THE IMPACTS OF CLIMATE CHANGE AND RELATED CHANGES IN THE ATMOSPHERE ON THE OCEANS

A TECHNICAL ABSTRACT OF
THE FIRST GLOBAL INTEGRATED MARINE ASSESSMENT

UNITED NATIONS

REGULAR PROCESS FOR GLOBAL REPORTING AND ASSESSMENT OF THE STATE OF THE MARINE ENVIRONMENT, INCLUDING SOCIOECONOMIC ASPECTS

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Purpose and process of preparing the technical abstract

The present technical abstract is based upon the First Global Integrated Marine Assessment (first World Ocean Assessment), which was released in January 2016, and, in particular, upon the summary of that Assessment, which was approved by the General Assembly in December 2015.[1] The abstract was prepared pursuant to the programme of work for the period 2017-2020 for the second cycle of the Regular Process of the Ad Hoc Working Group of the Whole of the General Assembly on the Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects, which was adopted by the Working Group in August 2016 and endorsed by the Assembly in December 2016.[2] The programme of work provides, inter alia, for support for other ongoing ocean-related intergovernmental processes, including the preparation of technical abstracts specifically tailored to meet the needs of, among other intergovernmental processes, the United Nations Framework Convention on Climate Change and the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea, which in 2017 focuses its discussions on the theme "The effects of climate change on oceans".[3] In this regard, the technical abstract provides a synthesis of the information presented in the first World Ocean Assessment and does not introduce any new material or interpretation of the information presented in that Assessment.

The work of the Intergovernmental Panel on Climate Change was used, where climate is concerned, as the basis of the first World Ocean Assessment, as required in the outline of the Assessment endorsed by the General Assembly. The present technical abstract is therefore likewise based, where climate is concerned, on the work of the Panel.

The technical abstract was prepared by the Group of Experts of the Regular Process for Global Reporting and Assessment of the State of the Marine Environment for the second cycle of the Regular Process, on the basis of an outline prepared by the Group of Experts and discussed by the Bureau of the Ad Hoc Working Group of the Whole. Some members of the pool of experts of the Regular Process who contributed to the first World Ocean Assessment were part of the review process, together with the Group of Experts, the secretariat of the Regular Process (the Division for Ocean Affairs and the Law of the Sea of the Office of Legal Affairs of the Secretariat) and the Bureau of the Ad Hoc Working Group of the Whole. The secretariat of the Regular Process also assisted in the finalization of the technical abstract by the Group of Experts. The Bureau of the Ad Hoc Working Group of the Whole considered the technical abstract for presentation at the meetings under the United Nations Framework Convention on Climate Change and the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea.

1 See General Assembly resolution 70/235, para. 266. The full text of the first World Ocean Assessment, including the summary, is available from www.un.org/depts/los/rp.

2 See General Assembly resolution 71/257, para. 299.

3 Ibid., para. 339.

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I. Main issues

1. The ocean and the atmosphere are interconnected systems. Climate change is affecting them both. In particular, both are becoming warmer, with the ocean having absorbed about 93 per cent of the combined extra heat stored in the air, sea, land and melted ice between 1971 and 2010. In the ocean, this warming is in both the surface waters and the deeper water layers. The exchange of heat between the ocean and the atmosphere has led to changes in winds and in such phenomena as the El Niño-Southern Oscillation, which in turn affects currents and waves in the ocean.

2. Rising temperatures are likely to affect the distribution, reproduction and abundance of many marine species. For example, the distribution of fish species is already changing in some parts of the world. In addition, coral reefs are already experiencing repeated bleaching events in response to higher temperatures, and the consequent harm to reefs will affect both large- and small-scale fisheries for species that the reefs support. Moreover, in warmer seawater, smaller, low-nutrient plankton are likely to become more abundant, and larger, nutrient-rich plankton to decrease in abundance, with unpredictable effects on marine food webs.

3. The ocean has also absorbed much of the carbon dioxide emitted over recent decades, resulting in unprecedented acidification of the marine environment at different rates in different parts of the world. Among other effects, this decreases the availability of carbonate ions for plankton, reef-forming corals and shellfish to make and maintain their hard structures. Shellfish fisheries and coral reef systems and the fisheries that depend on them are likely to decline. In addition, effects on some plankton species may dramatically alter marine food webs.

4. Sea level is rising, with an anticipated median rise of 1 m over the 1980-1999 levels by 2100. Sea level rise will vary around the globe. It is likely to result in the inundation and more frequent tidal flooding of some coastal communities and affect the distribution of services provided by important coastal habitats, such as mangroves. It will also increase erosion in coastal zones.

5. Areas of eutrophication (overabundance of nutrients) and hypoxia (lack of oxygen) are increasing as a result of increased stratification and reduced mixing in the ocean water column, as well as through changes in patterns of upwelling. “Dead zones” (zones with insufficient oxygen to support life) and areas of low oxygen are also increasing, affecting organisms that live in these areas and fisheries relying on them.

6. Polar ice will be reduced or eliminated, affecting the production of ice algae, which is a basic component of the Arctic and Antarctic food webs. Species relying on ice algae, such as krill in the Southern Ocean, will be negatively affected, as will the many species, including whales and commercially important fish, that eat krill. The opening of the Arctic to shipping and other human activity is likely to bring with it increased risk of pollution to the region.

7. Overall, cumulative impacts on marine food webs and systems are likely to be significant and unpredictable owing to different rates of species migration, unforeseen consequences of changes to elements of the ecosystem, and changing ocean circulation.

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II. Changes in the ocean linked to climate change and related changes in the atmosphere

8. The Earth's ocean and atmosphere are fundamentally linked in a complex process. The winds blowing over the surface of the ocean transfer momentum and mechanical energy to the water, generating waves and currents. The ocean gives off energy as heat, which provides one of the main energy sources for atmospheric motions. Heat is also transferred from the atmosphere to the ocean, generating sea temperature increases. Likewise, there are transfers of gases between the ocean and the atmosphere, mainly with carbon dioxide being absorbed by the ocean from the atmosphere and oxygen being released by the ocean into the atmosphere. Consequently, major features of the ocean are changing significantly as a result of enhanced levels of atmospheric carbon dioxide and related changes in the atmosphere.

A. Sea temperature

9. The ocean's large mass and high heat capacity enable it to store huge amounts of energy, more than 1,000 times that found in the atmosphere for an equivalent increase in temperature. The Earth is absorbing more heat than it is emitting back into space, and nearly all that excess heat is entering the ocean and being stored there. The ocean has absorbed about 93 per cent of the combined extra heat stored by warmed air, sea, land and melted ice between 1971 and 2010. The Intergovernmental Panel on Climate Change reaffirmed in its fifth assessment report its conclusion that global sea surface temperatures have increased since the late nineteenth century. The temperature in the upper ocean (down to about 700 m), and hence its heat content, varies over multiple time scales, including seasonal, inter-annual (for example, those associated with the El Niño-Southern Oscillation), decadal and centennial periods. Depth-averaged ocean temperature trends from 1971 to 2010 are positive (that is, they show warming) over most of the globe. The warming is more prominent in the northern hemisphere, especially in the North Atlantic, but is spatially very variable. Zonally averaged upper-ocean temperature trends show warming at nearly all latitudes and depths. However, the greater volume of the ocean in the southern hemisphere increases the contribution of its warming to the global heat content.

10. During the past three decades, approximately 70 per cent of the world's coastal areas have experienced significant increases in sea surface temperature. This has been accompanied by an increase in the yearly number of extremely hot days along 38 per cent of the world's coastline. Seasonal warming has also been occurring at a significantly earlier date in the year along approximately 36 per cent of the world's temperate coastal areas (between 30° and 60° latitude in both hemispheres).

11. Not only is the upper ocean becoming warmer, but ocean warming has also been recorded in numerous deep water habitats and is particularly significant in marginal seas. In particular, there is evidence that the warming of the Mediterranean between 1950 and 2000 has had an impact on its deep-sea communities, particularly affecting cold water corals (chaps. 5, 36A, 36F and 42).[1]

1 In the present technical abstract, the chapters referred to are chapters of the first World Ocean Assessment (available from www.un.org/depts/los/rp). When placed at the end of a paragraph, such references apply to all preceding paragraphs up to the previous such reference. The citations on which the text is based can be found in those chapters.

B. Sea level rise

12. It is very likely that extreme sea level maxima have already increased globally since the 1970s, mainly as a result of the global mean sea level rise. Globally averaged sea level has risen by 3.2 mm a year for the past two decades; about a third of this is derived from thermal expansion from anthropogenic warming, causing ocean thermal expansion. Some of the remainder is due to fluxes of freshwater inflow from the continents, which have increased as a result of the melting of glaciers and of the polar continental ice sheets.

13. Regional and local sea level changes are also influenced by natural factors, such as regional variability in winds and ocean currents, vertical movements of the land and adjustment of the levels of land in response to changes in physical pressures on it (for example, from the movement of tectonic plates), combined with human impacts of changes in land use and coastal development. As a result, sea levels will rise more than the global mean in some regions and will fall in others. A 4°C warming by 2100 (which is projected in the high-end emissions scenario in the fifth assessment report of the Intergovernmental Panel on Climate Change) would lead, by the end of that period, to a median sea level rise of nearly 1 m above the 1980-1999 levels (chap. 4).

C. Ocean acidification

14. Rising concentrations of carbon dioxide in the atmosphere are resulting in increased uptake of that gas by the ocean. About 26 per cent of the increasing emissions of anthropogenic carbon dioxide is absorbed by the ocean, where it reacts with seawater to form carbonic acid, a process known as ocean acidification. In chemistry, whether a liquid is acid or basic (alkaline) is measured on the pH scale: the lower the figure, the more acid the liquid. Throughout the past 25 million years, the average pH of the ocean has remained fairly constant between 8.0 and 8.2, with seasonal and spatial variations. In the past three decades, however, declines have been observed in the pH of the ocean, and if carbon dioxide emissions continue at present levels, model projections suggest that the oceanic average could reach a pH of 7.8 by the year 2100. This is well outside the range of average pH change of any other time in recent geological history. This lower pH results in fewer carbonate ions being available in the seawater. In general, because the ocean is mixed more slowly than the atmosphere, the absorption of carbon dioxide is much higher in the uppermost water levels (down to about 400 m), which is where the greatest amount of biological activity occurs.

D. Salinity

15. Alongside broad-scale ocean warming, shifts in ocean salinity (salt content) have also occurred. Variations in the salinity of the ocean around the world result from differences in the balance between freshwater inflows (from rivers and glacier and ice cap melt), rainfall and evaporation, all of which are affected by natural climate phenomena, as well as by climate change. Changes in the broad scale of patterns of rainfall will produce changes in ocean salinity, as higher rainfall will increase dilution and thus lower salinity, while lower rainfall will have the reverse effect. Observed changes to ocean salinity, which are calculated from a sparse historical observing system, suggest that areas of lower precipitation and higher evaporation, such as subtropical ocean regions, have become more saline, while areas of higher precipitation and lower evaporation, such as equatorial waters in the Pacific and Indian Oceans, have become less saline. Changes in salinity result in changes in the density of water, thereby driving ocean circulation. Ongoing change to ocean salinity is likely to have an effect on the circulation and stratification of seawater (chaps. 4 and 5).

E. Stratification

16. Differences in salinity and temperature among different bodies of seawater result in stratification, forming horizontal seawater layers, with limited exchanges between them. Increases in the degree of stratification, resulting from changes in temperature and salinity, have been noted around the world, particularly in the North Pacific and, more generally, north of 40°S. Increased stratification brings with it a decrease in vertical mixing in the ocean water column. This decreased mixing, in turn, reduces the oxygen and nutrient content of upper surface layers

and also reduces the extent to which the ocean is able to absorb heat and carbon dioxide, because less cool water is brought up to the surface, where such absorption takes place (chaps. 1 and 4-6).

F. Ocean circulation

17. The intensified study of the responses of the ocean to climate change has led to a much clearer understanding of the mechanisms of ocean circulation and its annual and decadal variations. As a result of changes in the heating of different parts of the ocean, patterns of variation in heat distribution across the ocean are also changing. There is some evidence that this results in changes to the atmospheric circulation and to the global circulation through the open ocean, which may lead, over time, to reductions in the transfer of heat from the equatorial regions to the poles and into the ocean depths. Thus, water masses are also moving differently in areas over continental shelves: for example, shifts in the water masses in the Gulf of Saint Lawrence have contributed, at least in part, to decreases in the dissolved oxygen concentration of deep water layers in the Gulf (chaps. 5 and 36A).

G. Impacts of storms and other extreme weather events

18. Increasing seawater temperatures provide more energy for storms that develop at sea. The scientific consensus is that this will lead to fewer but more intense tropical cyclones globally, although there will be variability regionally. Evidence exists that the observed expansion of the tropics since approximately 1979 is accompanied by a pronounced poleward migration of the latitude at which storms with maximum intensities occur. This will certainly affect coastal areas that have not been previously exposed to the dangers caused by tropical cyclones (chap. 5).

Photo credit: NASA Goddard Space Flight Cen

H. Reduced levels of dissolved oxygen (deoxygenation or hypoxia)

19. The levels of dissolved oxygen in the ocean in the tropics have decreased over the past 50 years, largely as a result of ocean warming. This has, for example, resulted in an expansion of the areas with the lowest levels of dissolved oxygen (oxygen-minimum zones), including the westward and vertical expansion of such zones in the eastern Pacific Ocean. Projected changes to surface temperatures and stratification are likely to result in a decreased transfer of oxygen from the atmosphere (oxygen solubility) and reduced ventilation of deeper waters, resulting in lower concentration of oxygen in the upper ocean across the tropics. Outside the tropics, current observations are not sufficient to determine trends, but it is expected that warming of the ocean and stratification will also result in declines in dissolved oxygen.

20. In coastal waters, low levels of oxygen are more related to inputs of nutrients from land and to the consequences of the resulting nutrient pollution; such effects are also strengthened by increases in stratification and reductions in circulation resulting from sea surface warming. Where currents flowing from the open ocean come up against narrow continental shelves, nutrient-rich, oxygen-poor water can be brought up into coastal waters and produce hypoxic zones (zones with low levels of dissolved oxygen) or even dead zones (zones with insufficient oxygen to support life, also called anoxic zones). Examples of this effect are found on the western coasts of America north and south of the equator, the western coast of sub-Saharan Africa and the western coast of the Indian subcontinent. Increases in the flow of some ocean currents may intensify this effect (chaps. 4-6 and 20).

I. Ultraviolet radiation and the ozone layer

21. Some greenhouse gases, especially chlorofluorocarbons, have an impact on the ozone layer in the stratosphere. The ozone layer in the Earth's stratosphere blocks most ultraviolet (UV) radiation emitted by the sun in the UV-B range (with a wavelength of 280-315 nanometres) from reaching the Earth's, and therefore the ocean's, surface. UV-B has a wide range of potentially harmful effects, including the inhibition of primary production by phytoplankton, changes in the structure and function of plankton communities and alterations of the nitrogen cycle. Consequently, stratospheric ozone depletion since the 1970s has been a concern. International action to address that depletion has been taken under the Montreal Protocol on Substances that Deplete the Ozone Layer, and the situation appears to have stabilized, albeit with some variation from year to year. Owing to the variations in the water depths to which UV-B penetrates, a consensus on the magnitude of the ozone depletion effect on net primary production and nutrient cycling has yet to be reached.

22. A potential effect of ultraviolet radiation on nanoparticles of titanium dioxide has, however, been identified. Titanium dioxide is used widely in white paints and finishes and in cosmetics and sunscreens. It breaks down into nanoparticles (up to one millionth of a millimetre). When exposed to ultraviolet radiation, such titanium dioxide nanoparticles act as a biocide and can thus adversely affect primary production by phytoplankton.


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III. Environmental and socioeconomic implications

A. Cumulative impacts

23. The pressures from climate change and related changes in the atmosphere, including acidification and deoxygenation, are only some of the current pressures to which the global marine environment is subject. The future state of the marine environment will be determined by the complex interaction of the full range of pressures and changes described in the first World Ocean Assessment, that is, not only those deriving from climate change and related changes in the atmosphere but also those from unsustainable fishing practices, pollution from shipping, seabed mining and hydrocarbon extraction, anthropogenic noise and coastal development, as well as newer pressures, such as those associated with the generation of energy from renewable sources (summary, theme G).

B. Changes in the food web

24. Shifts in primary productivity resulting from climate change will inevitably work their way up the food web. At each higher trophic layer, the effects in changes in the species composition and abundance of their food in the lower layers of the food web will make it more (or, in some cases, less) difficult for animals to survive and to raise their progeny. How these changes in the food web will affect top predators, such as marine reptiles, seabirds and marine mammals, is largely unknown. Habitat changes will also affect top predators: for example, bird species living in mangroves or foraging in seagrass beds will be affected by changes in those habitats.

25. It has been projected under some climate change scenarios that up to 60 per cent of the current biomass in the ocean could be affected, either positively or negatively, resulting in disruptions to many existing ecosystem services. For example, modelling studies of species with strong temperature preferences, such as skipjack and bluefin tuna, project major changes in range and/or changes in productivity.

26. Effects have been found in all regions. For example, in the North-West Atlantic, the combination of changes in the abundance of predators brought about by a number of factors, including overfishing and changes in climate, are the primary pressures that are thought to have brought about shifts in species composition amounting to a full regime change, from one dominated by cod to one dominated by crustacea. Likewise, in the North-East Atlantic and the North Sea, between 1960 and 2009, there were marked changes in the species composition of the plankton, the lowest level of the food web (that is, the variety of dinoflagellate species increased while abundance decreased relative to diatoms). This trend has been attributed to the combined effect of increases in sea surface temperature and wind shear during the summer.

27. Warm water phytoplankton species tend to be smaller and less productive than those in colder waters. As ocean temperatures have warmed, these species have been observed to be expanding into higher-latitude regions. Continuing expansion of these species has the effect of changing the efficiency of the transfer of energy to other parts of the food web, which is expected to result in biotic changes over major regions of the open ocean, such as the equatorial Pacific. Furthermore, increased ocean stratification and associated decreases in the transfer of nutrients from deeper layers of the ocean into the photic zone (the zone where sunlight penetrates sufficiently to support photosynthesis) is expected to cause significant variation in biological production (chaps. 38 and 52).

C. Plankton

28. Phytoplankton and bacteria carry out most of the primary production on which marine food webs depend. The climate-driven increases in the temperature of the upper ocean that had been predicted are currently causing shifts in phytoplankton communities. This may have profound effects on net primary production and nutrient cycles over the next

100 years. In general, when smaller plankton account for most net primary production, as is typically the case in nutrient-poor open ocean waters, it is lower, and the microbial food web dominates energy flows and nutrient cycles. Using satellite technology to study chlorophyll records over 22 years in 12 major ocean basins, scientists have established that the global annual ocean primary production has declined by 6 per cent between 1980 and 2012. Under such conditions, the carrying capacity for currently harvestable fish stocks is lower, and exports of organic carbon, nitrogen and phosphorus to the deep sea may be smaller, thus reducing its ability to support life.

29. On the other hand, as the upper ocean warms, the geographic range of nitrogen-fixing plankton (diazotrophs) is expected to expand. This could enhance the fixation of nitrogen by as much as 35-65 per cent by 2100. This would lead to an increase in net primary production, and therefore an increase in carbon uptake, and some species of a higher trophic level may become more productive.

30. The balance between those two changes is unclear. A shift towards less primary production or changes in the size structure of the plankton communities would have serious implications for human food security and support for marine biodiversity through disruption to food webs. The timing of the spring blooms of phytoplankton is also expected to change. This would also affect marine food webs because many species synchronize spawning and larval development with phytoplankton blooms and the associated peaks in abundance of zooplankton (microscopic animals that feed on phytoplankton and bacteria) (chap. 6).

D. Seaweeds and seagrasses

31. The growth and survival of cold water seaweeds, in particular kelps, are influenced by temperature, salinity and nutrient levels. Warm, nutrient-poor water has been observed to affect photosynthesis, resulting in reduced growth and widespread declines. Kelp die-offs have already been reported along the coasts of Europe and southern Australia and are largely associated with the impacts of changes in seawater conditions. Changes in species distribution have been noted in Northern Europe, Southern Africa and southern Australia, with warm-water-tolerant species expanding poleward. These changes can adversely affect rocky reef habitats and commercially harvested species contained within these habitats in coastal zones. The diminished kelp harvest reduces what is available for human food and the supply of substances derived from kelp that are used in various industries, including pharmaceuticals and food preparation. Communities with kelp-based livelihoods and their economies will thus be affected.

32. Seagrass beds serve to stabilize sediments and to protect the coastline zone from erosion, providing a platform for the growth of animals, such as fish and invertebrates (for example, shrimps) that graze and reproduce in them. Increased seawater temperatures have also been implicated in the occurrence of a wasting disease that decimated seagrass meadows in the north-eastern and north-western parts of the United States of America (chaps. 14 and 47).

E. Mangroves

33. Mangroves[2] dominate the intertidal zone of sheltered (muddy) coastlines of tropical, subtropical and warm temperate oceans. Mangrove distribution correlates with air and sea surface temperatures, so that they extend to about 30°N and to between 28°S in the Atlantic and 38°S in the Pacific. Their distribution is further limited by key climate variables, such as lack of rain and the frequency of cold weather events. Mangroves are important as breeding and nursery areas for fish species, for carbon sequestration (their high rate of carbon capture and storage is particularly significant), for climate regulation, shoreline stabilization and coastal protection, and as a potential source for the production of pharmaceuticals and of timber and fuelwood.

34. Mangroves may benefit from a greater potential range as areas north or south of their present distribution become warmer (although there are upper limits on the temperatures that they can tolerate). However, since they cannot survive in deeper water than their existing ranges, they are vulnerable to sea level rise, particularly in areas where they cannot expand their

2 The word “mangrove” is used to refer to both a specific vegetation type and the unique habitat (also called tidal forest, swamp, wetland or mangal) in which it exists.

range inland because of coastal defences or conflicting land uses. This is particularly the case on low-relief carbonate-based islands, where there is little or no supply of sediment for them to accumulate (chap. 48).

F. Corals

35. Nearly all corals in tropical and subtropical areas represent a symbiosis between the coral polyps, which form hard structures, and photosynthesizing algae. When ocean temperatures are too high, such corals become stressed and expel the symbiotic algae that give coral its colour and part of its nutrients, resulting in bleaching. Severe, prolonged or repeated bleaching can lead to the death of coral colonies, and repeated bleaching weakens their resilience. An increase of only 1°C to 2°C above the normal local seasonal maximum can induce bleaching. Although most coral species are susceptible to bleaching, their thermal tolerance varies. Many heat-stressed or bleached corals subsequently die from coral diseases.

36. Coral bleaching was a relatively unknown phenomenon until the early 1980s, when a series of local bleaching events occurred, principally in the eastern tropical Pacific and wider Caribbean regions. Rising temperatures have accelerated bleaching and mass mortality during the past 25 years. High ocean temperatures in 1998 and 2005 caused high coral mortality at many reefs, with little sign of recovery. Global analysis shows that this widespread threat has significantly damaged most coral reefs around the world. Where recovery has taken place, it has been strongest on reefs that were highly protected from human pressures. However, a comparison of the recent and accelerating thermal stress events with the slow recovery rate of most reefs suggests that degradation from temperature increase is outpacing recovery. The adverse effects of coral bleaching are more significant as coral reefs are also being degraded by destructive fishing, pollution, an increase in turbidity (which restricts sunlight from reaching the corals and thus decreases the productivity of the symbiotic algae), and other human activities, and through sea level rise and ocean acidification.

37. Losses of coral reefs can have negative effects on fish production and fisheries, coastal protection, ecotourism and other community uses of coral reefs. Current scientific data and modelling project that most of the world's tropical and subtropical coral reefs, particularly those in shallow waters, will have suffered from annual bleaching by 2050 and will eventually become functionally extinct as sources of goods and services. This will have not only profound effects on small island developing States and subsistence fishers in low-latitude coastal areas but also locally significant effects in major economies, for example the Great Barrier Reef in Australia and the Florida Keys in the United States (chaps. 7 and 43).

38. Cold water corals have only recently been studied extensively, since their location in deep water has made study difficult. However, it is clear that their growth is constrained by both temperature and the availability of carbonate ions: they are not found where the water is warmer than species-dependent limits (except for some species in the Red Sea), nor do they grow below the carbonate saturation horizon (the level below which carbonate minerals will dissolve). Rises in temperature have been shown to affect the deep-sea communities in the Mediterranean. Ocean acidification is another pervasive threat for many species of these corals. Because the carbonate saturation state in seawater is temperature-dependent, it is much lower in cold waters, and therefore cold water corals lie much closer to the saturation horizon. As ocean acidification proceeds, the saturation horizon will become shallower, thus exposing more cold water corals to undersaturated conditions. Cold water coral reefs, mounds and gardens support a highly diverse community, comprising faunal biomass that is orders of magnitude above that of the surrounding seafloor. In addition to this tightly associated community, cold water corals also serve as important spawning, nursery, breeding and feeding areas for a multitude of fishes and invertebrates. Damage to them will therefore have wider consequential effects (chap. 42).

G. Fish stock distribution

39. As seawater temperatures increase, the distribution of fish stocks and the fisheries that depend on them is shifting. While the broad pattern is one of stocks moving poleward and to greater depths in order to stay within waters that meet their tempera-

ture preference, the picture is by no means uniform, nor are those shifts happening in concert for the various species. Increasing water temperatures will also increase metabolic rates and, in some cases, the range and productivity of some stocks.

40. As indicated above, global climate models project that warming will lead to deoxygenation and stratification of the deep ocean. This will adversely affect both benthic (seabed) and pelagic (water column) ecosystems. In the North Pacific, decreased mid-water oxygen concentrations have been shown to be correlated with the decline of 24 mid-water fishes from eight families. Extended to larger scales, this could have significant adverse ecological and biogeochemical effects.

41. However, changes in fish stock distribution are often the result of a complex of causes. Reductions in fish stocks are often driven by overfishing, and it is frequently difficult to distinguish between effects of climate change and overfishing. This applies, for example, to such cases as the disappearance of cod from the Grand Banks off Canada and their replacement by crustacean species, such as lobsters, and the decline in North Sea cod and the increase in cod in the Barents Sea.

42. Small-scale fisheries are very important as a source of human food and income in the tropics. A significant number of women work in small-scale fisheries, and many indigenous peoples and their communities rely on these fisheries. Most of the people involved in small-scale fisheries live in developing countries, earn low incomes and often depend on informal work.

43. Reef fish form a large part of the catches of these small-scale fisheries, particularly in the Pacific. In addition to responding directly to the changes in sea temperature described above, the abundance of reef fish is influenced by the extent and condition of the coral reefs that they inhabit. Abundance can vary two- to tenfold over time, largely in association with the loss and subsequent recovery of coral reef habitats following storm events and bleaching. Small-scale fisheries are also likely to be more vulnerable to the impacts of climate change and increasing uncertainty than large-scale fisheries, since they have less opportunity for redeployment to new fisheries zones.

44. As fishing efforts move into new areas in pursuit of fish stocks with altered locations, there can be side effects on the ecosystems concerned. For example, the reduction in the cover of sea ice in the Arctic can lead to areas that have not previously been fished becoming subject to fishing, bottom trawling and the by-catch of species not previously likely to have been under this pressure.

45. This results in changes in ecosystems occurring at various rates, ranging from near zero to very rapid. Research on those effects is scattered, with diverse results, but as ocean climate continues to change, those considerations are of increasing concern for food production. Greater uncertainty for fisheries has social, economic and food security impacts, complicating sustainable management.

H. Shellfish productivity

46. Shellfish are particularly susceptible to decreases in the amount of dissolved carbonate ions in the water around them because this hinders their ability to form their calcium carbonate shells. In parts of the North Pacific, where seasonal upwelling of water with low pH occurs, impacts on the formation and growth of the shells of shellfish species have already been observed. This has required adaptation action to minimize impacts on shellfish aquaculture industries. As overall ocean pH and dissolved carbonate ion concentrations continue to decrease, more widespread changes to ecosystems, and thus impacts on the industries that rely on wild shellfish, are expected. Ocean acidification is not evenly distributed, so the effects will not be uniform across areas, and there will be substantial variation over small spatial scales. In addition, stratification can lead to bottom waters having dissolved oxygen levels insufficient to support shellfish, thus also reducing productivity.

47. Furthermore, temperature, salinity and other changes to the ocean will also alter shellfish distributions and productivity, positively or negatively in different areas. As with fishing, the course of those changes is highly uncertain and may be disruptive to existing shellfish fisheries and aquaculture (chap. 11).

48. Rising seawater temperature, coupled with high levels of nutrients, is one of the causes to which has been attributed the increases in toxic events associ-

ated with blooms of certain phytoplankton species. These toxic events include occurrences of paralytic shellfish poisoning affecting humans who consume infected shellfish. This very quickly (often within 30 minutes) produces symptoms that may include paralysis of arms and legs, loss of motor coordination and incoherent speech, and is frequently fatal. Increased frequency of such toxic phytoplankton blooms has been observed over the past three decades, particularly in coastal waters of both the western and eastern North Atlantic (chap. 20).

I. Nutrient pollution

49. Excessive anthropogenic inputs of nutrients, particularly nitrates, from the coast or through the atmosphere to the ocean cause nutrient pollution. The availability of high levels of nutrients, in particular compounds of nitrogen, can result in algal blooms. These occur when there is sufficient sunlight to support photosynthesis by the algae. Eventually, the nutrients are exhausted and the decay of the algae removes oxygen from the seawater as bacteria decompose the dead algae. Increased stratification resulting from climate change can make such problems worse. The decay of the algae can also intensify acidification locally. In addition, hypoxic zones, or even dead zones (anoxic zones), can be created by the upwelling of nutrient-rich water under the pressure of ocean currents. Such upwelling can worsen coastal eutrophication problems where such upwelling occurs (ibid.).

J. Coastal inundation and erosion

50. Sea level rise due to ocean warming, and the melting of land ice poses a significant threat to coastal systems and low-lying areas around the world through inundations, the erosion of coastlines and the contamination of freshwater reserves and food crops. To a large extent, such effects are inevitable, as they are the consequences of conditions already in place, but they could have devastating effects if mitigation and adaptation options are not pursued. Entire communities on low-lying islands (including Kiribati, Maldives and Tuvalu) have nowhere to retreat within their islands. Many coastal regions, particularly some low-lying river deltas, have very high population densities. More than 150 million people are estimated to live on land that is no more than 1 m above current high-tide levels, and 250 million at elevations within 5 m of that level. Because of their high population densities, coastal cities are particularly vulnerable to sea level rise together with other effects of climate change, such as changes in storm patterns. The rising sea level is also likely to lead to additional coastal erosion, when existing sea defences are overtopped or circumvented, or where coastlines may be subjected to higher frequencies of storms (chaps. 5, 7, 26 and 44).

K. Loss of sea ice in high latitudes and associated effects

51. The high-latitude ice-covered ecosystems host a globally significant array of biodiversity. The size and nature of those ecosystems make them important for the biological, chemical and physical balance of the biosphere. Biodiversity in those systems has developed remarkable adaptations to survive both extreme cold and highly variable climatic conditions. High-latitude seas are relatively low in biological productivity, and ice algal communities, unique to those latitudes, play a particularly important role in system dynamics.

52. Ice algae are estimated to contribute more than 50 per cent of the primary production in the permanently ice-covered central Arctic. As sea ice cover declines, this productivity may decline, and open water species may increase in abundance. The high-latitude ecosystems are undergoing changes at a more rapid rate than in other places on Earth. In the past 100 years, average Arctic temperatures have increased at almost twice the average global rate. Reduced sea ice, especially a shift towards less multi-year sea ice, will affect a wide range of species in those waters, particularly those that rely on iced areas for breeding, resting and feeding.

53. In the southern hemisphere, Antarctic krill (*Euphausia superba*) is a keystone species, being the preferred prey of many predators, including many fish, seabirds, seals and whales. Because the abundance of krill is closely linked to the extent of sea ice and its ice algae in the previous winter (the more sea ice, the more krill), any change in the extent of sea ice is likely to result in changes in food webs in Antarctic waters. As waters warm and the seasonal extent of

sea ice decreases, krill abundance is likely to also decrease, while the abundance of warmer water species, such as salps, will increase. Although many predators can switch between feeding on krill and on salps, the food quality obtained from salps is much lower than that of krill. Therefore, a shift in the Southern Ocean from communities dominated by sea ice to open water communities is likely to have adverse effects on many marine species for which krill is an important component of their prey (chaps. 36G, 36H and 46).

54. Although the number of ships transiting Arctic waters is currently low, it has been escalating for the past decade. The retreat of polar sea ice as a result of warming associated with climate change means that there are increasing possibilities for shipping traffic between the Atlantic and Pacific Oceans around the north of the American and Eurasian continents during the northern summer. The movement of species between the Pacific and the Atlantic Oceans demonstrates the scale of the potential impact. Routes through the Arctic are shorter and may be more economical (savings of 20-25 per cent have been suggested) than those currently used. Increased shipping brings with it increased risks of marine pollution from both acute disasters and chronic pollution, and the potential introduction of non-native species through hull fouling and discharged ballast water. The very low rate at which bacteria can break down spilled oil in polar conditions and the generally low recovery rate of polar ecosystems mean that damage from such pollution would be very serious. Furthermore, the response and clean-up infrastructure found in other ocean basins is largely lacking at present around the Arctic Ocean, making response to pollution events logistically more difficult. Those factors would make such problems even worse. Over time, the increased commercial shipping traffic through the Arctic Ocean and the noise disturbance that it creates may also displace animals, including marine mammals, away from critical habitats (chap. 17).

L. Communication risks

55. Submarine cables have always been at risk of breaks from submarine landslides, mainly at the edge of the continental shelf. As the distribution and intensity of cyclones, hurricanes and typhoons change as projected under climate change scenarios, submarine areas that have so far been stable may become less so under the impact of storms. This could lead to a higher incidence of submarine landslides and consequent damage to cables. With the increasing dependence of world trade on the digital transfer of data, such increased damage to submarine cables, in addition to breaks from other causes, such as ship anchors and bottom trawling, could delay or interrupt communications vital to world trade (chap. 19).

IV. Conclusion

56. The greatest threat to the ocean comes from a failure to deal quickly with the manifold problems that have been described above. Many parts of the ocean, including some areas beyond national jurisdiction, have been seriously degraded. If the problems are not addressed, there is a major risk that they will combine to produce a destructive cycle of degradation in which the ocean can no longer provide many of the benefits that humans currently enjoy from it.

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