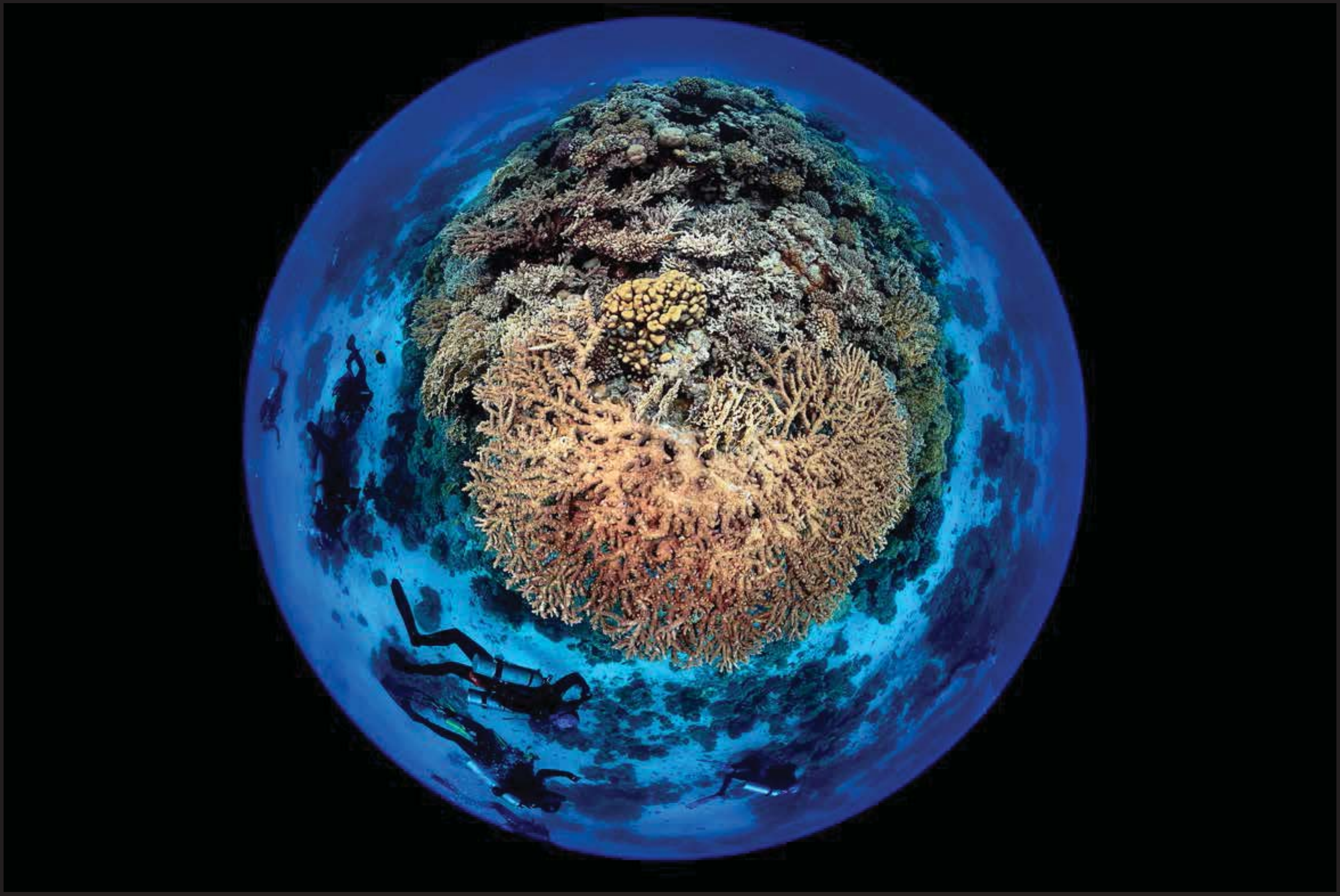
The Second
World Ocean Assessment

WORLD OCEAN ASSESSMENT II

Volume II



United Nations

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Cover photo: Yung-Sen Wu
United Nations World Oceans Day Photo Competition

United Nations publication
Sales no.: E.21.V.5
ISBN: 978-92-1-1-130422-0
eISBN: 978-92-1-1-604006-2

Printed at the United Nations, New York

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Chapter 9

Pressures from changes in climate and atmosphere

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Keynote points

- **Extreme climate events.** Marine heatwaves and tropical cyclones are shown to be increasing in severity owing to human activities and are having an impact on nature and human societies. Extreme El Niño events have been observed but, because they occur infrequently, a human influence has not been detected. All three phenomena are projected to increase in the future, with the severity of impacts also increasing, but such increases can be reduced by climate change mitigation efforts.
- **Sea level rise.** The alarming observed pace of sea level rise, combined with increasing storminess and coastal urbanization, has resulted in the amplified susceptibility of coastal cities to erosion and flooding and increased the need for substantial investments in hard infrastructure and the restoration of natural barriers, such as reefs.
- **Ocean acidification and deoxygenation.** The accelerated increase of anthropogenic CO_2 in the atmosphere is creating an increase in the acidification and deoxygenation of the ocean. Under such conditions, both in nature and in the laboratory, marine organisms that support ecosystems and human livelihoods and nutrition typically respond poorly. Marine habitats experience a loss of diversity, many long-lived organisms die and a few resilient species proliferate. Less serious damage to life-supporting ecosystems would be possible under lower-emission scenarios.
- **Other physical and chemical properties.** Changes in ocean temperature and salinity induced by climate change and human activities are affecting marine ecosystems by changing the distribution of marine species, decreasing the ecological value of coastal ecosystems and changing marine primary production. Human well-being and the economy are consequently affected.

1. Introduction

The first part of the present chapter is based on three topics in the context of extreme climate events related to the ocean, namely, marine heatwaves, extreme El Niño Southern Oscillation events and tropical cyclones. Both physical aspects of the impact of climate change on the phenomena and potential impacts on natural and human systems are considered. The conclusions are based on a much more detailed assessment that can be found in chapter 6 of the *Special Report on Oceans and Cryosphere in a Changing Climate* of the Intergovernmental Panel on Climate Change (2019).

An extreme event is one that is rare at a particular place and time of year. Definitions of “rare” vary, but an extreme event is normally as rare as, or rarer than, the tenth or ninetieth percentile of a probability estimated from observations. By definition, the characteristics of what is called an extreme event may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., high temperature, drought or total rainfall over a season).

The second part of the chapter expands upon pressures from changes in ocean physical and chemical properties. Projected sea temperature increases of up to 1.5°C over pre-industrial levels by 2050 will continue to drive latitudinal abundance shifts in marine species, including those of importance for coastal livelihoods. Many large coastal cities are located in deltaic settings and are vulnerable to floods because of their proximity to rivers and the sea, general low elevations and land subsidence (Nicholls and others, 2008).

Carbon dioxide emissions and global warming are also causing ocean acidification and deoxygenation. Those changes have consequences for the people who depend on healthy marine ecosystems worldwide. At the time of the first *World Ocean Assessment* (United Nations, 2017), the chemistry of ocean acidification was well understood, yet the consequences for ecosystems and society were poorly known. The effects of declining oxygen on nutrient cycles and fish stocks were predicted to worsen, especially when climate change-driven oxygen depletion combines with coastal eutrophication. Reduced biodiversity and declines in fish populations were linked to falling oxygen levels across the world's oceans. New information is provided on marine organism and ecosystem responses to ocean acidification and deoxygenation and related capacity-building.

In the present chapter, in conjunction with chapter 5, the climate change aspects of the present Assessment are developed. The present chapter expands on the pressures on marine ecosystems and human populations of some of the physical and chemical changes caused by climate change. Some related aspects are also covered in chapter 7K and chapter 15.

2. Climate pressures: extreme climate events and pressures from changes in ocean physical and chemical properties

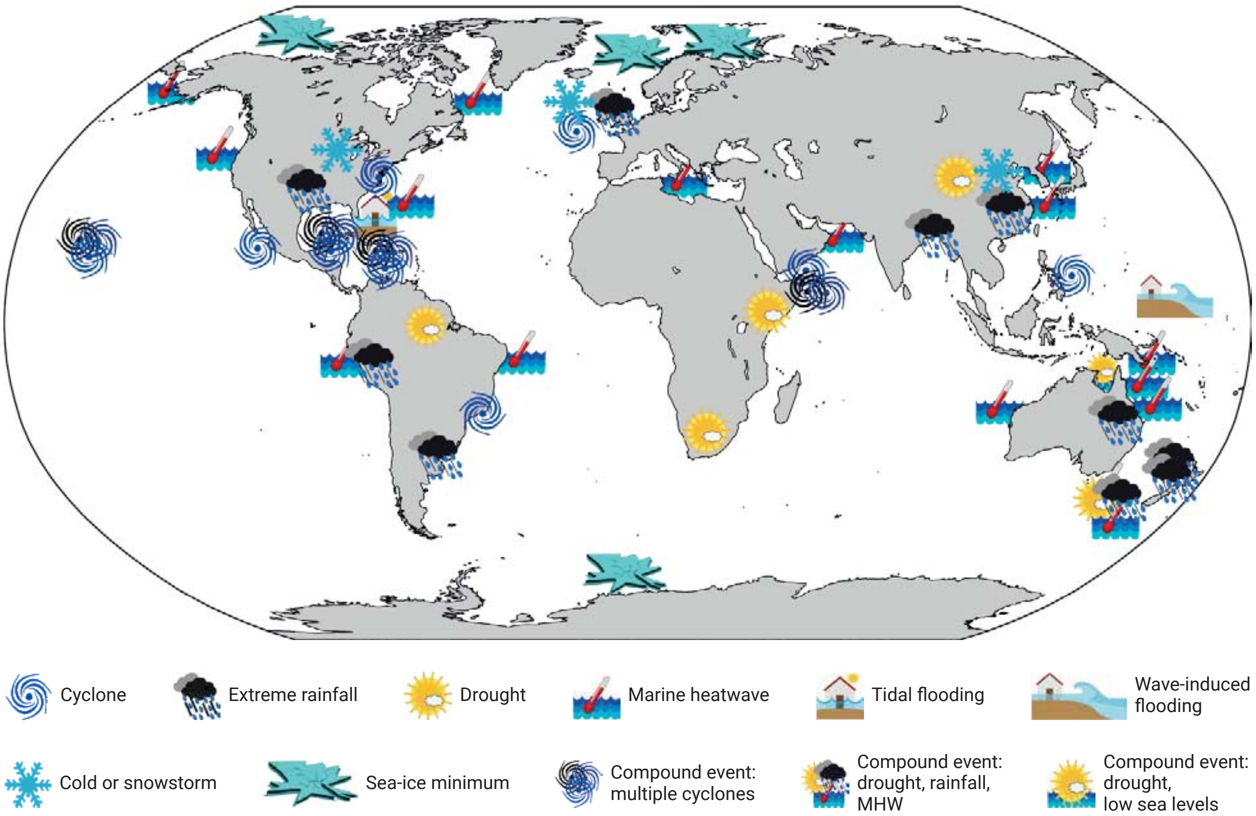
2.1. Extreme climate events

Marine heatwaves are periods of extremely high ocean temperatures that persist for days to months, that can extend up to thousands of km and can penetrate multiple hundreds of m into the deep ocean (Hobday and others, 2016). Over the past two decades, marine heatwaves have had a negative impact on marine organisms and ecosystems in all ocean basins, including critical foundation species such as corals, seagrasses and kelps (Hughes and others, 2018; Smale and others, 2019). Satellite observations reveal that marine heatwaves doubled in frequency between 1982 and 2016, and that they have also become longer lasting and more intense and extensive (Frölicher and others, 2018; Oliver and others, 2018). Between 2006 and 2015, 84 to 90 per cent of all globally occurring marine heatwaves were attributable to the temperature increase since the period 1850–1900 (Frölicher and others, 2018).

Marine heatwaves will further increase in frequency, duration, spatial extent and intensity under future global warming (Frölicher and others, 2018; Darmaraki and others, 2019), pushing some marine organisms, fish stocks and ecosystems beyond the limits of their resilience, with cascading impacts on economies and societies (Smale and others, 2019). Globally, the frequency of marine heatwaves is very likely to increase by a factor of about 50 times by the period 2081–2100 under the high-emission Representative Concentration Pathway (RCP) 8.5 scenario and by a factor of about 20 times under the low-emission RCP 2.6 scenario (Van Vuuren and others, 2011), relative to the reference period 1850–1900. Such future trends in marine heatwave frequency can largely be explained by increases in mean ocean temperature. The largest changes in the frequency of marine heatwaves are projected for the Arctic Ocean and the tropical oceans (figure I; Intergovernmental Panel on Climate Change (IPCC), 2019, chap. 6, figure 6.4).

Figure I

Locations of extreme events with an identified link to climate change caused by human activities



Source: Figure adapted from IPCC, 2019, figure 6.2.

Limiting global warming would reduce the risk of impacts of marine heatwaves, but critical thresholds for some ecosystems (e.g., kelp forests and coral reefs) will be reached even at relatively low levels of future global warming (King and others, 2017). Early warning systems, producing skilful forecasts of marine heatwaves, can further help to reduce vulnerabilities in fishing, tourism and conservation, but are yet unproven on a large scale (Payne and others, 2017; Tommasi and others, 2017).

One of the best data-rich examples of the impact of a marine heatwave on well-managed fisheries is of the Gulf of Alaska in the North Pacific. A prolonged warm ocean event weakened benthic ocean and surface mixing, in turn disrupting trophies, invertebrate and forage fish populations, and decimated the Pacific cod fishery, triggering a series of repeating mass marine mammal and seabird die-offs that had a ripple effect through coastal economies.

The El Niño Southern Oscillation is a coupled atmosphere-ocean phenomenon, identified by an oscillation between warm and cold ocean temperatures in the tropical central eastern Pacific Ocean and an associated fluctuation in the global-scale tropical and subtropical surface pressure patterns. Typically, it has a preferred timescale of about two to seven years. It is often measured by the surface pressure anomaly difference between Tahiti, French Polynesia, and Darwin, Australia, and/or the sea surface temperatures in the central and eastern equatorial Pacific (Rasmussen and Carpenter, 1982). It has climatic effects throughout the Pacific region and in many other parts of the world through global teleconnections. The warm phase of the Oscillation is called El Niño and the cold phase is called La Niña.

The strongest El Niño and La Niña events since the pre-industrial era have occurred during the past 50 years, and that variability is unusually high when compared with average variability during the last millennium (Cobb and others, 2013; Santoso and others, 2017). There have been three occurrences of extreme El Niño events during the modern observational period (1982/83, 1997/98, 2015/16), all characterized by pronounced rainfall in the normally dry equatorial East Pacific. There have been two occurrences of extreme La Niña (1988/89, 1998/99).

Extreme El Niño and La Niña events are likely to occur more frequently with global warming and are likely to intensify existing impacts, with drier or wetter responses in several regions across the globe, even at relatively low levels of future global warming (Cai and others, 2014; Cai and others, 2015; Power and Delage, 2018).

Sustained long-term monitoring and improved forecasts can be used in managing the risks of extreme El Niño and La Niña events associated with human health, agriculture, fisheries, coral reefs, aquaculture, wildfire, drought and flood management (L'Heureux and others, 2017).

A tropical cyclone is the general term for a strong, cyclonic-scale disturbance that originates over the tropical ocean. Based on one-minute maximum sustained wind speed, the cyclonic disturbances are categorized into tropical depressions (≤ 17 m/s), tropical storms (18–32 m/s) and tropical cyclones (≥ 33 m/s, category 1 to category 5) (Knutson and others, 2010). A tropical cyclone is called a hurricane, typhoon or cyclone, depending on geographic location.

Anthropogenic climate change has increased precipitation, winds and extreme sea level events associated with a number of observed tropical cyclones. For example, studies have shown that the rainfall intensity of tropical cyclone (Hurricane) Harvey increased by at least 8 per cent (8–19 per cent) owing to climate change (Risser and Wehner, 2017; Van Oldenborgh and others, 2017). Anthropogenic climate change may have contributed to a poleward migration of maximum tropical cyclone intensity in the western North Pacific in recent decades related to anthropogenically forced tropical expansion (Sharmila and Walsh, 2018). There is emerging evidence of a number of regional changes in tropical cyclone behaviour, such as an increase in the annual global proportion of category 4 or 5 tropical cyclones in recent decades, extremely severe tropical cyclones occurring in the Arabian Sea, cyclones making landfall in East and South-East Asia, an increase in frequency of moderately large storm surge events in the United States since 1923 and a decrease in frequency of severe tropical cyclones making landfall in eastern Australia since the late 1800s. There is low confidence that they represent detectable anthropogenic signals. Extreme wave heights, which contribute to extreme sea level events, coastal erosion and flooding, have increased in the Southern Ocean and the North Atlantic Ocean by about 1.0 cm per year and 0.8 cm per year over the period 1985–2018 (Young and Ribal, 2019).

An increase in the average intensity of tropical cyclones, and the associated average precipitation rates, is projected for a 2°C global temperature rise, although there is low confidence in future frequency changes at the global scale (Yamada and others, 2017). Rising sea levels will contribute to higher extreme sea levels associated with tropical cyclones in the future (Garner and others, 2017). Projections suggest that the proportion of category 4 and 5 tropical cyclones will increase (Knutson and others, 2015; Park and others, 2017). Such changes will affect storm surge frequency and intensity, as well as coastal infrastructure and mortality.

Investment in disaster risk reduction, flood management (ecosystem and engineered) and early warning systems decreases economic loss from tropical cyclones that occur near coasts and islands. However, such investments may be hindered by limited local capacities (e.g., ageing infrastructure and other non-climatic factors) that, for example, can lead to increased losses and mortality from extreme winds and storm surges in developing countries despite adaptation efforts. There is emerging evidence of increasing risks for locations affected by unprecedented storm trajectories. Management of risk from such changing storm trajectories and intensity proves challenging because of the difficulties of early warning and its receptivity by affected populations.

2.2. Sea level rise and cities

Cities located along coastlines and in archipelagic and island States are becoming increasingly susceptible to erosion and sea level rise (De Sherbinin and others, 2007; Hanson and others, 2011; Takagi and others, 2016). Many comprise large areas of reclaimed land (the gain of land from the sea, wetlands or other water bodies), which is retained and protected from erosion by hard engineered structures, such as sea walls and rock armouring (Sengupta and others, 2018). It is likely that many of such engineered coastlines will need to be adapted and upgraded to keep pace with rising sea levels. In highly urbanized environments that are often already heavily degraded, hard engineered structures are often the only option available and are considered to be successful options (Hallegatte and others, 2013; Hinkel and others, 2014), but there are a wide range of broader negative impacts of land reclamation and those structures on the surrounding environment (Dafforn and others, 2015). Globally, many regions (especially cities) are claiming that more than 50 per cent of their coastlines are armoured (e.g., Chapman, 2003; Burt and others, 2013), and that number will likely rise in the future in response to burgeoning economies, coastal populations and urbanization (e.g., see plans for the reclamation of the entire coastlines of two Malaysian states in Chee and others, 2017).

As an alternative to hard engineered coastal defences, construction of which is complex and expensive, where possible, natural coastal ecosystems such as mangroves and salt marshes should be used as natural barriers or combined with hard infrastructure using hybrid approaches (Temmerman and others, 2013). The use of such ecosystems can not only protect the land but also provide valuable ecosystem functions and services. As hard engineered coastal defences may be considered an effective short-term solution to coastal flooding, more investment will be needed owing to observed increasing storminess and sea level rise (Mendelsohn and others, 2012; Vitousek and others, 2017). By 2010, the global average sea level was calculated to be 52.4 mm above the 1993 level and, by 2018, it had risen to 89.9 mm above the 1993 level (National Oceanic and Atmospheric Administration (NOAA), 2019). The rate of change is also increasing. For the period 1993–2018, the rate of increase was calculated at 3.2 mm per year, while for the period 2010–2018, it was calculated to be much faster, at 4.7 mm per year. Despite significant uncertainties remaining, the Intergovernmental Panel on Climate Change predicts that sea level rise will continue for centuries, even if mitigation measures are put in place. The potential widespread collapse of ice shelves could lead to a larger twenty-first century sea level rise of up to several tenths of a metre (Church and others, 2013), which will have drastic consequences for coastal, archipelagic and small island cities, in particular those in low-lying areas.

Urbanization could, however, also provide opportunities for risk reduction, given that cities are engines of economic growth and centres of innovation, political attention and private sector investments (Garschagen and Romero-Lankao, 2015). Hallegatte and others (2013) conducted a global analysis of present and future losses in the 136 largest coastal cities. They predicted that global flood losses would increase from an average of $6 billion per year in 2005 to $1 trillion by 2050, with projected socioeconomic change, climate change and subsidence. Even if adaptation investments remain constant, flood probability, subsidence and sea level rise will increase global flood losses to $60 billion–$63 billion per year in 2050. The same study found that developing countries are particularly vulnerable to flood risk, with much lower investment in flood protection measures (Hallegatte and others, 2013).

Case study: Rotterdam

Low-lying cities in the Netherlands, a country that has long been a pioneer in both land reclamation and climate change adaptation, are taking a multipronged approach to the problem of sea level rise. For instance, Rotterdam's adaptation system is based on a flood and sea level rise defence system (C40 Cities, 2019) consisting of the Maeslantkering flexible storm surge barrier, permanent sand dunes along the coast, dykes along the rivers and a tailored "inner-dyke/outer-dyke" approach. The inner-dyke city, which is mostly below sea level, is formed by a system of polders drained by water outlets and pumps and protected by smaller secondary dykes. The outer-dyke city area (3–5.5 m above sea level), of 40,000 inhabitants, is vulnerable to rising sea level or smaller temporary floods. It is being adapted through the use of innovative technologies (e.g., floating buildings) and more traditional approaches (e.g., insulation of building facades and raising of electrical installations).

2.3. Pressures from changes in temperature

Ocean warming caused by anthropogenic climate change will continue for centuries after the anthropogenic forcing is stabilized (IPCC, 2019). It will affect marine ecosystems through increasing cumulative pressures owing to the changing climate and the intensity of human activities and is also interfering with other ocean properties, such as salinity and nutrient or carbon cycles, owing to the interconnection of all such processes.

Temperature-dependent biological sensitivity varies between species and is affected by other ocean properties. For example, for pelagic species, analysis of long-term trends in primary production has revealed that a rise in ocean temperatures, leading to enhanced stratification, nutrient limitation and shifts towards small phytoplankton, will have the greatest influence on decreasing the flux of particulate organic carbon to the deep ocean (Boyd and others, 2016; Fu and others, 2016). Reductions in particulate organic carbon flux are predicted at low and middle latitudes, but increases are possible at high latitudes, associated with a reduction in sea ice cover (Sweetman and others, 2017; Yool and others, 2017; FAO, 2018).

The special report entitled *Global Warming of 1.5°C* of the Intergovernmental Panel on Climate Change (2018) indicates that ocean ecosystems are already experiencing large-scale changes, and critical thresholds are expected to be reached at 1.5°C and higher levels of global warming. The changes to water temperatures are expected to drive some species (e.g., plankton and fish) to relocate to higher latitudes and cause novel ecosystems to assemble (Jonkers and others, 2019).

The increase in temperatures directly affects coastal communities, not only in terms of the effects on coastal marine ecosystems, but also on the ecosystem goods and services they deliver (Worm and others, 2006; Pendleton and others, 2016). They include, for example, the number of viable fisheries, the provision of nursery functions and the filtering services provided by coastal wetlands (Cochard and others, 2008; Barange and others, 2018). Coral reefs are one of coastal ecosystems heavily affected by ocean warming, and the coral bleaching phenomenon can affect not only marine life but also marine tourism.

Changes in temperature and salinity also have an impact on human well-being (food and health). With respect to food security, fish is one of the most consumed foods in the world and a major contributor to a healthy diet, owing to its proteins, fatty acids, vitamins and other elements that are essential for health (Hilmi and others, 2014). Climate change could decrease seafood availability (Golden and others, 2016) and, as a consequence, reduce protein supply to coastal communities, in general (Blanchard and others, 2017). That would have a strong impact on communities with high seafood dependence, including indigenous and other coastal communities.

An increased prevalence and transmission of diseases is also likely to occur with warmer ocean temperatures. Ocean warming could raise the risk of waterborne diseases and bloom algae toxins (see chap. 6a), affecting the populations and economies of affected areas. For example, the bacterial pathogen *Vibrio cholerae* is expected to grow faster owing to the increase in ocean temperatures (Semenza and others, 2017).

2.4. Pressures from changes in ocean chemistry

Ocean uptake of carbon dioxide emissions is rapidly changing seawater chemistry in a process known as ocean acidification (see chap. 5). As the partial pressure of carbon dioxide in seawater increases, it causes the carbonate saturation state to fall below levels suitable for globally important reef-forming taxa (Albright and others, 2018). Most coral reefs (shallow and deep) are vulnerable to rising CO_2 concentrations (Lam and others, 2019). Ocean acidification is causing the depth at which seawater is corrosive to carbonate to shoal, threatening deepwater coral reefs worldwide through dissolution and intensified bioerosion (Gómez and others, 2018). Ocean acidification combines with warming, rising sea level and more severe storms to reduce reef resilience on a global scale and augment reef destruction. In the Arctic, there has been a rapid expansion in the area where surface seawater is corrosive to calcareous organisms (Brodie and others, 2014).

Ocean acidification may affect all marine life, for example, through changes in gene expression, physiology, reproduction and behaviour (Riebesell and Gattuso, 2015; IPCC, 2019). Between 2005 and 2009, ocean acidification jeopardized a $270 million shellfish aquaculture industry that provided 3,200 jobs per year in Washington State, United States. Billions of oysters died in hatcheries because seawater had become corrosive to larval shells (Ekstrom and others, 2015). In addition to its negative impacts on calcifying phyto- and zooplankton, acidification can lower the nutritional value of seafood.

Ocean acidification also affects ecosystem properties, functions and services. Some groups of organisms do well in acidified conditions, but many taxa do not (Agostini and others, 2018). Many algae are resilient to the levels of ocean acidification projected under the Intergovernmental Panel on Climate Change RCP 8.5 scenario, yet shifts in community composition greatly alter seaweed habitats (Brodie and others, 2014; Enochs and others, 2015). Increased carbon availability stimulates primary production and can increase the standing stock of kelps and seagrasses (Russell and others, 2013; Linares and others, 2015; Cornwall and others, 2017), although microalgae and turf algae dominate acidified waters in exposed conditions (Agostini and others, 2018; Connell and others, 2018).

Research at natural marine CO_2 seeps has shown that there is about a 30 per cent decrease in macrofaunal biodiversity as average pH declines from 8.1 to 7.8 (Agostini and others, 2018; Foo and others, 2018), which is attributable to direct effects, such as increased metabolic costs of coping with hypercapnia, or indirect effects, such as increased susceptibility to predation (Sunday and others, 2017). Some corals grow well in seawater with elevated CO_2 concentrations, but the habitats they form lack diversity as reefs are degraded by ocean acidification owing to chemical dissolution and enhanced bioerosion, causing a shift to less diverse ecosystems. Chapter 7D also reviews the impacts of ocean acidification on coral reefs. The dual effects of increased CO_2 and decreased carbonate alter trophic interactions. Reductions in the abundance and size of calcareous herbivores contribute to the overgrowth of weedy turf algae and a simplification of food webs, with losses in functional diversity (Vizzini and others, 2017; Teixidó and others, 2018).

Damage from ocean acidification results in less coastal protection and less habitat for biodiversity and fisheries (Hall-Spencer and Harvey, 2019). Live coral cover on tropical reefs has nearly halved in the past 150 years, the decline accelerating over the past two decades owing to increased water temperature and ocean acidification exacerbating other drivers of coral loss. When combined with rising temperatures, sea level rise and increasing extreme climate events, ocean acidification further threatens the goods and services provided by coastal ecosystems. That is particularly important for those people who are heavily reliant on marine resources for protection, nutrition, employment and tourism (Lam and others, 2019).

Proposed actions to lessen the impacts of ocean acidification and to build resilience are primarily intended to reduce CO_2 emissions but also include: reduction of pollution and other stressors (such as overfishing and habitat damage); seaweed cultivation and seagrass restoration; water treatment, (e.g., for high-value aquaculture); adaptation of human activities such as aquaculture; and repair of damaged ecosystems (Cooley and others, 2016), for example, through the rewilding of the ocean.

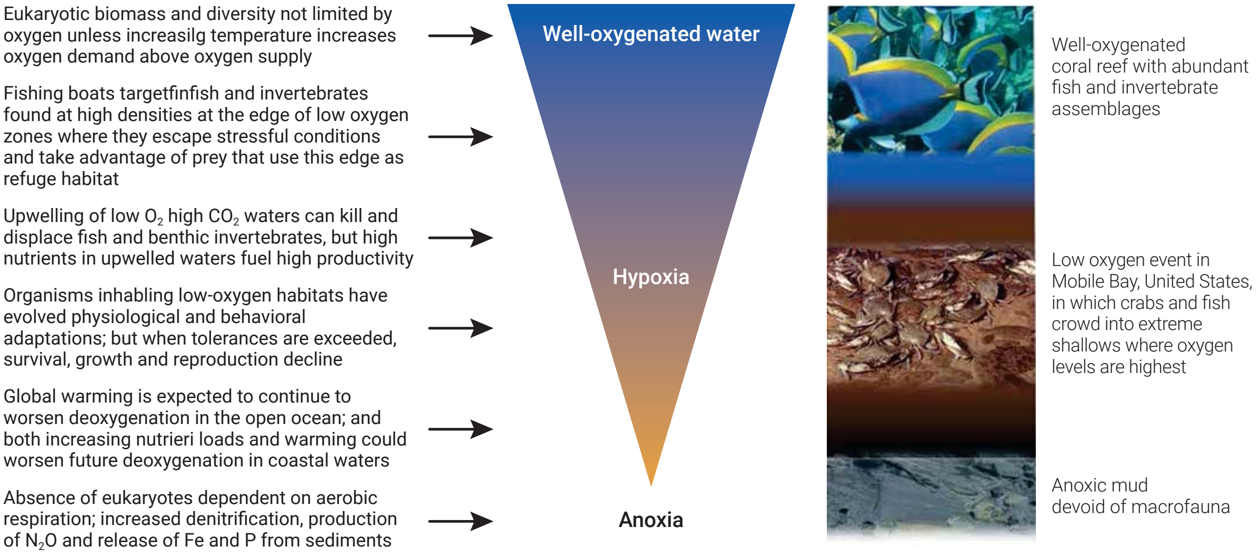
Regarding deoxygenation, since the middle of the twentieth century, the ocean (including coastal waters, such as estuaries and semi-enclosed seas) has lost about 2 per cent, or over 150 billion tons, of its total oxygen content (Schmidtko and others, 2017), and more than 600 coastal water bodies have reported oxygen concentrations of less than 2 mg per l (Diaz and Rosenberg, 2008; Breitburg and others, 2018). Climate change is projected to cause more oxygen decline in many coastal systems where deoxygenation is currently driven primarily by an oversupply of anthropogenic nutrients. Such deoxygenation is of great concern because oxygen is fundamental to life in the oceans (figure II; Laffoley and Baxter, 2019). It constrains productivity and biodiversity, regulates global cycles of nutrients and carbon, and is required for the survival of individual organisms (Breitburg and others, 2018). When oxygen is sufficient, it does not limit or negatively affect the physiology, behaviour and ecological interactions of organisms dependent on aerobic (oxygen-utilizing) respiration. Waters are considered to be hypoxic when oxygen levels are insufficient and those processes are impaired. A threshold value of 2 mg dissolved oxygen/l is often used to define hypoxia, but the oxygen concentration or saturation at which life processes are impaired varies considerably among species, processes and habitats and is affected by temperature.

As the oxygen content of water declines, an increasing fraction of production is diverted to microbes (Diaz and Rosenberg, 2008; Wright and others, 2012). Food webs change because of altered encounter rates and the species-specific effects of low oxygen on the feeding efficiencies of predators and escape behaviours of prey. Energy transfer to tolerant animals, such as gelatinous species, can increase (Keister and Tuttle, 2013). The roles of vision (McCormick and Levin, 2017) and carnivory (Sperling and others, 2016) can decline within low oxygen areas because those activities are energy intensive. In contrast, predation can intensify above low oxygen zones as visual feeders are forced into shallower waters with higher light levels (Koslow and others, 2011).

Declining ocean oxygen is expected to negatively affect a wide range of biological and ecological processes. The magnitude of the effects will vary among species and processes, however, and whether the magnitude of responses will be directly proportional to the magnitude of oxygen decline is uncertain. Some effects of oxygen decline are dependent on direct exposure within low-oxygen waters, while others involve the movement of organisms and material (e.g., nutrients, organic matter, greenhouse gases) among locations that vary in oxygen content, and still other effects are primarily dependent on oxygen levels at particular locations that are critical for a species or life stage. Many responses involve threshold oxygen levels at which biological functions can no longer be maintained.

The biomass and diversity of eukaryotic organisms tend to decline and species composition changes as oxygen declines (Gallo and Levin, 2016). As low-oxygen waters expand, tolerant species can expand their depth range, while ranges of species that are more sensitive contract (Sato and others, 2017). The relative abundance of species within systems reflects variation in species' tolerances to low oxygen and other co-stressors (Koslow and others, 2018). Organisms, including crustaceans and fish adapted to low-oxygen environments, can reach very high densities in low-oxygen areas (Pineda and others, 2016; Gallo and others, 2019). However, in naturally low-oxygen habitats, such as oxygen minimum zones, even very small changes (representing less than 1 per cent of the oxygen content of well-oxygenated surface waters) can result in the exclusion of species that would otherwise be abundant (Wishner and others, 2018).

Figure II
Control of oxygen over biological and biogeochemical processes in the open ocean and coastal waters



Eukaryotic biomass and diversity not limited by oxygen unless increasilg temperature increases oxygen demand above oxygen supply

Fishing boats targetfinfish and invertebrates found at high densities at the edge of low oxygen zones where they escape stressful conditions and take advantage of prey that use this edge as refuge habitat

Upwelling of low O$_2$ high CO$_2$ waters can kill and displace fish and benthic invertebrates, but high nutrients in upwelled waters fuel high productivity

Organisms inhabling low-oxygen habitats have evolved physiological and behavioral adaptations; but when tolerances are exceeded, survival, growth and reproduction decline

Global warming is expected to continue to worsen deoxygenation in the open ocean; and both increasing nutrieri loads and warming could worsen future deoxygenation in coastal waters

Absence of eukaryotes dependent on aerobic respiration; increased denitrification, production of N$_2$O and release of Fe and P from sediments

Well-oxygenated coral reef with abundant fish and invertebrate assemblages

Low oxygen event in Mobile Bay, United States, in which crabs and fish crowd into extreme shallows where oxygen levels are highest

Anoxic mud devoid of macrofauna

Source: Figure modified from Breitburg and others, 2018.

Note: Oxygen exerts a strong control over biological and biogeochemical processes in the open ocean and coastal waters. Whether oxygen patterns change over space, as with depth, or over time, as effects of nutrients and warming become more pronounced, biological diversity, biomass, and productivity decline with decreasing levels of oxygen.

Chronic exposure to suboptimal oxygen conditions can reduce growth (Thomas and others, 2019) and reproduction (Thomas and others, 2015). Numerical models indicate that those chronic effects can lead to population declines over time (Rose and others, 2018), even in the absence of direct low oxygen-induced mortality. Increased acquisition or progression of infections and decreased host immune responses resulting from exposure to low oxygen have been reported for a range of vertebrate and invertebrate hosts (Breitburg and others, 2019) and may increase the transmission of pathogens to humans through consumption of immunosuppressed hosts (Hernroth and Baden, 2018).

Microbes have evolved and adapted to exploit even the most extreme habitats on Earth, including those that contain no oxygen. Biogeochemical cycling of elements by microbes in the absence of oxygen leads to the production of greenhouse gases, including nitrous oxide and methane (Buitenhuis and others, 2018). The expansion of anoxic habitats could, therefore, lead to the increased release of greenhouse gases to the atmosphere, further increasing warming and stratification. That outcome is uncertain, however, because warming and stratification, both of which might increase greenhouse gas production, will also affect the rates and distribution of primary production upon which all other biological processes depend (Battaglia and Joos, 2018).

Ocean deoxygenation does not occur in isolation from other human-caused ocean stressors. With elevated ocean temperatures, microbes that are dependent on aerobic respiration and the vast majority of marine animals will need to consume more oxygen in order to survive (Pörtner, 2012). Elevated ocean temperatures therefore decrease the availability of suitable habitat both by increasing oxygen requirements and by inducing further oxygen loss. Predicted shifts in distribution poleward and into deeper, cooler waters, local extinctions and decreased maximum size of many fish species are attributed, at least in part, to increased oxygen requirements at warmer temperatures (Deutsch and others, 2015; Pauly and Cheung, 2018). The combined effects of ocean climate change stressors, namely, deoxygenation, warming and acidification, may also result in spatial, temporal and evolutionary mismatches between zooplankton and fish larvae that lead to altered larval fish growth and survival, and ultimately negative effects on fisheries (Dam and Baumann, 2017). More generally, the role of oxygen in converting food to energy means that oxygen supply can determine the amount of energy that is available to respond to other stressors (Sokolova, 2013).

Fisheries catches are often low in oxygen-depleted waters as a result of the avoidance behaviour of highly mobile species, as well as the mortality and recruitment failure of species that are sessile or have limited mobility (Breitburg and others, 2009; Rose and others, 2018). There is concern that low-oxygen areas and their expansion make fish and mobile shellfish more susceptible to overfishing (Craig, 2012; Purcell and others, 2017) by leading to high-density aggregations above and at the edge of low-oxygen waters (Craig, 2012; Stramma and others, 2012). For example, spatial shifts in fishing effort have been well documented in both the brown shrimp fishery in the Gulf of Mexico and the Dungeness crab fishery in Hood Canal, United States, whereby the spatial overlap between fishing fleets and target species increases as hypoxic zones increase on a seasonal basis or among years that vary in the spatial extent of hypoxia (Purcell and others, 2017; Froehlich and others, 2017). Fishing mortality may increase where such refuge locations are targeted and where shallower distributions increase catch rates (Purcell and others, 2017). Low-oxygen events have also been an important source of mortality in both finfish and shellfish aquaculture, causing substantial losses to local economies, with consequences to both human health and food security (Cayabyab and others, 2002; Rice, 2014).

3. Capacity-building: Global Ocean Acidification Observing Network and Global Ocean Oxygen Network

Sustainable Development Goal 14 addresses the need to “conserve and sustainably use the oceans, seas and marine resources for sustainable development”, including by meeting target 14.3, to “minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels”.[1] Concern about the problem of deoxygenation was also noted in the “Our ocean, our future: call for action” declaration, the outcome of the United Nations Conference to Support the Implementation of Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.[2]

The ability to attribute ecosystem impacts to changing ocean chemistry requires continued advances in ocean observation systems. Global initiatives in ocean research, such as Biogeochemical Argo, and the Global Ocean Acidification Observing Network and Global Ocean Oxygen Network of the Intergovernmental Oceanographic Commission are reducing barriers and building capacity in support of improved global understanding of ocean acidification and deoxygenation. The Global Ocean Acidification Observing Network and the Global Ocean Oxygen Network provide access to collaboration and mentoring in support of improving ocean observations of pH and oxygen through training sessions, partnerships and support for the creation of regional hubs. Currently, ocean acidification and deoxygenation observation and research efforts are concentrated in a relatively small number of countries, leaving large knowledge and capacity gaps around the world, especially in the southern hemisphere and in small island developing States and least developed countries (Global Ocean Acidification Observing Network (GOA-ON), 2019). Higher capacity to collect complex data and deliver better observations across the globe means that the predictive power of experiments and ecosystem models may improve as they replicate real-world scenarios more effectively to meet Goal 14.

Marine ecosystem services depend on which basic biotic functions are maintained (Connell and others, 2018), which ecosystem engineers and keystone species are retained (Sunday and others, 2017) and whether the spread of nuisance species is avoided (Hall-Spencer and Allen, 2015). Knowledge gaps for ecosystem responses to changes in ocean chemistry remain large. However, multi-stressor experiments and ecosystem models that incorporate advances in ecophysiology and genomics may better describe the scope of impact and reduce uncertainty about its extent. How deoxygenation is altering microbial pathways and rates of processes within the water column and the deep ocean needs to be better understood (Breitburg and others, 2018). The call by Riebesell and Gattuso (2015) for a shift towards multi-stressor and multispecies experiments to understand more specifically the ecological impacts of ocean acidification on marine communities has been taken up (Munday, 2017). Further advances will result from deepening and broadening the understanding of the relationships of ocean acidification and oxygen with other environmental drivers, how ecological processes and species interactions change under conditions that matter to them and how individual variation, plasticity and adaptation in response to ocean chemistry change shape impacts on marine ecosystems. Advancing research on those topics will support more

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[1] See General Assembly resolution 70/1.

[2] See General Assembly resolution 71/312, annex; see also https://oceanconference.un.org/callforaction.

effective measures to mitigate the impacts of ocean acidification and deoxygenation, which may, as a result, have less serious consequences for the millions of people who are dependent on coastal protection, fisheries and aquaculture in lower-emission scenarios.

4. Summary

Marine heatwaves are shown to be increasing in frequency and intensity owing to climate change caused by human activities and are having a mostly negative impact on marine ecosystems. Marine heatwaves and their impacts are projected to increase in the future but those increases can be strongly limited by efforts to mitigate climate change. Forecasting systems may be employed in adapting to the effects of marine heatwaves.

Extreme El Niño and La Niña events have been observed but, because they occur infrequently, a human influence has not been detected. Nevertheless, models indicate an increase in the frequency of both phases of the oscillation under future scenarios of global warming. As in the case of marine heatwaves, forecasting systems, which already exist, may be employed in risk management and adaptation.

While changes in the frequency and spatial distribution of tropical cyclones are hard to detect in the observational record, studies of individual cyclones have shown a human influence on their intensity, in particular, the associated rainfall. Changes in intensity are projected to increase in the future, with associated impacts on storm surges and coastal infrastructure.

Although all coastal cities are already facing rising sea levels, low-lying cities and developing countries that lack the ability to invest in coastal defence measures and natural barrier restoration will suffer damage and losses of a higher degree. Global population studies suggest that people are relocating to coastal areas and will continue to do so, thereby putting more people at risk economically and socially. Although cities are typically centres for innovation and investment, key examples demonstrate the difficulty in solving such complex problems in vulnerable locations.

Damage and losses are also driven by existing vulnerabilities in coastal infrastructure and may not be solely attributed to rising sea levels. Rather, increasing sea levels may exacerbate existing issues, increasing risk.

The complex interactions of temperature and salinity with nutrients and chemical cycles of the ocean imply that variations in those variables owing to climate change and anthropogenic impact thus affect marine ecosystems, population, coastal communities and the related economy. Ocean warming is causing significant damage to marine ecosystems, and species are losing their habitats, forcing them to adapt or relocate to new temperatures or look for new feeding, spawning or nursery areas.

Ocean acidity and the availability of sufficient oxygen both underpin the provision of marine ecosystem services to human society. Rapid changes in ocean acidity and falling oxygen levels caused by climate change and anthropogenic CO_2 emissions are, however, now being observed, which is changing marine habitats and ecosystems worldwide. Warming is causing oxygen levels to fall, and acidification is rapidly changing the carbonate chemistry of surface ocean waters, which together are reducing the growth and survival of many organisms and degrading ecosystem resilience.

Closing knowledge gaps in ocean science by supporting capacity-building efforts that increase the understanding of how the ocean and its ecosystems are responding to changes in ocean physical and chemical properties is an important pathway to reducing the impacts of such changes and achieving Sustainable Development Goal 14.

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