishes), the percentage of sites with acceptable environmental conditions (below the European Commission threshold criteria), range from 92 to 100 per cent for cadmium, lead and total mercury. Only 8 per cent of sites assessed for lead in mussels were above environmental concentrations. Therefore, all the assessed sites for biota in the database show acceptable marine environmental conditions, except 8 per cent of them for lead, according those criteria. On the contrary, levels in the coastal sediments above the assessment criteria (greater than effects range-low criteria), that is, non-acceptable environmental conditions, are 4 per cent, 53 per cent and 15 per cent for cadmium, total mercury and lead, respectively. The level of 53 per cent for mercury indicates the need for revised subregional assessment criteria; a mixture of natural and anthropogenic known sources might influence the assessment, especially in the Adriatic Sea, the Aegean Sea and Levantine Basin. In that regard, a revision of the current assessment criteria is under consideration (UNEP/MAP/MED POL, 2016a) and should result in a further refinement of the findings in future assessments.

Based on the values of environmental assessment criteria recommended for indicative purposes by decision IG. 22/7 of the Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean at their nineteenth ordinary meeting, held in Athens from 9 to 12 February 2016, overall, assessments reflect non-acceptable environmental conditions, in particular for lead in mussels in some locations and for lead and total mercury (53 per cent of sites are greater than effects range-low criteria) in coastal sediments, although some are known Mediterranean hotspots and natural input areas. To guarantee the control and achievement of targets to maintain acceptable conditions for cadmium and total mercury in biota, there is a need for continuous monitoring and assessment.

4.4.3. South Atlantic Ocean and wider Caribbean

GEOTRACES cruises in the South Atlantic are providing new assessments of dissolved lead inputs. A major flux (0.9 to 1.5 x 10⁶ kg/year) to the South Atlantic is from the Indian Ocean through the Agulhas Leakage, which supplies waters with elevated lead concentrations (annual mean concentration 5.8 µg/kg) that are equivalent to those provided by global atmospheric mineral dust deposition (1.6 x 10⁹ g/year, assuming 8 per cent of lead released from dust to seawater) (Paul and others, 2015). Currently, dissolved lead concentrations in the South Atlantic remain higher than pre-industrial levels, with 58 per cent of the dissolved lead in those waters originating from anthropogenic sources (Schlosser and others, 2019). It is expected that GEOTRACES data will continue to develop and contribute to the next Assessment.

Significant concentrations of aluminium, mercury and copper were found in sediments and fishes in the Caribbean, mainly in Sea Lots and Point Lisas harbours, Trinidad and Tobago, (Mohammed and others, 2012). Tributyltin also remains a concern in the Caribbean.

Phosphorus mining

Phosphate deposits are found across the world, in both sedimentary and igneous minerals. Currently, China mines the largest volume of phosphate, but Morocco is the largest exporter; however, most of the phosphate extraction and processing takes place far from the sea. Phosphorite mining and processing is a major source of inputs of mercury, cadmium
and lead, as well as chromium, nickel, copper, arsenic, thorium and uranium, to coastal waters (Gnandi and others, 2011). For example, in Togo, severe sediment, water and biota impact from metals has been documented, although other mining regions likely exhibit similar impacts. The phosphorite deposits of Togo, extracted since 1960 in the phosphate mines at Hahatoé and Kpogamé in southern Togo, are naturally enriched with metals and rare earth elements (Tanouayi and others, 2016). The ore processing allows the separation of the phosphorus-rich industrial fraction, leading to concentrations greater than 1 mm in seawater once phosphorite tailings are dumped into the ocean. Coastal sediments are highly enriched in trace metals and the calculated enrichment factors relative to the Earth’s crust are high. Such high loads of trace metals were also found in biota (fishes and mussels). The ratio of measured trace metal concentrations in biota to threshold limits set by the World Health Organization, herein defined as the relative health factor, was high in fishes, listed here from the highest concentrations to the lowest: selenium, arsenic, silver, nickel, manganese, iron, lead, cadmium, chromium, copper and zinc. Cadmium and aluminium were not accumulated. In mussels, the relative health factor was highest for iron, followed by arsenic, lead, selenium, manganese, nickel, silver, cadmium and copper (Gnandi and others, 2011).

4.4.4. Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Fish continues to be an important food product and the potential for fishes to be contaminated with a range of metals remains. In the Persian Gulf, most metals regularly exceeded maximum allowable levels in fish muscle, but cadmium and mercury concentrations exceeded the levels only by 10 per cent (Cunningham and others, 2019).

A recent study of a fish (Lethrinus nebulosus) off Qatar (Al-Ansari and others, 2017) in the Persian Gulf showed that mercury levels had improved in the region. Total mercury was highest in the liver (602 ± 192 μg/kg w.w.) and lowest in the gonad (71 ± 31 μg/kg w.w.), with muscle falling between the two. The study found an increasing trend compared with the levels detected 20 years earlier, but the levels were more in line with those reported in 2007. Concentration of mercury in sediments was in the range of 8–34.3 μg/kg for total mercury (Hassan and others, 2019).

Stable isotope studies showed that, in the Indian Ocean and the Arabian Sea, lead concentrations have been greatly affected by anthropogenic inputs (Lee and others, 2015). Those data serve as a baseline but will require future sampling to establish trends. In the western Indian Ocean, lead and cadmium levels were below levels of concern, although mercury in higher trophic species (swordfish, wahoo and blue marlin) often surpassed 1 mg/kg w.w. (Bodin and others, 2017). Over 13 per cent of swordfishes sampled in the Indian Ocean had mercury levels that surpassed 1 mg/kg w.w. and, in a global catch for comparison mercury levels, Indian Ocean swordfish levels had the most frequent and highest average mercury concentrations (Esposito and others, 2018).

4.4.5. North Pacific Ocean

Inputs from the Asian continent to the East China Sea and the North Pacific exhibit large episodic and seasonal pulses related to biomass burning and fossil fuel combustion (Qin and others, 2016). Total mercury levels in the deep waters of the North Pacific are elevated relative to surface and intermediate waters, but comparisons with historical data suggest that concentrations have not increased over the past 20 years (Munson and others, 2015).

4.4.6. South Pacific Ocean

Detailed mercury distribution in the South Pacific showed elevated concentrations in the Peruvian upwelling region and significant methylmercury, as high as 20 per cent of total
mercury (Bowman and others, 2016). Data in the region are not adequate to ascertain trends since the first Assessment, but values appear stable. The tropical South Pacific is a net source of mercury to the atmosphere but the exchange flux is lower than that of the North Atlantic (Mason and others, 2017).

4.4.7. Southern Ocean

Total mercury concentrations in the Southern Ocean are comparable to those in the South Pacific Ocean and the Atlantic Ocean. However, there are distinct regional features that include net mercury deposition along the ice edge of Antarctic sea ice, mercury enrichment in brine during sea ice formation and methylmercury formation south of the southern polar front (Cossa and others, 2011). Lead concentrations in water (6.2 µg/l) are comparable to those measured in more industrialized regions, such as the Baltic Sea, despite its remote location (Schlosser and others, 2016). Metal data in the region are too sparse to allow any trends since the first Assessment to be detected.

Rare earth elements

Contamination owing to “technology-critical elements” that are widely used in cost-effective low-carbon technologies, such as nuclear, solar, wind and bioenergy, as well as in carbon capture and storage technologies and electricity grids, and in medical products, has been observed since the beginning of the millennium (Bau and Dulski, 1996). Rare earth elements have been considered critical for the development and establishment of high-technology products. As a result of their application, an unavoidable release of such elements into the environment has been observed recently, thus increasing the number of trace elements acting as contaminants in the ocean. One of those elements, gadolinium, is used as a tracer of anthropogenic input in the study of positive anomalies (increased values relative to natural concentrations). The input of rare earth elements to the marine environment has been identified mainly through domestic sewage systems. In the past decade, positive anthropogenic gadolinium anomalies were found in marine waters globally as a result of drainage from densely populated areas, such as the North Sea (North-East Atlantic) (Kulaksiz and Bau, 2007), the San Francisco Bay and adjacent Pacific waters (Hatje and others, 2014), the Indian Ocean (Zhu and others, 2004; Ogata and Terakado, 2006; Akagi and Edanami, 2017) and the South Atlantic Ocean (Pedreira and others, 2018). In addition to gadolinium, other rare earth elements have been detected in raw phosphorite and mine tailings from phosphate mining at Hahatoé and Kpogamé (southern Togo) (Gnandi and others, 2011). However, scarce information exists on the environmental behaviour of those elements and on their impact on biota in marine systems. Although concentrations of anthropogenic gadolinium are rather low in marine waters, potential concerns regarding the effects of continuous exposure to low levels of gadolinium on aquatic organisms and human health have been arising (Hatje and others, 2018). The anthropogenic gadolinium complexes, originally considered to be safe for humans, have been shown to accumulate in humans and aquatic organisms.

4.5. Economic and social consequences and/or other economic or social changes

Metals of concern are non-essential trace elements that transfer through the trophic chain and ultimately bioaccumulate in the upper trophic levels of the oceans. The main social impact is that, despite some decreases in emissions, there are observed increases in concentrations of metals in higher trophic-level fish species, which have a direct impact on ecosystems, leading to apparent changes in food chains and, subsequently, human health risks (see chap. 8B) through ingestion. The risks are of particular concern to indigenous
communities that rely on specific food sources. A second impact is the potential decrease in fish stocks and the subsequent hardship for fishers who are constrained to go further from the coast, often with poor equipment, to catch fish. In certain regions, inputs and mining activities lead to regional deterioration that affects tourism and local economies.

5. Radioactive substances

5.1. Introduction

The waters, biota and sediments of the ocean all contain radioactivity. Much of it is from natural sources. Since the 1940s, however, there have been significant inputs from human activities. It is important to distinguish between the occurrence of ionizing radiation, emitted through the decay of radionuclides, and the impact of such radiation on biota, which varies according to the nature of the radiation (in particular, whether the radiation is of α (alpha) or β (beta) particles) and the part of the biota concerned. Studies of radioactive impacts on biota have concentrated on humans, but in the period since 2000, the International Commission on Radiological Protection, the international body of experts that agrees standards of radiation protection, has developed approaches for considering how to protect non-human biota.

5.2. Situation recorded in the first World Ocean Assessment

In the first Assessment, the levels of naturally occurring radioactivity in the ocean, ranging from the lowest levels in the South-West Atlantic to the highest levels in the North-East Atlantic, and levels of a typical anthropogenic radionuclide, ranging from the lowest in the Southern Ocean to the highest in, again, the North-East Atlantic, were noted. The most significant anthropogenic input has been from the testing of nuclear weapons, but that is now purely historical. Nuclear reprocessing plants were the second most significant anthropogenic source: such plants existed in 2014 in China, France, India, Japan and the Russian Federation, and further plants were under construction or planned in China, India, Japan and the Russian Federation. The nuclear accidents at Chernobyl and Fukushima resulted in large inputs of radioactive material to the ocean but were of limited concern by the time the first Assessment was written; immediately after the accident at Fukushima, increments to the input were limited. At the end of 2013, there were 434 nuclear power reactors in 30 countries, resulting in radioactive discharges to the ocean in orders of magnitude less than those from weapons testing, reprocessing plants and major accidents, and such discharges tend to decrease over time with improved technology, except for discharges of tritium, which have low radiotoxicity. Also noted was an anthropogenic concentration of naturally occurring radionuclides, in particular from scale cleaned from offshore oil and gas pipelines and phosphogypsum.

5.3. Description of the environmental changes between 2010 and 2020

5.3.1. General

The assessment of global levels of natural and anthropogenic radioactivity in the ocean in the first Assessment was based on studies carried out by the International Atomic Energy Agency (IAEA) in 1995 and 2005 (IAEA, 1995, 2005). No similar studies have since been undertaken, and the picture presented in the first Assessment thus remains the best available. However, IAEA is planning new studies of that kind in the early 2020s (personal communication from IAEA, 5 July 2019).
For radioisotopes with long half-lives, carriage by ocean currents can be significant, unlike terrestrial radioactive contamination. As with airborne transport of radionuclides, ocean currents can transport radioactive substances introduced into the marine environment to areas thousands of km away from the point of introduction. For example, the ratio of plutonium-240 to plutonium-239 in the Kuroshio Current zone in the North-West Pacific provides evidence that those radionuclides are being transported to that zone from the former atomic-bomb and nuclear-bomb Pacific Proving Grounds in the Federated States of Micronesia (Hong and others, 2011; Wu and others, 2019).

Although there have been no global surveys of the level of radioactivity in the ocean, there have been major advances over the past decade in the ability to measure low levels of the long-lived radioisotope iodine-129 (half-life 15.7 million years), a product of nuclear weapons testing and nuclear fuel reprocessing plants. Studies have now revealed its global distribution throughout the ocean and its application as a circulation tracer (He and others, 2013).

In addition, the Scientific Committee on Oceanic Research, under the International Council for Science, has instituted the international GEOTRACES programme to determine the distribution of trace elements and their isotopes throughout the ocean. The programme also includes anthropogenic radionuclides. As part of the programme, intercalibration efforts have demonstrated the ability to identify plutonium-239, plutonium-240 and caesium-137 from relatively small samples (Kenna and others, 2012). Radioisotope data collected through the GEOTRACES programme have also contributed substantially to the understanding of movements of material in the ocean (Malakoff, 2014).

In 2015, the Scientific Committee on Oceanic Research also set up Working Group 146, “Radioactivity in the Ocean, 5 decades later (RiO5)”, reverting to the theme of the first Working Group of the Committee in 1959. Working Group 146 has been tasked, among other things, with improving online resources for data on natural and anthropogenic radioisotopes in the ocean within the framework of the IAEA Marine Radioactivity Information System (MARIS) database, which contains measurements of radioactivity data in the marine environment found in seawater, biota, sediment and suspended matter (Scientific Committee on Oceanic Research (SCOR)-WG146, 2020).

5.3.2. Sources of radioactivity in the ocean

Developments with regard to the main sources of radioactive inputs to the ocean since 2014 (the base date for the relevant section of the first Assessment – chapter 20, section 10) have been as follows.

5.3.3. Nuclear weapons testing

The absence of atmospheric tests of nuclear weapons since 1980 has continued, and that source of inputs of radioactivity to the ocean therefore remains purely historical.

5.3.4. Nuclear reprocessing plants

The nuclear reprocessing plants mentioned in the first Assessment as functioning in 2014 (Gansu, China; Cap de la Hague, France; Kālpākkam, Tārāpur and Trombay, India; Tokai, Japan; Mayak, Russian Federation; and Sellafield, United Kingdom) remain in operation, but the Tokai plant is being decommissioned. The nuclear reprocessing plants at Cap de la Hague and Sellafield continue to represent the dominant source of anthropogenic radioactive inputs to the North-East Atlantic, and they contributed approximately 90 per cent of the total alpha discharges and approximately 80 per cent of the total beta (excluding tritium) discharges over the period 2007–2013. Nevertheless, there had been substantial reductions by 2016 in average discharges from the reprocessing plants in that period over the average levels in the period 1995–2001 – a reduction of about 40 per cent in total alpha discharges and about 85 per cent in total beta discharges (OSPAR, 2017b).
In China, the planning of a further nuclear reprocessing plant in Gansu is continuing. In India, work started on a nuclear reprocessing plant at Kālpākkam in 2017. In Japan, the nuclear reprocessing plant at Rokkasho is expected to reach completion by October 2022 (Japan Nuclear Fuel Limited (JNFL), 2020). In the Russian Federation, a new nuclear reprocessing plant at Zheleznogorsk is expected to be operational as of 2022 (World Nuclear Association (WNA), 2020).

5.3.5. Nuclear power plants

There were 450 commercial nuclear power reactors in 30 countries in operation at the end of 2018 (as compared with 434 in the same 30 countries at the end of 2013). The plants containing them have a total capacity of over 395,000 megawatts (MW). A little over 300,000 MW of that capacity is in countries of the Organization for Economic Cooperation and Development (OECD). About 55 more reactors are under construction. The plants produce over 15 per cent of the world’s electricity: the proportion ranges from about 70 per cent of the national supply in France to 2 per cent in the Islamic Republic of Iran (see table 1). That is a global average increase since 2013 of about 5 per cent. Other States that do not have nuclear power plants, such as Denmark and Italy, import substantial amounts of their electricity from neighbouring States that rely substantially on nuclear power (IAEA, 2019a).

For the nuclear power plants in the catchments of the Baltic and North-East Atlantic, the latest assessments show continuing reductions in the discharges of the various radionuclides that are monitored (other than tritium) (HELCOM, 2013; OSPAR, 2017b).

Detailed figures are not available for discharges in other global regions: the IAEA database on discharges of radionuclides to the atmosphere and the aquatic environment (information provided by national authorities on a voluntary basis) has not been updated since 2012, and much of the data in it are substantially older than that. As recorded in the first Assessment, tritium discharges from nuclear power plants are generally related to the level of electricity generation, and there is no accepted abatement technology.

Table 1
Proportion of electricity generated from nuclear power, 2018

<table>
<thead>
<tr>
<th>State</th>
<th>Percentage of electricity from nuclear power</th>
<th>State</th>
<th>Percentage of electricity from nuclear power</th>
<th>State</th>
<th>Percentage of electricity from nuclear power</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>71.7 (73.3)</td>
<td>Bulgaria</td>
<td>34.7 (30.7)</td>
<td>Pakistan</td>
<td>6.8 (4.4)</td>
</tr>
<tr>
<td>Slovakia</td>
<td>55.0 (51.7)</td>
<td>Armenia</td>
<td>25.6 (29.2)</td>
<td>Japan</td>
<td>6.2 (1.7)</td>
</tr>
<tr>
<td>Ukraine</td>
<td>53.0 (43.6)</td>
<td>Republic of Korea</td>
<td>23.7 (27.6)</td>
<td>Mexico</td>
<td>5.3 (4.6)</td>
</tr>
<tr>
<td>Hungary</td>
<td>50.6 (50.7)</td>
<td>Spain</td>
<td>20.4 (19.7)</td>
<td>South Africa</td>
<td>4.7 (5.7)</td>
</tr>
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<td>Sweden</td>
<td>40.3 (42.7)</td>
<td>United States</td>
<td>19.3 (19.4)</td>
<td>Argentina</td>
<td>4.7 (4.4)</td>
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<td>Belgium</td>
<td>39.0 (52.1)</td>
<td>Russian Federation</td>
<td>17.9 (17.5)</td>
<td>China</td>
<td>4.2 (2.1)</td>
</tr>
<tr>
<td>Switzerland</td>
<td>37.8 (36.4)</td>
<td>United Kingdom</td>
<td>17.8 (18.3)</td>
<td>Netherlands</td>
<td>3.1 (2.8)</td>
</tr>
<tr>
<td>Slovenia</td>
<td>35.9 (33.6)</td>
<td>Romania</td>
<td>17.2 (19.8)</td>
<td>India</td>
<td>3.1 (3.5)</td>
</tr>
<tr>
<td>Czechia</td>
<td>34.5 (35.9)</td>
<td>Canada</td>
<td>14.5 (16.0)</td>
<td>Brazil</td>
<td>2.7 (2.8)</td>
</tr>
<tr>
<td>Finland</td>
<td>32.5 (33.3)</td>
<td>Germany</td>
<td>11.8 (15.4)</td>
<td>Islamic Republic of Iran</td>
<td>2.1 (1.5)</td>
</tr>
</tbody>
</table>

Source: IAEA, 2019a.

Note: Figures for 2013 are provided in brackets, for comparison.
5.3.6. Non-nuclear sources of radioactive discharges to the ocean

A number of human activities other than nuclear installations result in discharges to the ocean both of naturally occurring radioactive material and of artificial radionuclides produced other than for nuclear energy purposes. The main activities of that kind are offshore hydrocarbon installations and pipelines, nuclear medicine and the production of agricultural fertilizer from phosphate rock. Published data on such discharges are not available except for the North-East Atlantic and its adjacent seas.

The collection of information on discharges of naturally occurring radioactive material and other non-nuclear discharges to the North-East Atlantic and its adjacent seas started in 2005. For the oil and gas industry, there are enough data to set a baseline (2005–2011), but it is not yet possible to identify trends in such discharges to the marine environment (OSPAR, 2017b). Recent studies by the OSPAR Commission conclude that the major source of naturally occurring radioactive material reaching the North-East Atlantic is the offshore oil and gas industry, where produced water (water coming from the reservoir with the oil and gas) and the scale that it deposits in pipelines (which has to be cleared periodically) contain low levels of radionuclides (mainly lead-210, polonium-210, radium-226 and radium-228). The total alpha and total beta discharges from the oil and gas sector are 97 per cent and 10 per cent of the discharges from all sectors, respectively (OSPAR, 2017b, 2018c). Of the total non-nuclear beta discharges, the largest contribution is iodine-131 from the medical subsector. Tritium discharges from the non-nuclear sector are insignificant compared with the nuclear sector (OSPAR, 2018c).

The production of agricultural fertilizers from phosphate rock results in the production of phosphogypsum (which is mainly a compound of calcium, but also contains naturally occurring radioactive material). It has often been discharged as slurry to the sea, but that now seems to have been widely phased out. Such discharge continues in Morocco (where there are new regulations and a review), Tunisia and elsewhere (Hermann and others, 2018; El Kateb and others, 2018). Morocco has, however, set up a system of improved management of phosphogypsum discharges (an investment of $120 million) so that discharges comply with international standards, in particular through marine outfalls equipped with diffusion systems along their ends (communication from the Government of Morocco).

5.3.7. Nuclear incidents

There have been no significant major nuclear incidents since 2011.

In relation to the 2011 incident in Fukushima, Japan, the United Nations Scientific Committee on the Effects of Atomic Radiation has reviewed the scientific work carried out on the maritime transport of radionuclides from the Fukushima Daiichi nuclear power plant since its 2013 report (which had concluded that effects on marine biota would be only local), and concluded that there were no reasons to change its conclusions.10

Activities to track the plume of low-level radioactivity in the North Pacific resulting from the Fukushima incident are ongoing (Men and others, 2015; Buesseler and others, 2017), and the plume has now been tracked into North American continental waters (Smith and others, 2015). Most notably, measurements of the long-lived iodine-129 (Hou and others, 2013; Otosaka and others, 2018; Suzuki and others, 2018) have provided critical information about ocean circulation and iodine biogeochemistry in the waters receiving radionuclides from Fukushima. Five years after the Fukushima accident, measurements of caesium-137 found highest activities in brackish groundwater underneath sand

beaches (Sanial and others, 2017), suggesting a previously undocumented submarine groundwater pathway for the storage and release of radionuclides to the ocean. However, the levels measured by Japan in the marine environment are low and relatively stable (IAEA, 2019b).

A study of Pacific bluefin tuna (Thunnus orientalis) caught off the coast of California, United States, around four months after the Fukushima accident showed a tenfold increase in radio-caesium concentrations (derived from Fukushima) compared with pre-Fukushima specimens. However, such radioactivity was approximately thirty times less than that emanating from concentrations of the naturally occurring radionuclide potassium-40 in both pre- and post-Fukushima fish samples (Madi- gan and others, 2012).

IAEA maintains databases on the dumping of radioactive waste at sea (which occurred between 1947 and 1993) and inputs from accidents and losses at sea. The last compilation of an inventory from the databases was published in 2015 (IAEA, 2015). The only incident that it records since 2010 is the entry into the ocean in 2015 of a Russian satellite with a small nuclear power pack.

5.4. Economic and social consequences and/or other economic or social changes

The pressures to increase the proportion of the world’s supply of electricity that is not derived from fossil fuels means that there continues to be significant interest in the generation of electricity from nuclear power plants. As noted above, there has been a 5 per cent increase in the generation of such electricity in the period 2013–2018.

A new development is the construction of the world’s first floating nuclear power plant by the Russian Federation. The Akademik Lomonosov completed initial testing in April 2019, to be ready to enter into service in December 2019 in the sea off the Russian port of Pevek, to replace an existing nuclear power plant and a combined heat and power plant (Power Engineering International (PEI), 2019). The Russian nuclear industry has also suggested collaboration with India over the development of floating nuclear power plants (Singh, 2019).

5.5. Regional aspects

There have been no significant studies of the global distribution of natural or anthropogenic radionuclides since the first Assessment, but, as noted above, IAEA is proposing to carry out some new assessments. As recorded in the first Assessment, both naturally occurring radioactivity in the ocean and the nuclear sources of anthropogenic inputs of radioactive material are significantly concentrated in the northern hemisphere. In the southern hemisphere, only Argentina, Brazil and South Africa have nuclear power plants.

5.6. Outlook

As noted in section 5.4, there may well be an increase in the number and scale of nuclear power plants. Linked with such increases is a likely increase in the scale of reprocessing of nuclear fuel. However, experience over recent decades suggests that there will be some offsetting reductions in the levels of radioactivity in discharges from such plants. As recorded in the first Assessment, the estimated highest current levels of committed effective doses to humans of radioactivity from food from the sea are less than a quarter of the IAEA recommended annual limit for the exposure of the general public to ionizing radiation. There is no evidence to suggest any recent significant change. Provided that adequate monitoring is maintained, therefore, such developments are not likely to be of concern.
6. Pharmaceuticals and personal care products

6.1. Introduction

As the population in the coastal regions grows, the size and number of cities grows with it. In particular, as megacities grow near the coast, river mouths and deltas, the anthropogenic pressure on coastal and marine ecosystems is increasing. The urbanization of coasts has direct implications for the input of PPCPs. An increasing number of people will need an increasing amount and number of pharmaceuticals and will apply an increasing amount and number of personal care products. At the same time, food production, such as aquaculture, will be of increased importance and will also lead to the input of pharmaceuticals for veterinary purposes. The picture is even more complicated when looking at demographic change and ageing populations, in particular in the western world. They will lead to an increasing application of certain pharmaceuticals per capita.

PPCPs include all chemicals used for health care, cosmetics and medical purposes. More than 3,000 PPCPs are currently marketed and new compounds enter the market yearly (Arpin-Pont and others, 2016). It is clear that the development of pharmaceuticals and their use in medicine is of considerable value to human society. Nevertheless, their fate is an environmental issue. PPCPs are often analysed together because their input pathways to the environment are similar. PPCPs reach the environment mainly indirectly through wastewater from households or agriculture (livestock farming). They are mostly washed off or excreted unchanged and released directly in the wastewater systems. As processes to remove PPCPs from wastewater are not efficient and most of the compounds are not degraded or are only slowly degraded, the products reach the aquatic environment through the wastewater effluents (Heberer, 2002; Verlicchi and others, 2012; Caldwell, 2016). Some PPCPs, such as ultraviolet filters in sunscreens, can also enter the ocean directly during recreational activities. They are often considered to be “pseudo-persistent” as their degradation is slow in relation to the large quantities that are input or discharged into the environment (Rivera-Utrilla and others, 2013; Bu and others, 2016).

However, it has been shown that several PPCPs may also be degraded to transformation products that could be more toxic (Kallenborn and others, 2018). Until now, most studies on PPCPs have been conducted in relation to the occurrence of PPCPs in influents and effluents of wastewater treatment plants (Fang and others, 2012; Rodil and others, 2012; Tamura and others, 2017), lakes and rivers (Sköld, 2000; Loos and others, 2010; Gothwal and Shashidar, 2015; Molins-Delgado and others, 2017). Many PPCPs have been detected in freshwater systems and, consequently, may end up in marine ecosystems. However, the available data are very limited. Consequently, PPCPs were not discussed or evaluated in the first Assessment.

The broad range of medicinal products available for human or veterinary use that can reach the marine environment may lead to a global environmental problem (Klatte and others, 2017). Owing to the continuous presence of pharmaceuticals in the aquatic environment entering through different entry pathways, they are regarded as a class of pseudo-persistent contaminants (Bu and others, 2016). Pharmaceuticals reach production volumes of up to 100,000 tons per year (Aus der Beek and others, 2016), representing nearly $1.5 trillion in the global pharmaceutical market by 2021, with further expansion predicted. The main drivers for the development are market expansion and demographic changes, including an ageing population (International Federation of Pharmaceutical Manufactures & Associations (IFPMA), 2017; Roig, 2010; Arnold and others, 2014). Pharmaceuticals go through a strict approval procedure in order to ensure
effectiveness and patient safety (Taylor, 2016). However, long-term ecotoxicological studies for risk assessment to prevent undesirable environmental effects have only rarely been considered (Sanderson and others, 2003; Fent and others, 2006; Boxall and others, 2012). Since only limited data on the occurrence of a variety of pharmaceuticals in the coastal environment are available, pharmaceuticals with environmental relevance need to be monitored (Gaw and others, 2014; Richardson and Ternes, 2014; Arpin-Pont and others, 2016; Pazdro and others, 2016).

6.2. Situation recorded in the first World Ocean Assessment

PPCPs were included in section 2 of chapter 20 on hazardous substances (United Nations, 2017b), alongside classical POPs and heavy metals. They were not considered or evaluated in their own right.

6.3. Description of the environmental changes between 2010 and 2020

To date, there are few studies on the occurrence of PPCPs in marine ecosystems. However, there is increased interest in the occurrence of PPCPs in the ocean, not least because marine ecosystems are assumed to be affected by contamination by PPCPs and increasingly sensitive analytical capabilities are available (Picot-Groz and others, 2014). Available data based on the occurrence of PPCPs in seawater, sediment and marine organisms have recently been collected and published by Bebianno and Gonzalez-Rey (2015) and Arpin-Pont and others (2016). The most frequently investigated and detected compounds were antibiotics (erythromycin, sulfamethoxazole and trimethoprim; see figure IV), anti-epileptics (carbamazepine), caffeine, non-steroidal anti-inflammatory (ibuprofen, ketoprofen) and analgesics (acetaminophen). Among cardiovascular drugs, atenolol and gemfibrozil were most frequently detected or exhibited the highest relative concentrations (Arpin-Pont and others, 2016).

Limited amounts of data were available for personal care products (Bebianno and Gonzalez-Rey, 2015; Arpin-Pont and others, 2016). Available data cover musk fragrances, disinfectants (triclosan) and some ultraviolet filters, the most relevant of which are benzophenone-3 and octocrylene. Triclosan was detected at concentrations of up to 99.3 ng/l in water in Victoria Harbour, China (Wu and others, 2007). Concentrations of benzophenone-3 up to 2,013 ng/l were detected in water at Folly Beach, South Carolina, United States (Bratkovics and Sapozhnikova, 2011). Octocrylene that is used not only in sunscreens but also in food additives enters coastal areas either directly or indirectly through wastewater. Concentrations of octocrylene were up to 1,409 ng/l in water and up to 3,992 ng/g d.w. in mussel tissues (Arpin-Pont and others, 2016; Picot-Groz and others, 2014).

The majority of the measurements of PPCPs in marine waters have been conducted in the North Atlantic Ocean, the North Sea, the Baltic Sea, the Mediterranean and the Asian Pacific Ocean (table 2). In Asia, in particular in China, a number of different PPCPs were measured in seawater, sediments and biota in estuaries and in the Chinese marginal seas (Xu and others, 2013; Zhang and others, 2013b; Na and others, 2013; Nödler and others, 2014; Kallenborn and others, 2018; Kötke and others, 2019). The studies showed that PPCPs are present in all areas of the ocean, with higher levels in areas that are directly affected by anthropogenic activities. Recently, a number of studies have been carried out at coastal sites in the Arctic and Antarctic. In contrast, however, very few PPCP measurements have been taken in the marine environment of the southern hemisphere and very little information exists for PPCP levels in sediments (Arpin-Pont and others, 2016).
In addition to the occurrence of antibiotics and their transformation products in the marine environment, antibiotic-resistant genes have also been found in bacteria and soil in the Pacific Ocean and the Arctic Ocean (McCann and others, 2019; Hatosy and Martiny, 2015). The occurrence of antibiotic-resistant genes in the marine environment can be linked to the coastal run-off of antibiotic-resistant bacteria from terrestrial sources, anthropogenic antibiotic run-off and selection for resistance in response to antibiotics introduced in the marine environment (Allen and others, 2010; Hatosy and Martiny, 2015).

The availability of data on PPCPs in the Arctic environment has been even more limited than for temperate marine systems. Nevertheless, Kallenborn and others (2018) concluded that the group of compounds are relevant pollutants, even in remote regions, including the Arctic. Based on recent studies, the character of local PPCP sources, such as sewage treatment, in combination with the low-temperature Arctic climate and limited technological standards for waste treatment facilities in Arctic settlements all contribute to extending the environmental stability of the residues compared with conditions found in lower-latitude regions (Kallenborn and others, 2018). More than 100 PPCP-related compounds have been identified in virtually all Arctic environmental matrices, from coastal seawater to high trophic-level biota. Some 22 of a total of 110 compounds were identified in seawater (Kallenborn and others, 2018), with the highest concentrations registered for citalopram (antidepressant), carbamazepine (anti-epileptic) and caffeine (stimulant). Relatively high levels of certain PPCPs in the Arctic environment are not necessarily linked to higher consumption rates but may more likely be explained by higher environmental stability in the low-temperature Arctic climate. That is considered to be of critical relevance when significant amounts of antimicrobial agents are released, thus enhancing the potential for the development of resistance (Gullberg and others, 2011; Kallenborn and others, 2018).

Although PPCPs have been suggested for inclusion in the list of hazardous substances for decision-making on control measures and there is clear evidence that PPCPs are present in all ocean areas and in marine organisms, the data are still insufficient for most PPCPs detected to assess the trend levels in water and the exposure effects on marine organisms.
Table 2
Concentrations of major pharmaceuticals and personal care products measured in coastal waters (ng/l)

<table>
<thead>
<tr>
<th>Location</th>
<th>Erythromycin</th>
<th>Clarithromycin</th>
<th>Sulfamethoxazole</th>
<th>Sulfamethazine</th>
<th>Roxithromycin</th>
<th>Iomeprol</th>
<th>Iopromide</th>
<th>Diclofenac</th>
<th>Carbamazepine</th>
<th>Bezafibrate</th>
<th>Ibuprofen</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic, Tromsø (Norway)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>Kallenborn and others, 2018</td>
</tr>
<tr>
<td>Arctic, Longyearbyen (Norway)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.d.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1.0–4.0</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.4–1</td>
<td></td>
<td></td>
<td>Kallenborn and others, 2018</td>
</tr>
<tr>
<td>Arctic, Tromsø (Norway)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.d.–0.7</td>
<td></td>
<td>Weigel and others, 2004</td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>n.d.–0.14</td>
<td>0.03–0.42</td>
<td>0.74–3.29</td>
<td>0.48–1.05–34.5</td>
<td>0.42–3.34</td>
<td>n.d.–0.84</td>
<td>1.98–10.6</td>
<td>n.d.–0.64</td>
<td>n.d.–0.7</td>
<td>n.a.</td>
<td></td>
<td>Kötke and others, 2019</td>
</tr>
<tr>
<td>North Sea</td>
<td>0.13–0.94</td>
<td>0.4–1.66</td>
<td>1.78–13.0</td>
<td>0.26–2.86</td>
<td>7.66–207</td>
<td>7.27–34.1</td>
<td>4.78–29.7</td>
<td>n.d.–2.06</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Kötke and others, 2019</td>
</tr>
<tr>
<td>Himmerfjärden (Sweden)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>4.0–12.0</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.d.–0.7</td>
<td>n.a.</td>
<td></td>
<td>Magnér and others, 2010</td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>n.d.</td>
<td>14</td>
<td>21</td>
<td>n.a.</td>
<td>98</td>
<td>45</td>
<td>9.2</td>
<td>22</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Nödler and others, 2014</td>
</tr>
<tr>
<td>Oslofjord</td>
<td>n.a.</td>
<td>n.d.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.d.–48.0</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.d.–52.0</td>
<td>n.a.</td>
<td></td>
<td>Kallenborn and others, 2018</td>
</tr>
<tr>
<td>Aegean Sea</td>
<td>n.d.</td>
<td>16</td>
<td>3.8</td>
<td>n.a.</td>
<td>83</td>
<td>109</td>
<td>4.6</td>
<td>3.5</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Nödler and others, 2014</td>
</tr>
<tr>
<td>Adriatic Sea</td>
<td>5.8</td>
<td>n.d.–36</td>
<td>n.a.</td>
<td>29</td>
<td>n.a.</td>
<td>n.d.</td>
<td>3.1</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Nödler and others, 2014</td>
</tr>
<tr>
<td>Adriatic Sea</td>
<td>n.a.</td>
<td>0.02–1.02</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.11–0.36</td>
<td>0.02–0.14</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>Loos and others, 2013</td>
<td></td>
</tr>
<tr>
<td>Mediterranean</td>
<td>9</td>
<td>5</td>
<td>14</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.d.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Moreno-González and others, 2015</td>
</tr>
<tr>
<td>Santos Bay</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.d.</td>
<td>n.a.</td>
<td>n.d.</td>
<td>326.1–2094</td>
<td>n.a.</td>
<td></td>
<td>Pereira and others, 2016</td>
</tr>
<tr>
<td>Red Sea</td>
<td>n.a.</td>
<td>63</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>14020</td>
<td>110</td>
<td>n.a.</td>
<td>508</td>
<td>n.a.</td>
<td>Ali and others, 2017</td>
<td></td>
</tr>
<tr>
<td>Bohai Sea and Yellow Sea</td>
<td>0.69</td>
<td>0.07</td>
<td>1</td>
<td>0.01</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Zhang and others, 2013b</td>
</tr>
<tr>
<td>Jiaozhou Bay</td>
<td>4.5</td>
<td>0.58</td>
<td>9.6</td>
<td>0.04</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
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<td>n.a.</td>
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<td>Zhang and others, 2013a</td>
</tr>
<tr>
<td>Yantai Bay</td>
<td>0.82</td>
<td>0.03</td>
<td>1.4</td>
<td>0.02</td>
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<td>n.a.</td>
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<td>n.a.</td>
<td></td>
<td>Zhang and others, 2013a</td>
</tr>
<tr>
<td>Southern Yellow Sea</td>
<td>0.5</td>
<td>3</td>
<td>7.7</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
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<td>n.a.</td>
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<td>Du and others, 2017</td>
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<td>East China Sea</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.5–3.5</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>Fisch and others, 2017</td>
<td></td>
</tr>
<tr>
<td>Pearl River delta</td>
<td>n.d.–126</td>
<td>n.d.–40.6</td>
<td>n.d.–12.0</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>Xu and others, 2013</td>
<td></td>
</tr>
<tr>
<td>South China Sea</td>
<td>21</td>
<td>11.4</td>
<td>7.03</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>Liang and others, 2013</td>
<td></td>
</tr>
<tr>
<td>Sydney (Australia) estuary</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>3.0–12.5</td>
<td>n.a.</td>
<td>n.d–2.7</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Birch and others, 2015</td>
</tr>
</tbody>
</table>

Abbreviations: n.a., not available; n.d., not detected.
7. **Atmospheric pollutants (nitrogen oxides, sulfur oxides)**

7.1. **Introduction**

Combustion is a major source of nitrogen oxides (NO\(_x\)) and sulfur oxides (SO\(_x\)) in air emissions. Of particular interest for the marine environment are the emissions from shipping that contribute to air pollution. The local and regional environmental issues connected to shipping emissions are, to a large degree, coupled with shipping intensity, but such emissions can also contribute to global pollution.

7.2. **Situation recorded in the first World Ocean Assessment**

In chapter 17 of the first Assessment (United Nations, 2017a), emissions of NO\(_x\) and SO\(_x\) in areas of heavy traffic were discussed, as were the contribution of those compounds to acid rain and to human health.

7.3. **Description of the environmental changes between 2010 and 2020**

Total annual NO\(_x\) emissions from shipping have been estimated at about 19,000 kilotons (2013–2015), of which about 91 per cent derives from international shipping, with the rest deriving from domestic shipping and fishing vessels (6 per cent and 3 per cent, respectively) (Olmer and others, 2017). Total annual nitrogen emissions from international shipping on the Baltic Sea amount to approximately 80 tons, which is about 5 per cent of the total NO\(_x\) emissions in the Baltic Sea countries (Gauss and others, 2018).

The adverse effects of air pollution caused by shipping are an issue of interest to the International Maritime Organization (IMO), which, on the basis of annex VI to the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto,\(^{11}\) endeavours to reduce emissions of, for example, SO\(_x\) (and, indirectly, particulate matter) and NO\(_x\) from ships through international agreements. There are also IMO-designated emission control areas, in which the restrictions with respect to emissions of SO\(_x\) and/or NO\(_x\) are more stringent. As at 1 January 2020, the global limit for sulfur content in the fuel oils used by shipping was reduced from 3.5 per cent by mass to 0.5 per cent, while since 2015, the limit has been reduced to 0.1 per cent in the emission control areas. There are four emission control areas: the Baltic Sea area and the North Sea area (presently only for SO\(_x\), but will include NO\(_x\) from 2021), the North American area and the United States Caribbean Sea area. The implementation of the North Sea and Baltic Sea SO\(_x\) emission control areas led to a significant reduction of sulfur dioxide concentrations in bordering port cities and coastal regions, which benefited the health of coastal citizens (European Union, 2018). The requirement was also set to reduce acidification resulting from SO\(_x\) deposition at sea (European Environment Agency (EEA), 2013). It is estimated that the implementation of the Baltic Sea NO\(_x\) area will reduce nitrogen deposition at sea by about 40 per cent by 2040 (Karl and others, 2019). Despite those improvements, a modelling study of the longer-term perspective shows that, without additional measures, the current IMO and European Union regulations will cut SO\(_2\) emissions of international shipping up to 2030, but that after that, emissions will grow again. The pattern is even more pronounced for NO\(_x\) emissions; it is expected that, after 2030, the emissions from international shipping will exceed those from land-based sources in the European Union, if no further control is applied (International Institute for Applied Systems Analysis (IIASA), 2018).

To meet the stricter sulfur regulations without switching to more expensive fuel of lower sulfur content, an increasing number of ships (7 ships in 2010, 256 in 2015 and more than 4,400 in 2020) have been equipped with an exhaust gas cleaning system, also known as scrubbers, which allows for continued use of heavy fuel oil. In the scrubber, the exhausts are washed in a fine spray of water, and in the simplest and most common form, open-loop scrubbers, the wash water is directly discharged back to the sea. In addition to sulfur oxides, other substances, such as metals and organic pollutants, are also washed out of the exhausts, and there is increasing concern that wide-scale discharge of scrubber wash water may affect the marine environment negatively (Koski and others, 2017; Ytreberg and others, 2019; Teuchies and others, 2020). For that reason, some ports, regions and countries have taken a precautionary approach and prohibited such discharges in their waters (Turner and others, 2017). They include many European ports, such as Rotterdam, the Netherlands, and ports in California, United States, and Singapore and, recently, China and Egypt also proposed such a ban in Chinese waters and the Suez Canal, respectively.

Further efforts to reduce the environmental impact of shipping include the IMO International Code for Ships Operating in Polar Waters,\textsuperscript{12} which promotes the identification of hazardous substances on the basis of routine operations and navigational and shipping accident reports. As a consequence of the stricter global sulfur rules and the encouragement to not use heavy fuel oil in the Arctic, more alternative fuel blends have entered the market. More research is needed to determine the potential toxicity of the new fuels.

8. Hydrocarbons from terrestrial sources, ships and offshore installations, including arrangements for response to spills and discharges

8.1. Situation recorded in the first World Ocean Assessment

As described in the first Assessment, the impact of hydrocarbons, for example, from oil spills, can affect the marine ecosystem both physically, through the oiling of birds, mammals and beaches, and chemically, through toxic components, such as polycyclic aromatic hydrocarbons. Depending on concentration and exposure, the effects may be acute or chronic (Lindgren and others, 2012). Hydrocarbons enter the marine environment through many pathways. Land-based sources include urban run-off and coastal refineries, while shipping-related sources include operational discharges and accidents and, for offshore oil and gas facilities, operational discharges, accidents and blow-outs. In addition, atmospheric fallout and natural seeps are substantial sources. It was posited in 2003 that the total range from all sources may have reached 470,000 tons to 8.4 million tons a year (National Research Council and Transportation Research Board, 2003), which can be compared with world crude oil production, for example in 1999, which was about 3.5 billion tons. The levels of polycyclic aromatic hydrocarbons are expected to decrease owing to tighter regulations of combustion plants, vehicles and so forth. In 2017, crude oil production increased by almost

\textsuperscript{12} International Maritime Organization, document MEPC 68/21/Add.1, annex 10.
25 per cent and was approaching 4.4 billion tons (Global Energy Statistics Yearbook, 2018).

8.2. Description of the environmental changes (between 2010 and 2020)

Based on global models of long-range atmospheric deposition of benzo(a)pyrene (B[a]P), one of the polycyclic aromatic hydrocarbon compounds, it is notably higher in the Adriatic Sea and the Aegean Sea in the Mediterranean, in coastal areas of the North Sea, in the North-East Atlantic and in the south-eastern part of the Baltic Sea, as well as in the northern Caspian Sea (figure V.A). However, on a global scale, the major emissions and deposition of B[a]P are to be found in the eastern and southern parts of Asia, where the atmospheric deposition is a magnitude higher or even more, compared with the levels illustrated in figure V (Gusev and others, 2018). The deposition of B[a]P in the Baltic Sea increased up to 2000, after which time the deposition rate seems to have levelled off.

Other important sources of hydrocarbons entering the ocean are shipping accidents, operational losses and illegal discharges from shipping. The global trend regarding shipping accidents leading to oil spills above 7 tons is, however, decreasing. According to the International Tanker Owners Pollution Federation (2019), the annual average number of spills in the period 2009–2018 was 6.4, compared with 35.8 for the period 1990–1999. The decrease in tanker spills is likely the result of improved safety measures in terms of the phaseout of single-hull tankers, which came into effect in 2003 (IMO, 2019), through an accelerated process following the disastrous accident involving the *Erika* tanker in 1999. The *Erika* and *Prestige* (2003) accidents also marked the starting point for maritime vetting inspections as a possible measure for cargo owners to demand higher safety standards, primarily for chemical and oil tankers (Powers, 2008). The declining trend in the number of tanker spills is even more pronounced taking into account the steady growth – close to an 80 per cent increase from 1990 to 2017 – in loaded crude, petroleum and gas shipping (United Nations Conference on Trade and Development (UNCTAD), 2018).

During the past 10 years, offshore oil production has remained at the same level, about 26 million–27 million barrels per day (International Energy Agency (IEA), 2018a), but its market share has shrunk as global oil production increased to approximately 95 million barrels per day in 2017 (IEA, 2018b). Aside from oil spills, the main impact from the offshore production of oil and gas is associated with the discharge of produced water, with global volume estimated to be up to 39.5 million m$^3$ per day (Jiménez and others, 2018), and the disposal of drilling waste (Bakke and others, 2013). Although several studies (e.g., Moodley and others, 2018) indicate sublethal effects from produced water on marine species, there is a general understanding that there is a low risk of long-term, widespread impact from produced water on marine species, but it cannot be verified from published literature (Bakke and others, 2013). However, the observed levels of DNA adducts in the livers of wild-caught fishes from regions with oil production in the North Sea above environmental assessment criteria raise concern regarding the effects of oil compounds on early life stages (Balk and others, 2011; Pampanin and others, 2017). There is a need for further studies on community and population levels to advance the current knowledge based on single-species toxicity data (Camus and others, 2015). The need is also relevant for environmental risk assessment prior to new offshore exploration. If a risk assessment is based on worst-case scenarios that are limited in their holistic validity, it may be biased in the handling of associated uncertainties (Hauge and others, 2014). From the marine environment perspective, an increasing area of concern is the decommissioning of offshore platforms.
The International Energy Agency (2018a) estimated that 2,500–3,000 offshore projects will probably need to be decommissioned, while today the annual average decommissioning rate is 120 platforms per year. The costliest part of platform decommissioning is plugging and abandoning wells. In the North Sea, the removal of all topsides and substructures has been required since 1998, under the OSPAR Convention. However, the “rig to reef” approach has been adopted in the United States and South-East Asia, allowing for parts of the subsea structures to be left and converted to artificial reefs. In the Gulf of Mexico, there are already more than 500 such permanently converted decommissioned rigs (IEA, 2018a).

**Figure V.A**
Spatial distribution of global scale annual mean modelled air concentrations (ng/m$^3$) of B[a]P for 2016

**Figure V.B**
Spatial distribution of global scale deposition fluxes (g/km$^2$/year) of B[a]P for 2016


9. **Other substances used on, and discharged from, offshore installations**

Beyond the environmental impact caused by its hydrocarbon content, produced water also contains elevated concentrations of metals, such as arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver and zinc, some in the range of $10^{2}$–$10^{5}$ times higher than background concentrations (Jiménez and others, 2018). Naturally occurring radioactive material originating from geological formations may also be present as dissolved solids in produced water. The most common such compounds are radium-226, radium-228 and barium (Bou-Rabee and others, 2009). To minimize the negative environmental impact of produced water, efforts are being made to: (a) use a small volume of water for the oil extraction process; (b) reuse the water; and (c) dispose of it at sea (Jiménez and others, 2018).

As concluded in the first Assessment, there are still knowledge gaps with respect to an assessment of the large-scale impact of produced water (OSPAR, 2018a). In the North Sea region, the OSPAR Commission has worked hard to achieve phaseout of the most toxic chemicals used in the offshore production industry until 2017. Although the target was not entirely reached, at least the chemicals on the OSPAR List of Chemicals for Priority

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13 The potentially negative effects of metals are described in section 4 of the present chapter.
14 The potentially negative effects of naturally occurring radioactive material are described in section 5 of the present chapter.
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Action were not used at all on the Norwegian continental shelf from 2014 to 2016. The total use and discharge quantity of chemicals on the Norwegian continental shelf peaked in 2013, and there was a similar trend regarding discharge on the United Kingdom continental shelf (OSPAR, 2018b). The total quantity of chemicals used offshore was 398,158 tons in 2016. A total of 71 per cent (weight) of the used chemicals were on the OSPAR List of Substances Used and Discharged Offshore which are Considered to Pose Little or No Risk to the Environment, 28 per cent (weight) were other non-substitution chemicals and 1 per cent comprised substitution chemicals (i.e., chemicals that contain one or more substances that are candidates for substitution). In addition to the work done on phasing out toxic chemicals, new technologies, for example, advanced oxidation processes for the remediation of produced water, have also been proposed (Jiménez and others, 2018).

10. Relationship to the Sustainable Development Goals

The atmospheric deposition of various pollutants on water (or land) is directly related to Goal 14 but is also relevant to most, if not all, Sustainable Development Goals, for example, Goals 2 and 6 or Goals that might have an impact on air emissions, including Goals 1 and 8, as one of the prerequisites for life on earth is the supply of clean and healthy water.

The presence of POPs at concentrations likely to cause deleterious effects means that it is unlikely that Sustainable Development Goal target 14.1 will have been achieved by 2025. For many of the legacy POPs, such as PCBs, emissions, discharges and losses are very low; the issue is the re-emergence from sediments owing to the resistance of POPs to biodegradation. There also remains a clear need to increase scientific knowledge (Sustainable Development Goal target 14.a and other Goals) around the cumulative impacts of the growing mixture of chemicals to which marine biota are being exposed.

Sustainable Development Goal target 3.9 will be hard to achieve with respect to POPs, metals, PPCPs and hydrocarbons, specifically with respect to achieving a substantial reduction in water pollution. The impacts of POPs, metals, PPCPs and hydrocarbons on human health have not been evaluated in the present chapter but it has been recognized that marine mammals are being affected by POPs, with concentrations for some POPs and metals decreasing only slowly and with increasing concentrations affecting top predators.

The achievement of Sustainable Development Goal target 2.1 will require more concerted monitoring programmes covering the edible portion of marine plants and animals to ensure the quality of marine food sources.

The available information on the impact of ionizing radiation from anthropogenic sources on the marine environment suggests that it probably does not pose a significant problem for the achievement of Sustainable Development Goal target 14.1. However, there are significant gaps in the information available on discharges of radionuclides in much of the world.

Relevant PPCPs should be included in already established long-term international, national and regional monitoring programmes to serve as a scientific basis for region-specific “watch lists” for PPCPs, in particular in coastal waters. There should be no segregation of environmental regulations and legislation between terrestrial and marine ecosystems at the national and international levels, with coastal areas treated as a transition zone in

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15 See General Assembly resolution 70/1.
the “catchment-to-sea continuum” and as the link between Goals 6 and 14.

As the impacts of increased anthropogenically produced carbon dioxide become more significant in the ocean, it becomes more evident that the marine biota is being exposed to yet another stressor – ocean acidification. The pH decreases (see chap. 9), along with the increase in temperature and decrease in dissolved oxygen, pose a risk that biota already made vulnerable by their contaminant loading will succumb to the multiple stressors (see also chap. 25) they are experiencing. It would be desirable to reduce the presence of multiple stressors in the ocean along with climate action.

11. Key remaining knowledge gaps

In the first Assessment, the need to work through a number of different organizations was highlighted as limiting the possibility of making clear comparisons between the environmental quality of different ocean areas because of the use of different measuring techniques and the very different ranges of the varieties of chemicals being observed. That situation remains.

Information on the atmospheric deposition of various pollutants is heavily dependent on the modelling approaches used to increase the spatial coverage. To be able to model the deposition, there is a significant need for high quality data on emissions and deposition. The data need to be collected and used in regional and/or global modelling to facilitate the production of high-resolution spatial and temporal deposition estimates. However, the availability of that kind of fundamental data is limited, especially for some ocean areas, which is quite evident from the present Assessment, for which there is a lack of information for a large part of the ocean.

Changes in industrial production will result in changes in compartmental patterns as well as the point sources and substance mixtures. With the broadening of the Stockholm Convention, there is a need for information on the concentrations of the compounds detailed in the Convention that are found in the environment to permit the consideration of cumulative impacts (see chap. 25) and the effectiveness of the processes aimed at eliminating the emissions and use of those compounds.

Critically, the biological effects and cumulative impacts of the chemicals detailed in the Stockholm Convention require considerable research to allow appropriate status assessments to be prepared, especially in cases where changes are attributable to the impact of increased atmospheric greenhouse gas concentrations (e.g., ocean warming, ocean deoxygenation, ocean acidification and changing rates of respiration).

Current efforts and ongoing time series under the GEOTRACES programme will improve both global and regional resolution. However, significantly higher resolution is needed to improve estimates of trends with respect to trace elements and their isotopes. Time series in the South Atlantic and across the South Pacific are currently lacking for hazardous substances, as are data for the Southern Ocean. The extent of transboundary marine pollution is yet to be properly investigated. The mapping of contamination of coastal waters and sediments requires a more integrated effort, together with more globally targeted studies of biota such that effects can be determined on a larger (oceanic) basis.

It is necessary to coordinate spatial and temporal sampling for metals such that the data reflect a global strategy. That will require integrated efforts, possibly including the UNEP regional seas conventions and action plans,
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with both coastal and open ocean sampling. As sampling resolution is optimized, such that changes in concentration can be detected with a known confidence, quality control and quality assurance guidelines, including inter-calibrations, will be required.

Very limited detailed information is published of the levels of discharges of radioactive substances to the marine environment, outside the North-East Atlantic and its adjacent seas. It is known that substantial monitoring is carried out. There is, therefore, a case for restarting and extending the IAEA database on discharges of radionuclides to the atmosphere and the aquatic environment as a means to provide much wider publication of the information.

Likewise, the intention of IAEA to repeat the studies carried out by the Agency in 1995 and 2005 (IAEA, 1995, 2005) on the levels of natural and anthropogenic radioactivity in fishes and seawater in the different major fishing areas is welcomed. It would be an appropriate contribution to the United Nations Decade of Ocean Science for Sustainable Development (2021–2030).

A review of the studies of the impact of ionizing radiation on crustaceans concludes that there is poor coverage of data, in particular in the field, on the subject and suggests that similar problems may exist with other phyla (Fuller and others, 2019), which implies that there is a need for further research on the subject.

The quite large number of PPCPs identified in marine ecosystems is primarily indicative of the capability of today’s analytical method for the identification and quantification of those substances and their metabolites. It does not necessarily reflect the full range of PPCPs present in the marine environment. The ultratrace concentrations of PPCPs in seawater, sediments and biota are still a significant challenge for existing analytical methods. However, technological developments and novel applications will further decrease limits of quantification and, in addition, will lead to the identification of new and presently unidentified PPCPs (Kallenborn and others, 2018).

Both active and passive sampling strategies and analytical methodologies for the analysis of PPCPs and their metabolites in the marine environment need to be harmonized. That will ensure common data quality and allow more effective data comparison between laboratories and geographic regions (Arpin-Pont and others, 2016).

Because PPCPs are mostly excreted unchanged or as metabolites, it is not appropriate to target only the parent compounds; the major transformation products must be included in both the analytical procedures and the risk assessments (Rivera-Utrilla and others, 2013).

To date, there is no comprehensive data set available covering the worldwide occurrence of PPCPs in the coastal regions and the open ocean, which means that it has not been possible to conduct any potential assessment of the impacts of PPCPs on marine organisms. It would be desirable to create a database to support the risk assessment and modelling and provide information for the international management of PPCPs. Owing to the lack of adequate data, especially for the different trophic levels in marine webs, a safety factor of 10,000 needs to be applied, which results in a high uncertainty of the risk characterization of the compounds (European Medicines Agency (EMEA), 2018).

To further evaluate the ecotoxicity of the investigated PPCPs and to estimate whether the observed concentrations may have an effect on marine ecosystems, it will be important to improve the data on marine test organisms. Such efforts should focus on the impacts of chronic toxicity characterized by low-dose exposure in long-term studies, which would include the behaviour of mixtures of chemicals (Deruytter and others, 2017).
12. Key remaining capacity-building gaps

The complex nature of the mixtures that comprise POPs and PPCPs, coupled with the fact that, even at very low concentrations, those compounds can be toxic, means that there is a need to develop the necessary analytical capabilities on a global scale.

Sampling and subsequent analyses in the open ocean and in coastal and shelf seas need to be undertaken in a systematic, quality-assured manner on a global basis, covering both the original and new POPs, as detailed in the Stockholm Convention, as well as metals, PPCPs, radioactive substances, NO\textsubscript{x}, SO\textsubscript{x}, and hydrocarbons. Although significant analytical challenges are expected, such an approach will permit precise spatial and temporal assessments to be made, which will ultimately inform better management decisions with respect to the utilization of POPs, PPCPs and other materials that may be deleterious to the marine environment.

POPs continue to accumulate in the polar regions and in top predators but neither present straightforward sampling opportunities. Therefore, greater effort must be put into more harmonized monitoring plans such that the collection of samples for the determination of POP concentrations is integral to as many programmes as practicable, especially in regions known to be affected by POPs. Furthermore, there needs to be a greater awareness and understanding of the movement of POPs through food webs. The development of trophic magnification factors should allow concentrations across food webs to be modelled, providing an indication of the probable concentrations of POPs in species that are difficult to sample.

Re-emergence is a significant source of POPs that is contributing to the sustained elevated concentrations of, for example, PCBs. However, establishing a clear understanding of the routes and pathways through which contaminants enter seas will enable better evaluation and targeting of measures, provide information on issues of potential re-emergence and potentially offer the possibility of predicting recovery times. In addition, a major consideration for future assessments should be the determination of the environmental realities attributable to multiple mixed effects, in particular, the impact on the environment not just of single substances or substance groups but the complex and potentially magnifying effects of numerous contemporary hazardous substances.

Over the many decades of analyses, the instrumentation has improved, as have sampling methodology and sample preservation. However, in determining temporal trends, it is often the determined concentration that is given the most attention, with less consideration given to the relevant limit of detection of the instrument for that sample. In that context, there is a need to consider the more technical and specific aspects of the analysis (Mangano and others, 2017). In addition, to support future assessments, it will be necessary to review and harmonize the threshold values utilized in the individual indicators, to ensure their relevance and application. Furthermore, gaining a comprehensive overview of novel sources of contaminants, in particular those emerging from offshore activities, such as wind farms, will also be beneficial.

There is a need to develop laboratory facilities that can improve knowledge of the toxicity of POPs and PPCPs in marine systems. Furthermore, it is essential that an infrastructure be put in place that will permit assessments of the contribution of POPs and PPCPs to the wider cumulative impacts of the multiple stressors to which marine species and habitats are being exposed, especially a changing climate and ocean acidification.

As with other monitoring of hazardous substances, there are major gaps in the capacities of most developing countries to monitor...
concentrations of POPs, metals, PPCPs and radionuclides in the marine environment.

The Minamata Convention on Mercury\textsuperscript{16} entered into force on 16 August 2017 and includes articles to support parties thereto, including with respect to capacity-building and technical assistance, as well as health aspects, public awareness, education and monitoring. There are 113 parties to the Convention (as of July 2020).

Moreover, efforts should be made to reduce all the sources of inputs of those hazardous substances to the ocean.

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\textsuperscript{16} UNEP(DTIE)/Hg/CONF/4, annex II.


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