

Subsection 5B

Chapter 4

Ocean hazards of natural origin

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Key points

- A methodological approach that integrates ocean hazards of natural origin into the One Health concept is proposed (see figure I).
- Identifying pathways is essential for assessing the impact of ocean hazards of natural origin on natural and human environments across oceanic scales and for enhancing ocean and coastal resilience.
- Pathways linking “pressures”, “ocean hazards” and “impacts-disasters” serve to illustrate the distinctions within ocean hazards of natural origin (see figure XVI).
- Pathways connecting “impacts-disasters” and “mitigation-management-adaptation” serve to highlight available strategies in a multi-hazard context (see figure XVII).

1. Introduction

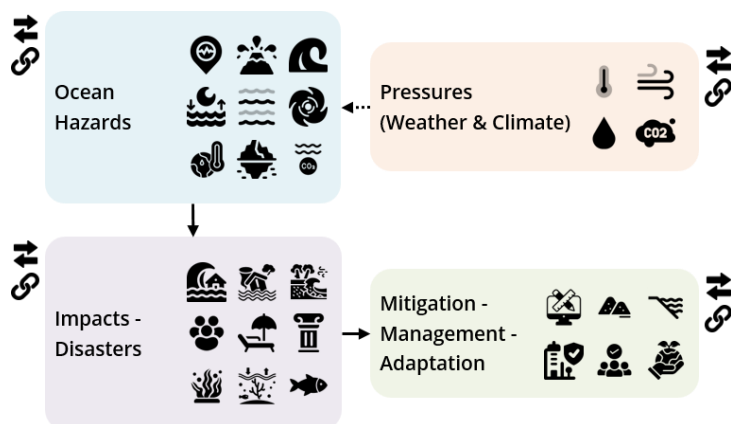
Ocean hazards of natural origin can be classified into four categories: (a) geophysical or geological; (b) ocean weather, hydrology and climate; (c) ecological; and (d) biological (Pinardi and others, 2024). The present chapter is focused on categories (a), (b) and, partly, (c) (for acidification and deoxygenation, since those hazards largely affect those under categories (c) and (d)). Aspects regarding (c) and (d) are also addressed in other chapters (see sect. 4, chaps. 4–6; and subsection. 5B, chaps. 1 and 2; see also table 2).

The present chapter is a new addition to the *World Ocean Assessment*. In the first and second *Assessments*, elements that were relevant to ocean hazards or integrated them within broader environmental and ecological frameworks were addressed; however, in the third *Assessment*, the topic has been elevated to a focused chapter. Accordingly, the approach presented below is intended to serve as a blueprint for future versions of the *Assessment*.

The approach taken is graphically represented by the flow chart contained in figure I. Its aim is to highlight “pathways” that connect the four core components, with the goal of facilitating a structured overall assessment of ocean hazards of natural origin within the framework of the third *World Ocean Assessment*. The approach is aligned with the nationally determined contributions and dialogues under the United Nations Framework Convention on Climate Change (UNFCCC) in relation to the role of ocean hazards of natural origin in the above context and to the road map towards ocean/coastal resilience (UNFCCC, 2023, 2024a, 2024b).

Figure I

Flow chart of the approach to the present chapter, including its four core components



Source: Prepared by the writing team.

Note: Arrows denote the pathways between core components; “pressures” make part of the pathways only for hazards affected by weather and climate, hence the dotted line; double arrows denote information exchanges and link icons refer to other chapters of the third *World Ocean Assessment* as presented in 0).

2. Ocean hazard analysis

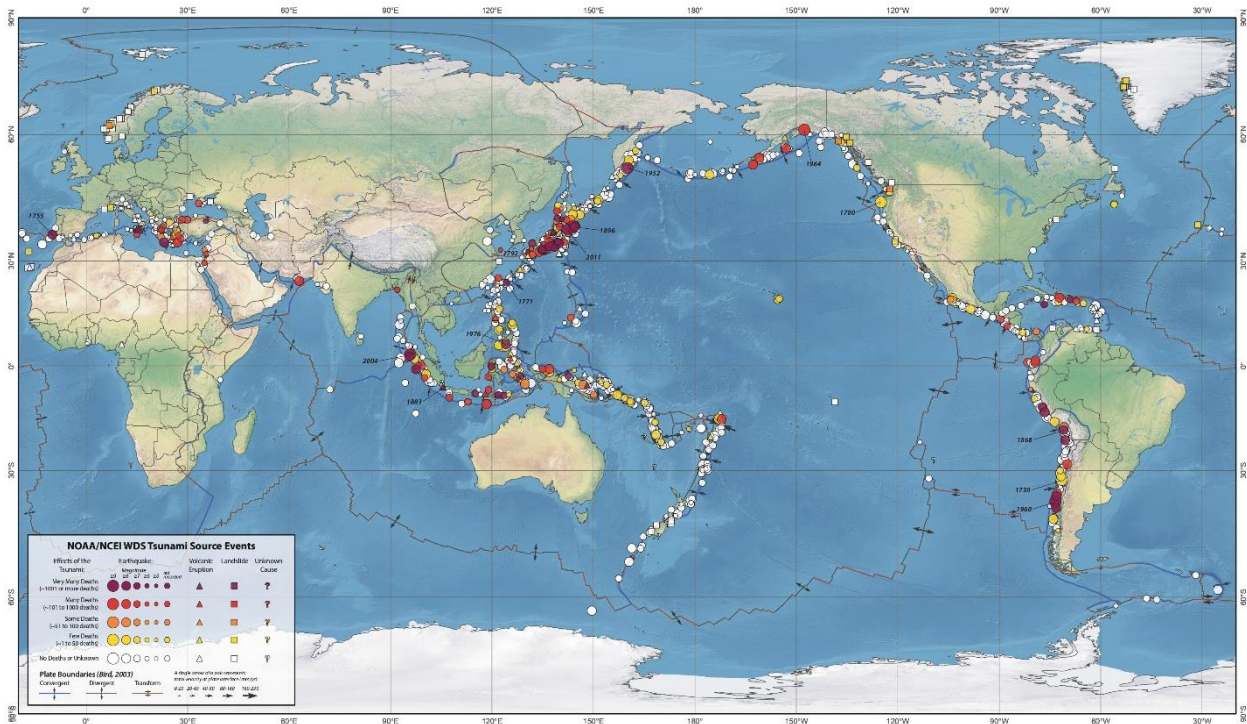
The present part of the chapter contains an analysis of ocean hazards of natural origin within the context of identifying pathways that connect the “pressures”, “ocean hazards” and “impacts-disasters” components (see figure I). It is divided into 17 sub-parts, each containing a description of a distinct hazard. An analysis is presented in figure XVI. Information in figure XVI reflects the assimilation of available knowledge regarding the examined hazards in the relevant literature (see 0 1). Figure XVI should not be interpreted beyond its intended use, considering the uncertainties arising from such large-scale assessments when studying phenomena with significant local and regional variations. In that light, the present chapter is fundamentally linked to section 4, chapters 1 to 3, of the third *World Ocean Assessment*, with detailed links identified in 0 table 2.

Tsunamis

Geohazards can have major impacts on the human and natural environment, ranging from direct impacts (loss of life and damage to infrastructure and property), to indirect impacts (economic loss, social disruption and environmental degradation). Tsunamis are long sea waves with wave periods typically within the minutes to hour range. Their wavelengths are in the order of tens to hundreds of km depending on the dimensions of their causes (Levin and Nosov, 2016). Although tsunamis can be produced by several mechanisms (Bryant, 2008), submarine geological processes produce the majority of these waves. Shallow submarine earthquakes with moment magnitude greater than 6.5 produce 79% of the global number of tsunamis, while submarine volcanic eruptions or landslides produce 18%. Most tsunamis, including the largest, are generated along subduction zones (see figure II). Tsunamis caused an estimated 250,000 deaths and \$280 billion in economic losses between 1998 and 2017 (United Nations Office for Disaster Risk Reduction (UNDRR), 2018).

Figure II

Known tsunami sources from 1610 B.C.E. to 2023 C.E.



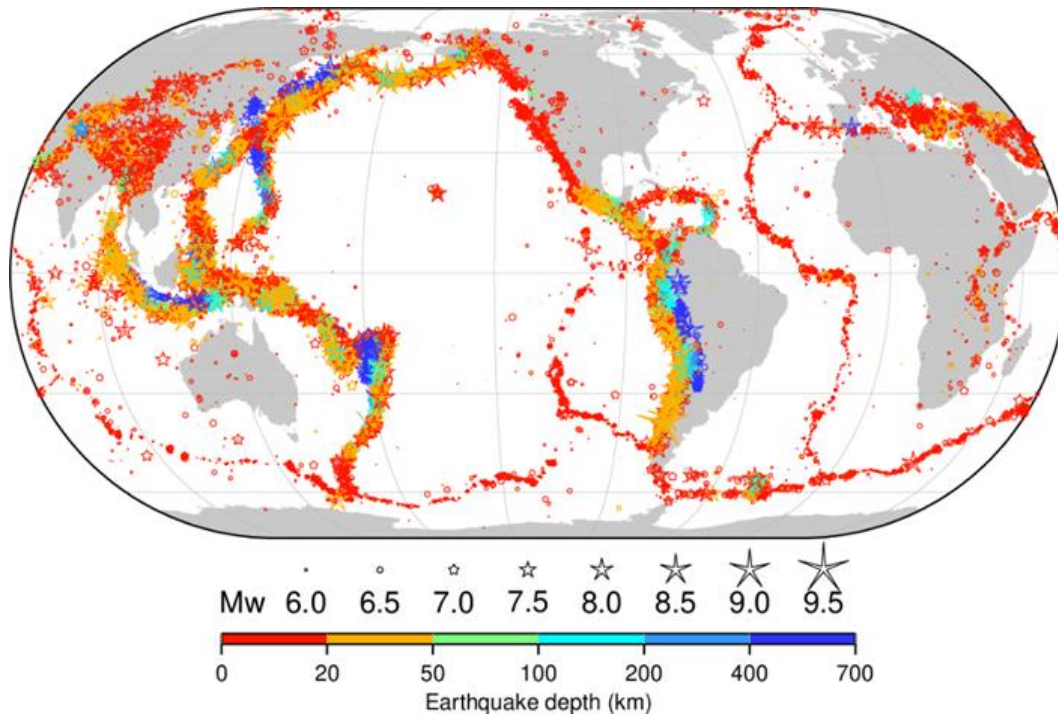
Source: Intergovernmental Oceanographic Commission, 2019.

Earthquakes

Global seismic activity is concentrated mainly along the boundaries of moving lithospheric plates (Lay and Wallace, 1995; see figure III). The sudden rupture of rocks releases stored dynamic energy in the form of seismic waves. Every year, on average, about 15 to 18 earthquakes of magnitude 7 or greater occur globally, and there are hundreds that exceed magnitude 6 (United States Geological Survey (USGS), 2024). Although most tectonic earthquakes occur at shallow depths (focal depth of less than 80 km), seismic activity has been observed at depths of up to about 720 km (the maximum depth of lithospheric subduction). Seismic waves travel from the seismic source in all directions within the Earth's interior, reaching the surface and causing the ground to shake. Earthquakes that occur in association with volcanic activity represent less than 10% of the total number of earthquakes. Earthquakes caused an estimated 500,000 deaths and \$380 billion in economic losses between 1998 and 2017 (UNDRR, 2018; Wallemacq and Rowena, 2018).

Figure III

Epicentres of earthquakes



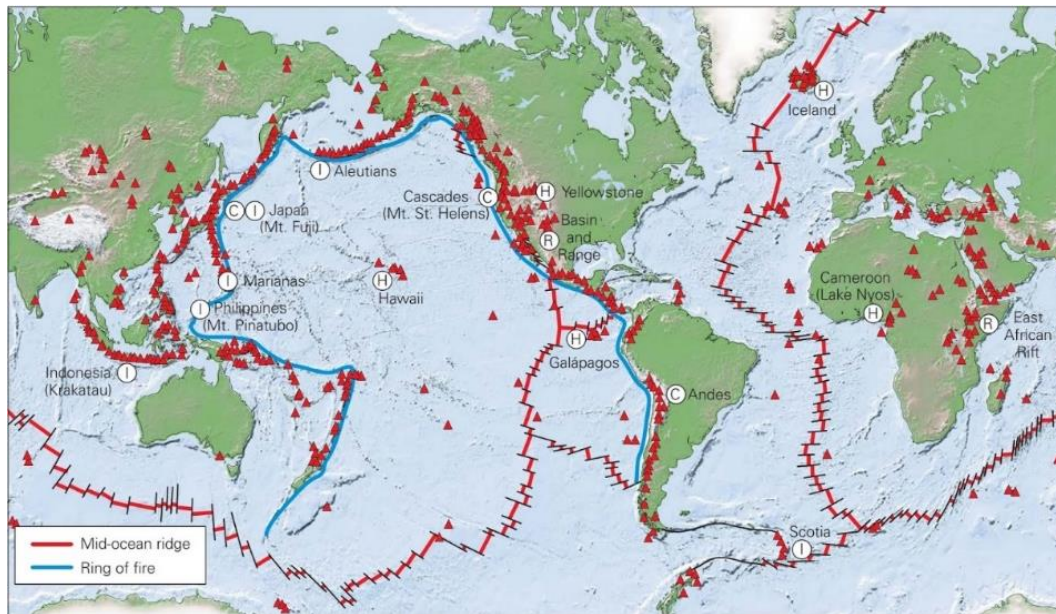
Source: International Seismological Centre (ISC), 2024.

Volcanic eruptions

The geographical distribution of active volcanoes worldwide is similar to that of earthquake sources (Loughlin and others, 2017; see figure IV). More than 75% of all active volcanoes are located along submarine and coastal volcanic belts, such as the Ring of Fire in the Pacific Ocean. Strong volcanic eruptions that occur near populated areas become dangerous or even destructive. Over the past 500 years, volcanic eruptions are estimated to have caused more than 200,000 deaths (Muzeau and others, 2010), with roughly half of those occurring during the period from 1900 to 2009 (Doocy and others, 2013b).

Figure IV

Main lithospheric plates and distribution of volcanoes



Source: Learning Geology, 2024.

Tectonic subsidence

In regions characterized by subduction zones, the overriding lithospheric plate may experience subsidence. As the subducting plate pulls down the Earth's crust, large areas can gradually sink. This is a large-scale geodynamic process that is driven by plate tectonics mechanisms (Turcotte and Schubert, 2002). Tectonic subsidence may also occur suddenly in the overriding plate during a large subduction zone earthquake. Therefore, during large earthquakes, fault rupture can cause abrupt subsidence, thereby triggering tsunamis or permanently lowering parts of the coastline. Furthermore, in regions near convergent boundaries, heavy sediment deposition from rivers or glaciers can cause the crust to bend and subside due to weight (often seen in coastal or delta regions). Tectonic subsidence in coastal regions lowers the land relative to sea level, making those areas more vulnerable to flooding, storm surges and sea level rise. Gradual subsidence over time can cause damage to infrastructure, especially in areas where the land is subsiding unevenly. The opposite process, tectonic uplift, can also cause similar damage to infrastructure and lead to changes or disruptions in navigable waterways.

Coastal erosion

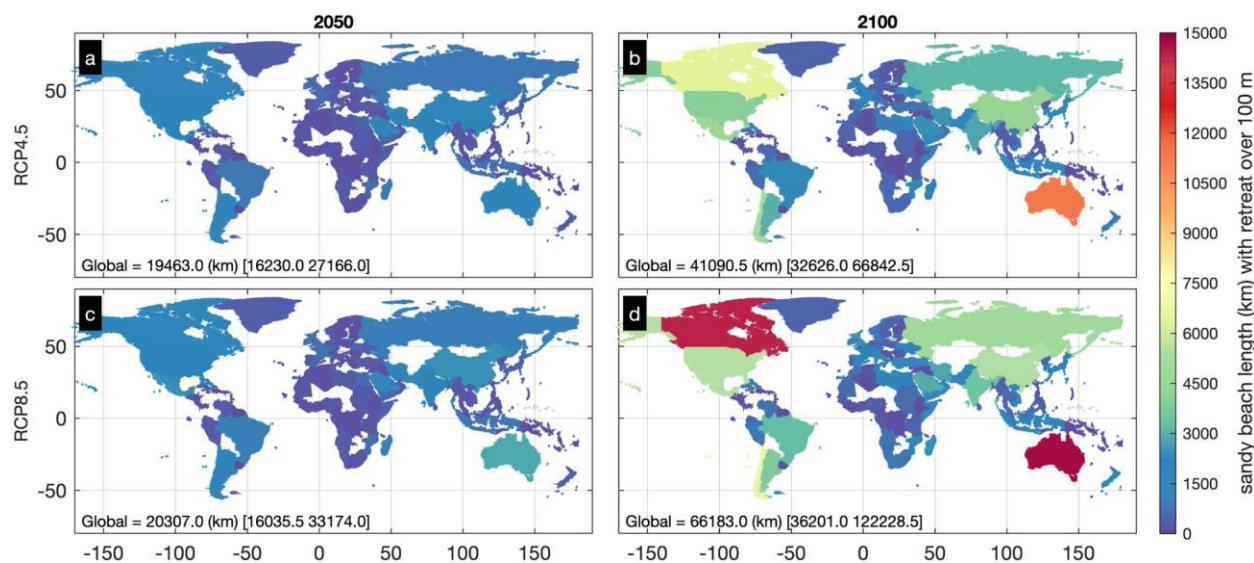
Through a global assessment of shoreline typology using satellite imagery (Hulskamp and others, 2023), 26%, 12%, 27% and 33% of ice-free shorelines were classified as sandy, muddy, rocky and vegetated, respectively, using automated image detection validated at over 50 sites. Luijendijk and others (2018) provide historical sandy shoreline position change rates during the period from 1984 to 2016, showing that 24% of sandy coasts had eroded, 28% had accreted and 48% had remained stable.

It has been stated with high confidence (Intergovernmental Panel on Climate Change (IPCC), 2021) that sandy shorelines will retreat in most regions of the world in the absence of additional sediment sources or

physical barriers to shoreline retreat (for erosion trends for high-latitude permafrost-built shorelines, see sect. 4, subchap. 5K). The total length of sandy shorelines around the world projected to retreat by more than 100 m by the end of the century is about 35% greater under Representative Concentration Pathway (RCP) 8.5 (about 130,000 km) compared with that under RCP 4.5 (about 95,000 km). [Vousdoukas and others \(2020\)](#) find that 13.6–15.2% (36,097 km–40,511 km) of the world’s sandy coastline could face shoreline retreat of more than 100 m by 2050, increasing to 35.7–49.5% (95,061 km–131,745 km) by the end of the century. Concentrating on the densely populated low-elevation coastal zone of the world, comprising 31% of the world’s sandy coastline, [Vousdoukas and others \(2020\)](#) show that about one third of the global low-elevation coastal zone will experience shoreline retreat of more than 100 m by 2050, an estimate that reaches 52% and 63% by the end of the century, under RCP 4.5 and RCP 8.5, respectively (see figure V).

Figure V

Projected retreat of sandy shorelines



Source: [Vousdoukas and others, 2020](#).

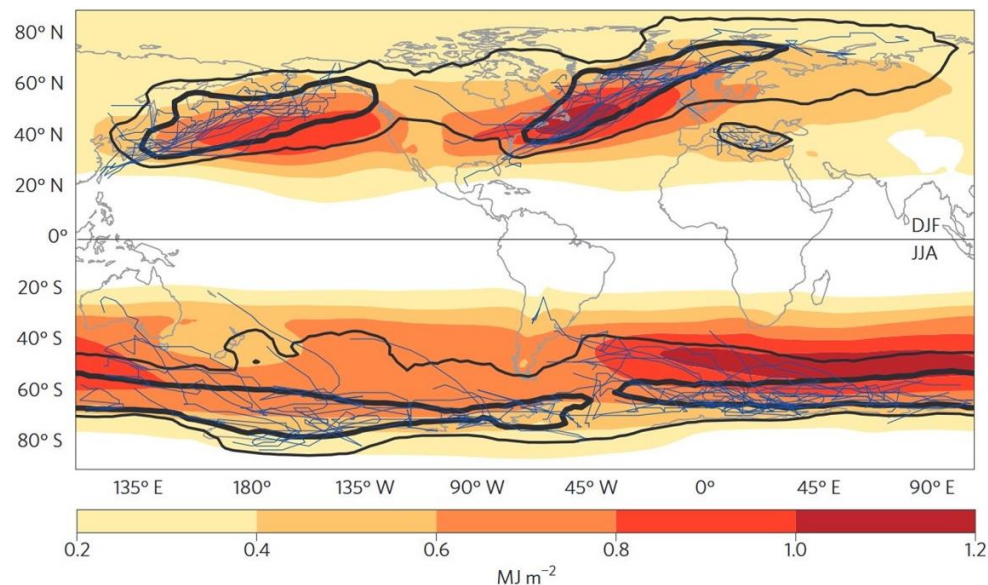
Note: Length of sandy beach coastline projected to retreat by more than 100 m by 2050 (a, c) and 2100 (b, d), under RCP 4.5 (a, b) and RCP 8.5 (c, d), by country.

Tropical and extratropical cyclones Cyclogenesis occurs through different mechanisms at varying latitudes (Emanuel, 1991) and plays a crucial role in global circulation by transporting heat and moisture. Cyclogenesis is a significant hazard for coastal areas and maritime activities, especially in the form of tropical cyclones, which are warm-core, axisymmetric vortices with radii of between 100 km and 1,000 km, fuelled by thermodynamic disequilibrium between the atmosphere and ocean surface. Tropical cyclones are known as hurricanes or typhoons, depending on the region. These terms also refer to specific classifications of tropical cyclones that exceed certain wind speed thresholds in different regions. Annually, around 90 tropical cyclones occur globally (Emanuel and others, 2023) and cause severe impacts in coastal regions through strong winds, intense rainfall and storm surge effects. Extreme events can lead to hundreds of thousands of casualties (Cervený and others, 2017). Since the 1970s, increased coastal exposure and climate change have exacerbated damage and the number of affected individuals

(Kunze, 2021). At higher latitudes, Extratropical cyclones, such as polar lows and Mediterranean hurricanes (Medicanes or tropical-like cyclones) (see Miglietta and Rotunno, 2019), which are smaller and shorter-lived than tropical cyclones, are influenced by sea-surface heat fluxes and baroclinic instability and significantly affect annual precipitation in coastal areas (Schultz and others, 2019). Accurate tracking and property assessment of cyclones is vital for disaster management and long-term preparedness. However, challenges remain in identifying long-term trends due to limited observational records and inter-annual variability. Although studies indicate potential increases in tropical and tropical-like cyclone intensity due to warming, projections regarding frequency changes and poleward migration of maximum intensity remain uncertain (Knutson and others, 2020). In addition, sea level rise may heighten storm impacts even if storminess decreases (Lionello and others, 2017).

Figure VI

Wintertime extratropical storm eddy kinetic energy and track density



Source: Shaw and others, 2016.

Note: Wintertime (adapted for northern and southern hemispheres) extratropical storm eddy kinetic energy (colour) and track density (contours). Thick/thin contours: 20/10 tracks (10^6km^{-2}) per season; blue lines: individual tracks for the top 0.5% most intense cyclones.

Metetsunamis

Metetsunamis are long barotropic ocean waves generated by the resonance between atmospheric perturbations and sea surface oscillations. This resonance can occur when the propagation velocities of these atmospheric disturbances and sea waves align, in the ocean (Proudman resonance) or along coastlines (Greenspan resonance), or through interactions between incoming waves and the oscillation characteristics of a harbour or bay. Nearshore processes, such as topographic amplification or focusing, can further enhance such waves (Ličer and others, 2017). Depending on the mechanisms involved, metetsunamis may manifest as solitary waves that impact coastlines or as seiches that oscillate in bays,

with amplification reaching up to 100 times the “inverse barometer” response to the atmospheric disturbance (Pattiaratchi and Wijeratne, 2015).

While the triggering conditions for meteotsunamis occur at large scales, significant events arise only when multiple conditions coincide (Monserrat and others, 2006). Consequently, meteotsunamis often exhibit local characteristics, with hotspots where such events frequently occur (e.g. the Mediterranean Sea, the East China Sea, the East Coast of the United States of America and the Great Lakes in North America; Rabinovich, 2020). Severe meteotsunami events can cause considerable economic losses and affect local economies (see, for example, Šepić and others, 2016), and possibly lead to fatalities.

Characterizing meteotsunami hazards is challenging in terms of both short-term early warning planning and long-term climate-proof coastal planning. Early warning systems use approaches such as synoptic indices that correlate atmospheric patterns with meteotsunamis, high-resolution numerical modelling of relevant physical processes and probabilistic methods (Denamiel and others, 2023). Global adjustments in sea level monitoring protocols to one-minute intervals, which were initiated following the Indian Ocean tsunami that occurred in 2004, have improved meteotsunami detection and long-term climatological trend reconstruction. Advances in technologies, such as high-frequency radars and global navigation satellite system sensors, have also enhanced tsunami monitoring in the ionosphere (Angove and others, 2021).

Figure VII

Locations of meteotsunami occurrences



Source: Pattiaratchi and Wijeratne, 2015.

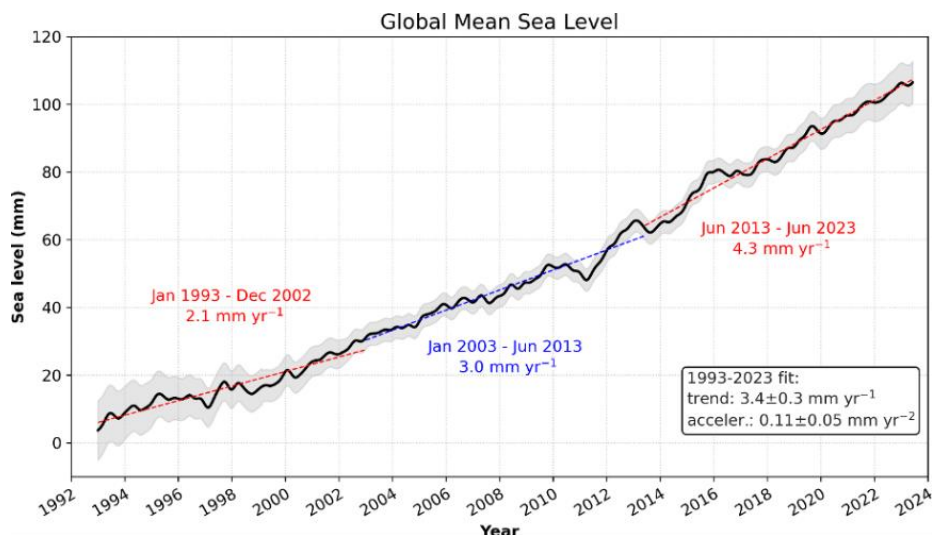
Sea level rise

It is well established that the ice loss from the Greenland and Antarctic ice sheets, glacier mass loss and the expansion of ocean volume from ocean warming (Cazenave and Moreira, 2022) cause global sea level to rise, and human influence has very likely been the main driver of such increases since at least 1971 (IPCC, 2021). It is also well established that the rate of global sea level rise is increasing (von Schuckmann and others, 2024; World Meteorological Organization (WMO), 2024), with a very likely acceleration rate of 0.094 mm/yr^2 ($0.082\text{--}0.115$) for the period from 1993 to 2018 (IPCC, 2021). At the

regional scale, sea level rise is not uniform. While most areas show a positive trend, localized regions with negative trends can also be observed (Fasullo and Nerem, 2018). It is well established that, in the past 30 years, nearly 50% of the ocean has experienced sea level rise at rates exceeding the global average, particularly in regions influenced by major western boundary currents, as well as parts of the western Pacific, the Indian Ocean and some areas of the Atlantic Ocean (von Schuckmann and others, 2024). Although at the regional scale sea level trends are still dominated by steric changes (Stammer and others, 2013), studies show that accelerated land ice melt will lead to associated fingerprints becoming detectable (Tamisiea, 2011; Coulson and others, 2022; IPCC, 2019). Sea level rise has increased the adverse effects of coastal floods (well established), storms and tropical cyclones (established but incomplete), and hence the consequent losses and damages, the increasing vulnerability of inhabitants and infrastructure and food security risk, in particular in low-lying areas and island States (IPCC, 2022). Adaptation and mitigation measures, such as the restoration of mangroves and coastal wetlands, reduce the risks from sea level rise (IPCC, 2022).

Figure VIII

Global mean sea level rise



Source: von Schuckmann and others, 2024.

Note: Global mean sea level time series from January 1993 to June 2023 (curve) and its uncertainty envelope (shaded).

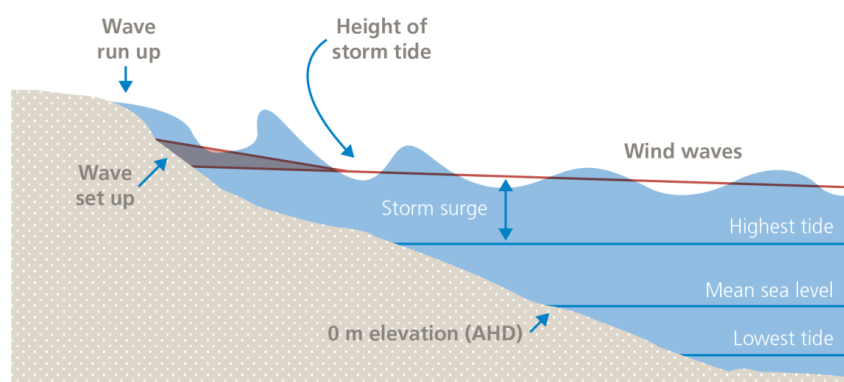
Waves and wave run-up

Wave run-up is a combination of wave set-up and shoreline oscillation (swash) from each incoming wave (see figure IX). It includes contributions from sea, swell and infragravity waves, varying over seconds to minutes. On gently sloping beaches, infragravity wave run-up can dominate. During storms, wave run-up on open coast beaches may reach 3 to 6 m above other components (Hughes, 2016). Run-up characteristics change depending on beach and offshore wave properties (Holman, 1986) and is the main driver of beach-face hydrodynamics and morphodynamics (Elfrink and Baldock, 2002). Run-up also plays a critical role in dune erosion during storm conditions (Ruggiero and others, 2001) and structure overtopping (van der Meer and Stam, 1992). Run-up is therefore key to successful coastal planning and management and a critical parameter in assessing the effect of sea level rise on coastal inundation.

Wave run-up is closely related to many of the hazards presented in the present part of the chapter (tsunamis, tropical and extratropical cyclones, meteotsunamis, sea level rise, and storm surge and coastal flooding). Accordingly, it is difficult to disengage its assessment from a multi-hazard approach when it comes to the flow chart contained in figure I, especially considering that, with the exception of tsunamis, all other related hazards will be exacerbated by climate change. There are several studies highlighting regional variability in wave climate under present and future conditions. Nevertheless, regardless of regional variability, there appears to be consensus that major impacts will derive from significant increases in wave heights, changes in the frequency of occurrence and magnitude of extremes, and changes in wave directionality (Casa and others, 2024; Lobeto and others, 2021).

Figure IX

Schematic representation of the surf zone



Source: Department of Sustainability and Environment (DSE), 2012.

Storm surge and coastal flooding

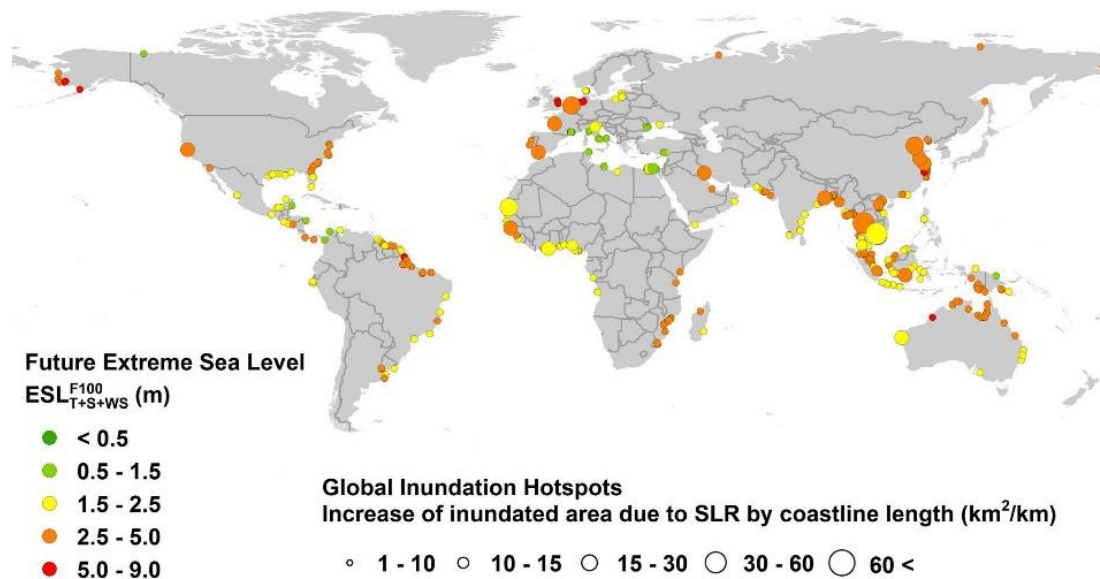
Coastal flooding is the episodic or permanent flooding of low-elevation coastal zone due to extreme total water levels. Extreme total water levels are composed of relative sea level rise, which combines sea level rise and local subsidence, storm (wind and pressure-driven) surge, tides and wave set-up (Rueda and others, 2017). In many cases, storm surge is the dominant contributor to extreme total water level. Hazards associated with coastal flooding are highly likely to increase in the coming decades for the majority of the world's coastlines (IPCC, 2021). Vousdoukas and others (2018) project a global increase by 2100 of 34 to 76 cm of the 100-year return period extreme total water level under the RCP 4.5 scenario, and an increase of 58 to 172cm under the RCP 8.5 scenario. Moreover, after 2050, the present-day high return period extreme total water levels is expected to become much more frequent in the majority of the world's coastal areas, especially in the tropics (Vitousek and others, 2017), even under the most optimistic 1.5°C warming scenarios (Tebaldi and others, 2021).

Looking at coastal flooding impacts on a global scale, without taking coastal protection and adaptation into account, an estimated area of $533 \times 10^3 \text{ km}^2$ (512–603), a total of 148×10^6 (128×10^6 – 171×10^6) people and assets valued at $7,761 \times 10^9$ \$ (6,466–9,135) would be at risk under a present day 100-year return period extreme total water level event, increasing by 2100 by 33%, 36% and 32% under the RCP 4.5 scenario, respectively, and by 48%, 52% and 46% under the RCP 8.5 scenario, respectively (Kirezci and others, 2020). Within the above context, impacts on food systems (especially fisheries and aquaculture)

should not be overlooked (Sühring and others, 2023). Looking at risk, Tiggeloven and others (2020) found a 150-fold increase in expected annual damage by 2100 under the RCP 4.5-Shared Socioeconomic Pathway 2 scenario if no adaptation to coastal flooding occurs. When applying different adaptation scenarios, the increase reduces to 11- to 39-fold, depending on the adaptation pathway selected.

Figure X

Global hotspot regions of changes in episodic coastal flooding in 2100 under Representative Concentration Pathway 8.5 (difference between projected episodic flooding in 2100 minus present-day episodic flooding)



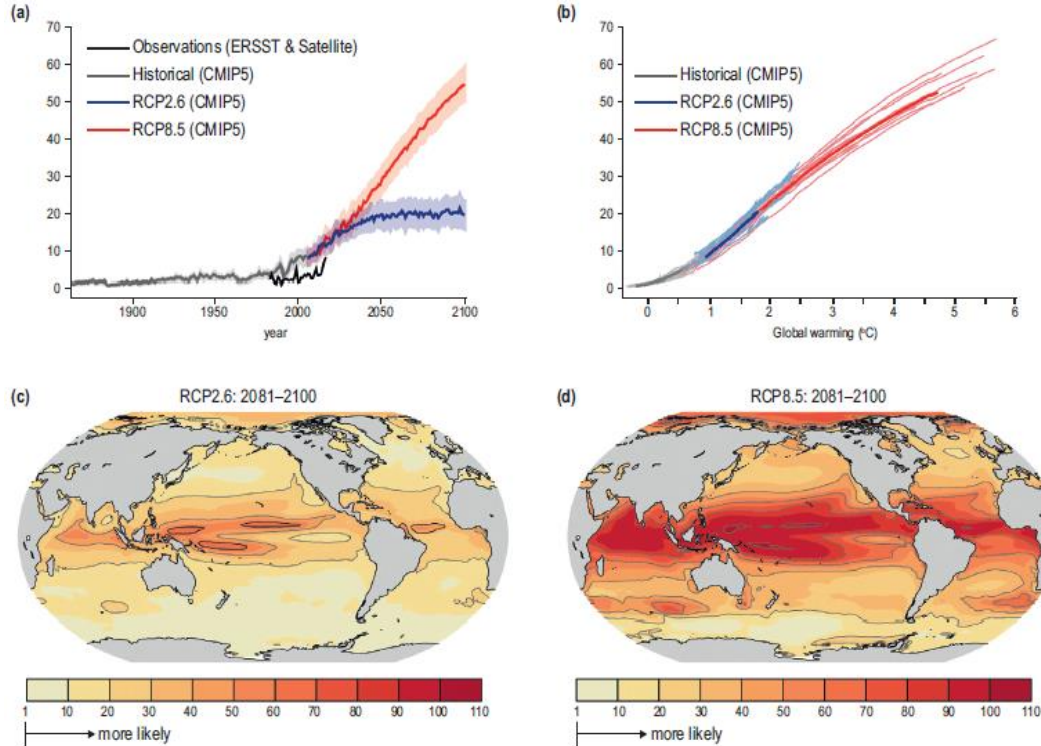
Source: Kirezci and others, 2020.

Marine heatwaves

A marine heatwave is a period of at least five consecutive days of sea surface temperatures above the ninetieth climatological percentile (Hobday and others, 2016). Marine heatwave result from air-sea interactions, shifts in ocean currents and climate variability such as El Niño (IPCC, 2019). It is well established that, since the 1980s, marine heatwave frequency has doubled, with further increases expected, especially in tropical and Arctic waters, and human influence has very likely contributed to most of them since at least 2006 (IPCC, 2019 and 2021). With further increases in intensity and frequency observed, and projected in the coming decades, marine heatwaves are emerging as pervasive stressors for marine ecosystems globally (Smith and others, 2023; see figure XI), thereby exposing species and ecosystems to environmental conditions beyond their tolerance and acclimation limits (IPCC, 2022). Adverse impacts already reported include the reduction of primary production, the migration or reduction of endemic species, the emergence of species from other regions and mass mortality of organisms (Smith and others, 2023; Oliver and others, 2019; Garrabou and others, 2022). Those changes can, in turn, have adverse impacts on human systems, including on fisheries and aquaculture (Cheung and Frölicher, 2020; IPCC, 2022; Wakelin and others, 2021).

Figure XI

Global and regional changes in the probability ratio of marine heatwaves



Source: IPCC, 2019.

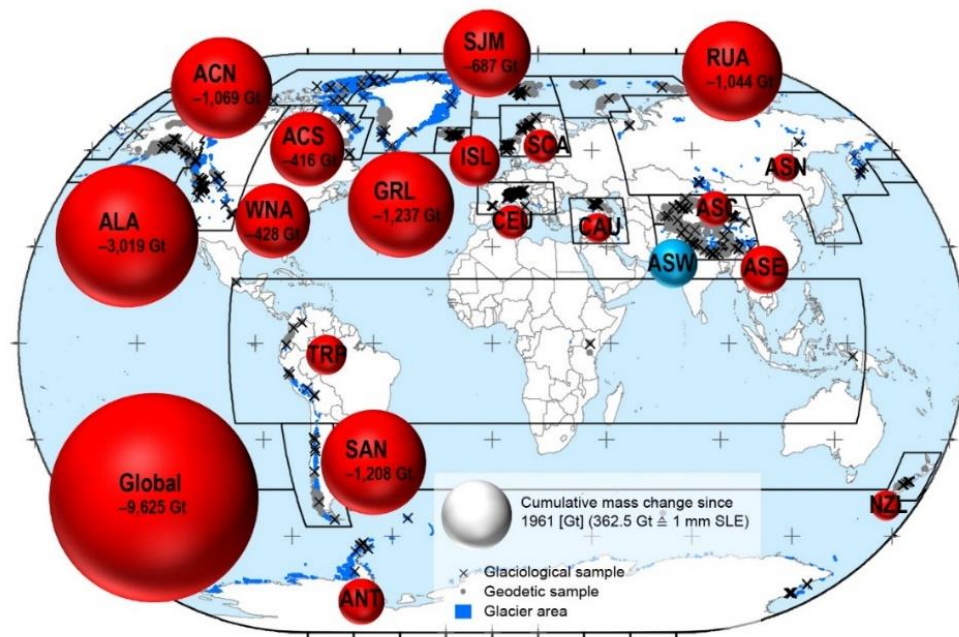
Note: The probability ratio is the fraction by which the number of marine heatwave days per year has changed since 1850–1900. (a): changes in the annual mean probability ratio of marine heatwaves exceeding the ninety-ninth percentile of pre-industrial local daily sea surface temperature averaged over the ocean. (b): same as (a), but the probability ratio is plotted for different levels of global surface atmospheric warming and for the individual models. The simulated time series in (b) are smoothed with a 10-year running mean. (c) and (d): simulated regional changes in the multi-model mean probability ratio of marine heatwaves exceeding the preindustrial ninety-ninth percentile in 2081–2100 for the RCP 2.6 scenario (c) and the RCP 8.5 scenario (d).

Glacial melt

Glacial melt refers to the large-scale melting of glaciers and ice sheets, which releases vast amounts of freshwater into the world's oceans. Glacial melt contributes to sea level rise, while the influx of freshwater disrupts ocean salinity and density, thereby also modifying habitat conditions, nutrient availability and the biological productivity of affected regions (IPCC, 2019). Ice loss from glaciers and ice caps accounts for about 60% of the ice loss that contributes to sea level rise, with the remaining attributed to the melting of the Antarctic and Greenland ice sheets (Meier and others, 2007; see figure XII). As a result, sea level rise has reached approximately 1.48 ± 0.26 mm per year from all ice-covered regions (Jacob and others, 2012). According to projections, glacier melt could contribute an additional 10 to 25 mm to sea level rise by 2100 (Meier and others, 2007), while the Greenland ice sheet alone could contribute between 75 and 140 mm to sea level rise over the same period (Gillet-Chaulet and others, 2012). Freshwater input from glacial melt affects regional dynamics and global overturning circulation (Cenedese and Straneo, 2023), while also affecting nutrient and carbon cycling, thereby influencing primary and secondary productivity in marine ecosystems (Oliver and others, 2020). This affects not only coastal areas, but also the freshwater discharged downstream through glacial-fed rivers (Hock, 2014).

Figure XII

Regional share of glaciers in sea level rise from 1961/62 to 2015/16



Source: World Glacier Monitoring Service, 2024; adjusted from Zemp and others, 2019.

Heavy rainfall and river flooding

Heavy rainfall in watersheds and associated river flooding can pose significant threats for downstream coasts, through compound flooding, degraded water quality, saltwater intrusion and threats to marine ecosystems. Compound flooding is the simultaneous occurrence of multiple flood drivers, including storm surges, river overflow and torrential rain. Such flooding is particularly severe and can exacerbate the impacts on coastal areas by increasing flooding extents and flow depths (Wright and others 2019; Shen and others, 2019). Effects typically extend to saltwater intrusion, which contaminates drinking water supplies and affects water quality for years (Marques and others, 2020), leading to direct or indirect health risks for coastal communities. River and compound flooding also affect coastal ecosystems and habitats, through nutrient or sediment transport, physical or biogeochemical changes and habitat disruption (Ge and others, 2021; Furnas, 2011). Climate change is expected to modify the spatial and temporal modulation of rainfall regimes, leading to increased frequency of intense precipitation events and higher flood risks in many regions (IPCC, 2021). This is particularly evident in tropical and subtropical areas, where more intense rainfall is projected to increase flood frequency and magnitude (Winarta and others, 2019). Assessing the impacts of climate change on compound flooding involves significant uncertainties due to the complex interplay of various factors. For example, in Europe, the Mediterranean coasts might currently experience the highest probability of compound flooding; however, according to future projections, there are emerging high probabilities along parts of the northern European coast (Bevacqua and others, 2019).

Drought

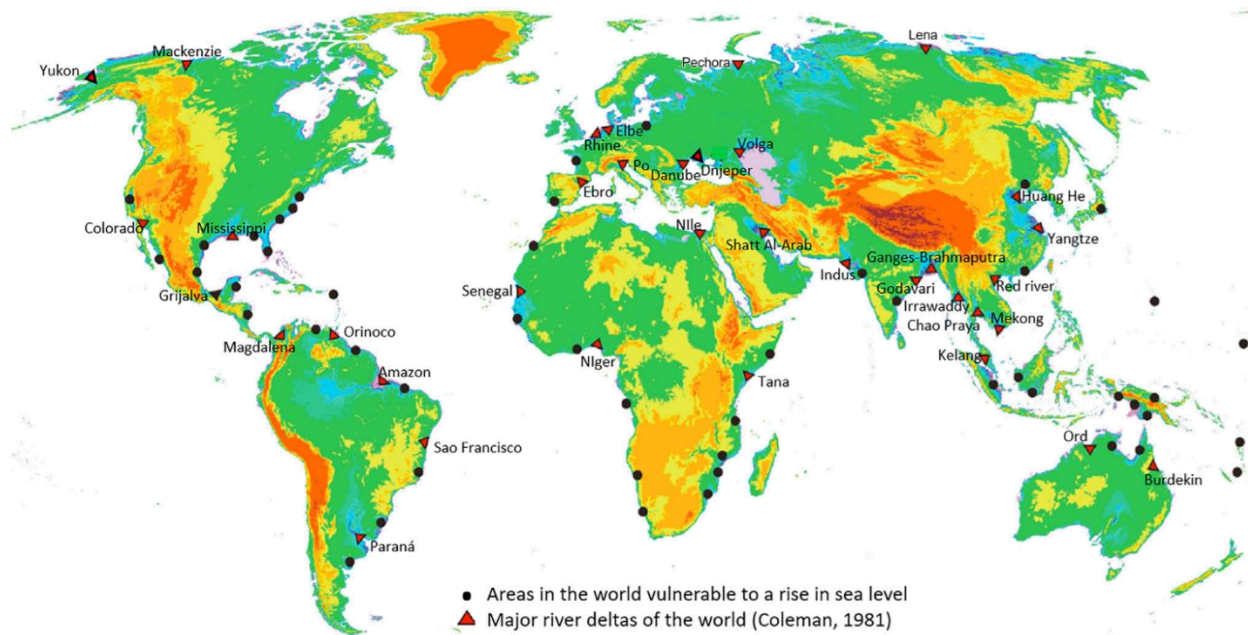
Although drought is typically considered to be a terrestrial hazard, it can have significant impacts on coastal regions, affecting various aspects of the natural and human environment (Mishra and Singh, 2010). Drought can have an impact on water resources (reduced freshwater availability and salinization of coastal aquifers) (Yihdego, 2017), on ecosystems and biodiversity (Mafi-Gholami and others, 2020) and on human activities (agriculture, industry, energy production, tourism and human health) (Miyani, 2015; Mishra and others, 2010). Droughts occur in both developed and developing countries, with significant impacts on the global ecosystem, varying from region to region. South and South-East Asian countries have been experiencing increasing droughts due to changing precipitation patterns (Miyani, 2015), while the Mediterranean, Amazon, southern Africa and Central America are projected to be the most affected regions by extreme multivariate drought in the future (Tabari and Willems, 2023; Dai, 2011 and 2013). Climate change is expected to exacerbate drought conditions, leading to more frequent and severe droughts (IPCC, 2021), while the combined effects of sea level rise and coastal flooding and drought will place further stress on coastal regions, leading to increased salinization and reduced groundwater quality (Shishaye, 2021).

Saltwater intrusion

Saltwater intrusion, or the migration of saltwater into freshwater coastal aquifers, has significant environmental impacts on coastal regions (Werner and others, 2013). The increase in water salinity has an immediate impact on drinking water quality and supplies (Moore and Joye, 2021). It also affects crop yields and soil health through biochemical changes in aquifers, which has a detrimental impact on food security in vulnerable regions (Hu and others, 2024; Tully and others, 2019). Saltwater intrusion alters coastal ecosystems, which affects vegetation and wildlife that are dependent on freshwater (Visschers and others, 2022).

Figure XIII

Global hotspots of groundwater vulnerability to saltwater intrusion and sea level rise



Source: Modified from van der Gun, 2021; Coleman, 1981.

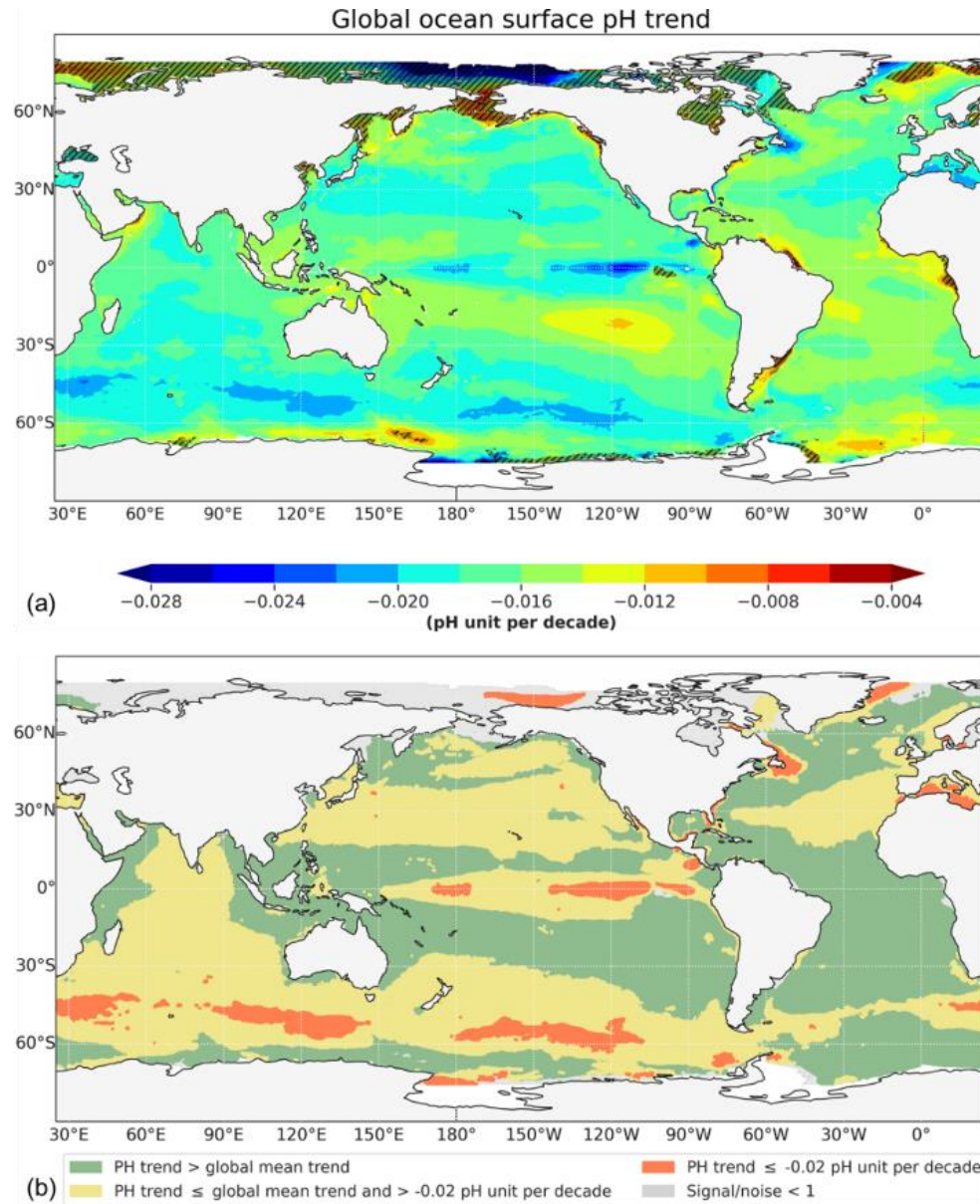
Saltwater intrusion is a global issue, affecting most coastal aquifers to varying degrees. Areas in China, India and Viet Nam are particularly vulnerable due to their low elevation and high population density, and are thus among the most studied in relevant research. Climate change is expected to enhance saltwater intrusion impacts through increased sea levels, extremes in waves and coastal flooding (OHingst and others, 2024; Werner and Simmons, 2009), while the interplay between multiple hazards (primarily identified at the terrestrial level (e.g. heavy rainfall, river flooding and droughts)) along with human activities (e.g. freshwater pumping) will probably result in unprecedented effects in already problematic coastal areas and elsewhere (Safi and others, 2018).

Ocean acidification

The ocean is a major player in the global carbon cycle and an important sink for anthropogenic carbon dioxide (CO₂), helping to moderate climate change (Gruber and others, 2019). It is highly likely that the ocean has absorbed between 20 and 30% of total anthropogenic CO₂ emissions since the 1980s (IPCC, 2019). The decrease of ocean pH is referred to as ocean acidification (IPCC, 2021). Addressing ocean acidification is among the targets of Sustainable Development Goal 14 of the 2030 Agenda for Sustainable Development.

Figure XIV

Global ocean surface pH trends



Source: von Schuckmann and others, 2024.

Note: (a): global ocean surface pH trend computed over the period 1985–2022; (b): magnitude of the pH decrease rates.

Open ocean surface pH has declined by a very likely range of 0.017–0.027 pH units per decade since the late 1980s, with the decline in surface ocean pH very likely to have already emerged from background natural variability for more than 95% of the ocean surface area (IPCC, 2019). Ocean acidification has spread deeper in the ocean (Fassbender and others, 2023), surpassing 2,000 m in depth in the northern North Atlantic and in the Southern Ocean (IPCC, 2021). Acidification, in conjunction with other climate

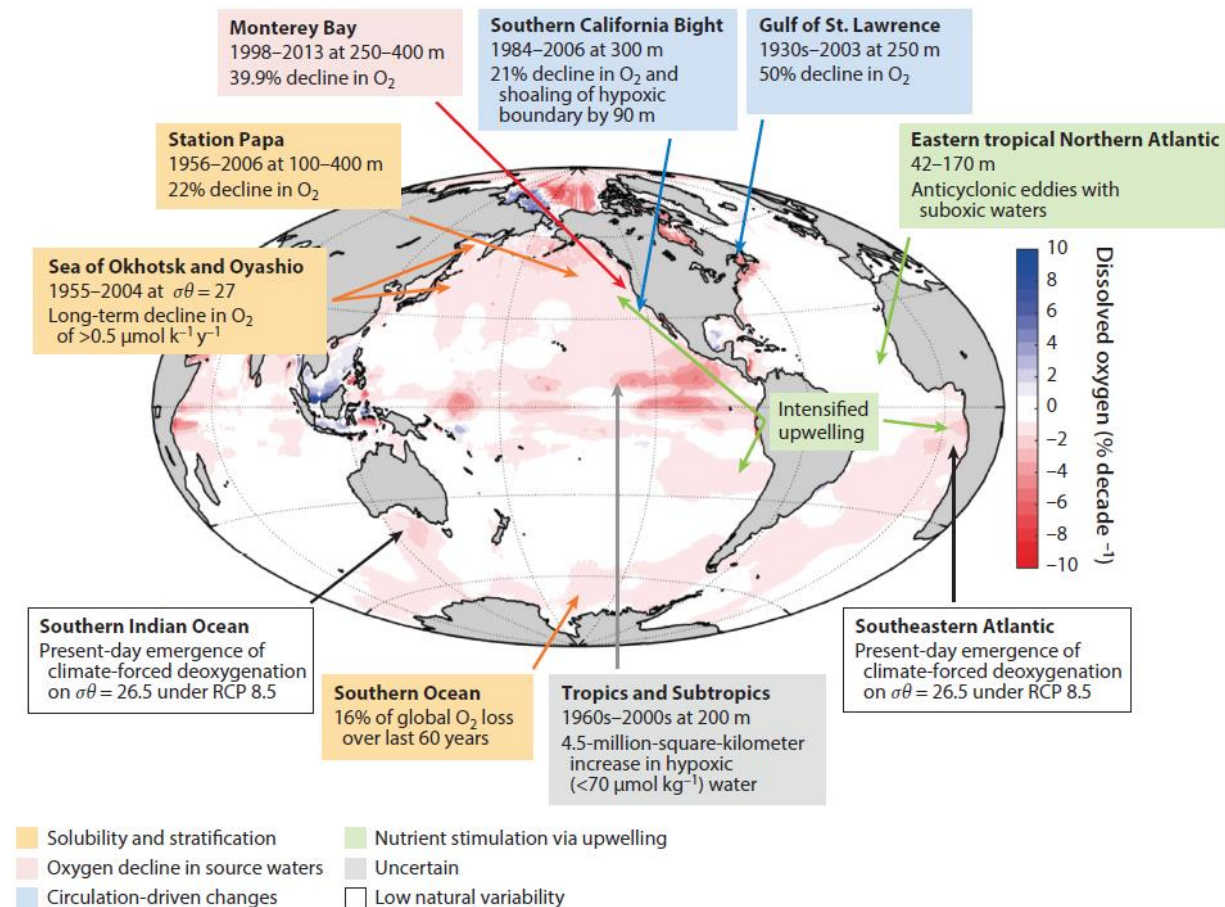
change-related environmental stresses, puts at risk many valuable ecosystem services, such as fisheries, aquaculture and shoreline protection (Doney and others, 2020; IPCC, 2022). In addition, together with ocean warming, ocean acidification threatens the future growth of coral reefs (Cornwall and others, 2021) and has diverse adverse impacts on marine biodiversity (IPCC, 2019; Teixidó and others, 2024).

Ocean deoxygenation

It is well established that oxygen loss in the ocean, known as deoxygenation, is a significant consequence of climate change and has been further intensified by other global changes. Over the past 50 to 100 years, deoxygenation has already emerged in most of the global open ocean, which has experienced an average oxygen decline of 2% or more, with even more pronounced losses in intermediate waters (100–600 m) of the North Pacific, East Pacific, tropical regions and the Southern Ocean (Levin, 2018; Oschlies and others, 2018; Breitburg and others, 2018). Natural oxygen variability has made it difficult to detect the emergence of a climate-forced signal of oxygen loss; the observed open-ocean deoxygenation and the expansion of oxygen minimum zones are attributed only in part to human influence (IPCC, 2021).

Figure XV

Representative long-term records of open ocean deoxygenation in intermediate waters superimposed on full ocean percentage change in dissolved oxygen per decade since 1960



Source: Levin, 2018.

Note: $\sigma\theta$: density surface.

Continued global ocean deoxygenation is projected to persist under most emissions scenarios, but with regional heterogeneity (IPCC, 2021). Notably, even small changes in oxygenation can have significant biological and biogeochemical effects, including for ocean productivity, nutrient cycling, carbon cycling and marine habitat (IPCC, 2019). Together with warming and acidification, deoxygenation alters ecological communities by increasing the spread of physiologically suboptimal conditions for many marine fish and invertebrates. It is well established that these and other responses have subsequently driven habitat loss, population decline, increased risks of species extirpation, and extinction and rearrangement of marine food webs (IPCC, 2022).

Figure XVI

Pathways connecting the “pressures”, “ocean hazards” and “impacts-disasters” components contained in figure I

Pressures	Ocean Hazards															
	Tsunamis	Earthquakes	Volc. Eruptions	Subsidence	Coastal Erosion	Cyclones / Meteotsunamis	Sea-level rise	Waves / Wave runup	Storm Surge / Coastal Flooding	Marine heatwaves	Glacial melt	Heavy rainfall / River flooding	Droughts	Saltwater intrusion	Acidification / Deoxygenation	
Ocean temperature						●	●	●		●	●	●			●	●
Air temperature						●				●	●	●	●	●	●	●
Wind				●				●					●	●	●	●
Precipitation								●			●	●	●	●	●	●
CO2											●					●
Time Scales	Event	●	●	●		●		●	●	●		●	●	●	●	●
	Years		●			●			●		●	●	●	●	●	●
	Decades and/or above				●	●	●	●	●		●	●	●	●	●	●
Impacts -Disasters	Loss of land	●	●		●		●	●	●		●	●				
	Loss of life	●	●	●				●	●		●	●				
	Infrastructure damage	●	●	●		●	●	●	●		●	●				
	Property damage	●	●			●	●	●	●		●	●				
	Livelihood disruption	●	●	●		●	●	●	●		●	●	●			
	Navig./Shipp. challenges	●	●	●		●	●	●	●		●	●	●			
	Tourism disruption	●	●	●		●	●	●	●	●	●	●	●			●
	Cultural heritage LD ¹	●	●	●		●	●	●	●		●	●	●			
	Habitat LD ¹	●		●		●	●	●	●		●	●	●	●	●	●
	Biodiversity LD ¹	●		●		●	●	●	●	●	●	●	●	●	●	●
	Saltwater intrusion	●		●		●	●	●	●		●	●	●	●	●	●
	Water quality issues	●	●	●		●	●	●	●		●	●	●	●	●	●
	Food systems disruption	●	●	●		●	●	●	●	●	●	●	●	●	●	●
	Coastal Erosion	●	●	●		●	●	●	●		●	●	●	●	●	●
Coastal Flooding	●	●	●		●	●	●	●	●	●	●	●	●	●	●	
World Oceans	Arctic Ocean						●			●	●					●
	North Atlantic ²	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	South Atlantic ³	●	●	●		●	●	●	●	●	●	●	●	●	●	●
	Indian Ocean ⁴			●	●	●	●	●	●	●	●	●	●	●	●	●
	North Pacific Ocean	●	●	●		●	●	●	●	●	●	●	●	●	●	●
	South Pacific Ocean	●	●	●		●	●	●	●	●	●	●	●	●	●	●
	Southern Ocean										●					●

¹ Loss/Destruction or Loss/Disruption

² Incl. Baltic Sea, Black Sea, Medit. Sea, North Sea

³ Incl. Wider Caribbean

⁴ Incl. Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden, Persian Gulf

- Light severity
- Medium/Strong severity
- Low importance
- Medium/High importance

3. Towards ocean and coastal resilience

This part of the chapter analyses strategies towards ocean and coastal resilience that serve this chapter's context of identifying pathways that connect the components "impacts-disasters" and "mitigation-management-adaptation" (see [subsect. 5B, chap. 4, including figure I](#)), referring to single- and multi-hazard assessment. It is divided into nine sub-parts. Some of the hazards presented [below](#) are grouped, as relevant strategies typically address multiple hazards. In the 58 national adaptation plans submitted, the most commonly identified climate hazard was sea level rise, along with ocean acidification, saltwater intrusion and increased sea surface temperatures (UNFCCC, 2024c). Furthermore, of the Parties that included an ocean-based measure in their national adaptation plans, 12% included reference to human- and climate-induced ocean changes, such as acidification, extreme weather events, sea level rise, storms and drought (UNFCCC, 2024a).

The "mitigation-management-adaptation" strategies presented in this part of the chapter are closely aligned with evolving international climate policy frameworks on ocean resilience (UNFCCC, 2023, 2024a,2024b). Ecosystem-based adaptation, enhanced early warning systems and risk-informed planning are prioritized as integral parts of the national adaptation plans that have been developed or are under development (UNFCCC, 2024a and 2024c). Likewise, focus on community engagement and robust governance relates to calls under the United Nations Framework Convention on Climate Change for inclusive, "whole-of-society" approaches to climate resilience.

An analysis of the efforts undertaken under the present part is presented in [figure XVII](#). Information in [figure XVII](#) reflects the assimilation of available knowledge regarding the examined strategies in the relevant literature (see also [table 1](#)). It is noted that the [figure](#) is not focused on specific technical or managerial solutions, but rather serves to divide strategies into the categories "risk reduction" and "governance/institutional/social transformation", in accordance with [Pinardi and others \(2024\)](#). [Figure XVII](#) should not be interpreted beyond its intended use, considering the uncertainties arising from such large-scale multi-hazard assessments when studying phenomena with significant local and regional variations, as well as existing knowledge gaps in relevant research. Given the above, this part of the chapter is fundamentally linked to section 4, chapter 2, and to subsections 5A and 5B of third *World Ocean Assessment*, with detailed links identified in [table 2](#).

Geophysical and geological hazards

Understanding the impacts of geohazards highlights the need for effective mitigation and adaptation strategies, including preparedness actions, improvement of building codes, development of early warning systems and land-use planning. For instance, after the Tohoku earthquake and tsunami in Japan in 2011, the Government invested heavily in building higher sea walls along the coastline to protect communities and in developing high-tech early warning systems in the country (National Research Institute for Earth Science and Disaster Resilience (NIED), 2024). On a global scale, warning services are provided by regional systems operating in different ocean basins (IOC, 2023). These systems focus on end-to-end tsunami warning and mitigation, and are coordinated by IOC of the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a global "system of systems". Communities must be aware and prepared to respond quickly to these extremely short-notice and fast-onset events (IOC, 2022; UNDRR, 2024). Earthquakes can cause extensive damage on land but also liquefaction in coastal zones and partial collapse of structures (e.g. the Loma Prieta earthquake in 1989 and its impact on the San Francisco-Oakland Bay Bridge). Following that earthquake, the public and private sectors made substantial investments in redevelopment and seismic retrofitting programmes to reduce the impact of future earthquakes and enhance earthquake resilience (Zoback, 2014).

Cyclones and meteotsunamis

When meteotsunami risk is recognized and protection is economically justified, for example for strategic infrastructure, design criteria for coastal structures and flood protection systems can be adapted to account for those events (de Jong and others, 2021). Nevertheless, in most cases, early warning remains the backbone of meteotsunami risk reduction, although key obstacles include observational challenges (limited spatial and temporal data) and modelling difficulties (accurate location and timing predictions, considering local geomorphology). Relevant benefits can be derived from

relatively small investments in existing multi-hazard coastal warning systems and emerging technologies (Vilibic and others, 2016).

Cyclone impacts are typically mitigated through different management approaches comprising risk reduction strategies and post-event response and recovery (Hoque and others, 2017). Risk reduction in particular has traditionally mostly involved tackling vulnerability and exposure of coastal assets, infrastructures and communities by means of technological instruments, such as early warning systems, and changes in urban planning and building practices. As these approaches struggle to keep pace with the increasing pressures on coastal areas, new techniques based on geoengineering principles are emerging as potential lines of development for risk reduction to address the characteristics of cyclones as a hazard factor (Miller and others, 2023). In both cases, addressing education, training, involvement of coastal communities and issues related to social acceptance and trust is key to risk reduction.

Sea level rise and glacial melt

Addressing current coastal impacts, managing future risks and preventing accelerated sea level rise after 2050 all require immediate mitigation and adaptation (Nicholls and others, 2018). The most urgent adaptation challenge is chronic flooding at high tide (IPCC, 2022). Adaptation planning and implementation needs up to 2050 are projected to increase significantly in most inhabited coastal regions (IPCC, 2019 and 2021). Risks can be anticipated and adaptation measures can be planned and implemented over the coming decades, given that adaptation capacity and governance frameworks to manage the risks of projected sea level rise typically require decades to become effective (e.g. IPCC, 2022; Haasnoot and others, 2021). Without timely action, vulnerable communities will face a reduction in adaptation options and bear disproportionate impacts (IPCC, 2022). Effective responses include decision analysis, land-use planning, public participation and conflict resolution, with the aim of charting adaptive pathways and managing governance challenges posed by sea level rise (IPCC, 2019). Furthermore, evidence-informed risk management, strengthened stakeholder dialogue and coordination, and enhanced action and support for finance, technology and capacity-building has been prioritized internationally (UNCC, 2025). It is well established that available near-term adaptation options include engineered, sediment- or ecosystem-based protection; land-use planning to reduce vulnerability; and advance (land reclamation) or retreat strategies (relocation) (IPCC, 2022; IPCC, 2019). Only avoidance and relocation can remove coastal risks for the coming decades, while other measures only delay impacts temporarily, have increasing residual risk or perpetuate risk and create ongoing legacy effects and virtually certain property and ecosystem losses (Siders and others, 2019). Large-scale relocation has immense cultural, political, social and economic costs and equity implications, which can be reduced by fast implementation of climate mitigation and adaptation policies (IPCC, 2021, 2022; Haasnoot and others, 2021). Ecosystem-based adaptation, such as planting and conserving vegetation, landward migration and sediment supply, can reduce impacts on human settlements and generate substantial co-benefits across various socioeconomic dimensions, but they require space for sediment and ecosystems and have site-specific physical limits (IPCC, 2022; Neijnsens and others, 2021; UNFCCC, 2023, 2024b).

Since the main direct impact of glacial melt is its contribution to sea level rise, strategies are largely covered by the previous paragraph). Beyond that, hazard-specific measures include using geotextiles to cover glaciers (Senese and others, 2020), creating submerged barriers or dams in front of ice sheets and glaciers (Hunt and Byers, 2019) and a wide range of other geoengineering approaches (Lockley and others, 2020).

Coastal erosion, waves and wave run-up, and storm surge and coastal flooding

Mitigating coastal erosion and flooding involves strategies aimed at protecting shorelines, preserving natural landscapes, minimizing the impacts of shoreline retreat on coastal infrastructure and reducing the hazards posed by rising sea levels, storm surges and high tides on coastal communities (IPCC, 2022). Risk mitigation and adaptation strategies should ideally operate across multiple timescales to be effective. In the short term, this includes implementing early warning systems and emergency response protocols and maintaining existing protective infrastructure (Singhvi and others, 2022; Winter and others, 2020). In the medium term, the focus could be shifted to the upgrading of infrastructure, the consideration of nature-based solutions, such as mangrove restoration, and the development of comprehensive coastal zone management plans (Andersson and others, 2022). Long-term strategies may require transformative approaches, such as relocation from high-risk areas (Revell and others, 2021), major infrastructure redesign and strategic rethinking

of land-use planning, that account for projected sea level rise and increased storm intensity and frequency (IPCC, 2022). Successful implementation requires careful alignment of these temporal scales along adaptation pathways (Haasnoot and others, 2013) with an appropriate multilevel governance framework that spans from emergency response to long-term socioeconomic planning, while ensuring continuity across political cycles (Rocle and others, 2021; Bisaro and others, 2020). Successful risk reduction strategies depend heavily on community buy-in, local knowledge integration and social justice considerations. Vulnerable coastal communities, particularly those with limited resources, often face disproportionate risks while being the least resilient to coastal flooding and erosion (IPCC, 2022).

Marine heatwaves

Well-established impacts of marine heatwaves have been reported for different types of ecosystem, particularly warm-water coral reefs, rocky shores, kelp systems, estuaries, lagoons, mangroves, seagrasses, sandy beaches, semi-enclosed seas, shelf seas and the Arctic region (IPCC, 2022). Socioeconomic systems (including those of Indigenous Peoples and local communities) that rely on these ecosystems are threatened by marine heatwave impacts on incomes, on economic sectors, such as fisheries and tourism, and, in the case of coral reefs, on shoreline protection from waves (IPCC, 2022). Management and adaptation strategies include the use of high-resolution data, forecasts and early warning systems to better prepare for marine heatwave and collect data on their effects (Holbrook and others, 2020; McAdam and others, 2023). These data can be used to guide economic sectors, such as aquaculture, in selecting new sites in order to reduce the likelihood of exposure to marine heatwaves (Sandersen and others, 2020; Liu and others, 2014), and can support active restoration efforts (Fox and others, 2021; Aoki and others, 2020). Early management intervention and shifts in management approaches (e.g. quotas or stock assessments and flexible harvesting strategies) can also help to limit the impacts of marine heatwaves (Le Bris and others, 2018; Pershing and others, 2018; Holbrook and others, 2020). Furthermore, marine protected areas (MPAs) and no-take zones, in addition to terrestrial protection surrounding vulnerable coastal ecosystems, cannot prevent marine heatwaves from occurring. Nevertheless, depending on the location and adherence by people to restrictions on certain activities, the cumulative effect of other stressors on vulnerable ecosystems can be reduced, thereby potentially helping to enhance the rate of recovery of marine life (IPCC, 2022; Arafeh-Dalmau and others, 2023). Moreover, MPAs are more likely to buffer the impacts of marine heatwaves if climate change responses are considered in their design (Smith and others, 2021).

Heavy rainfall and river flooding

Mitigation-management-adaptation strategies against heavy rainfall and river flooding extend beyond coastal zones. Regarding “traditional” defence infrastructure, reinforcing levees, dykes and barriers would protect low-lying coastal areas against coastal, river or compound flooding (Couasnon and others, 2020; Moftakhari and others, 2017), while retention basins and river regulation works would contribute to reducing downstream flooding risks (Winarta and others, 2019). Nature-based solutions (wetlands, mangroves, salt marshes and coastal dunes) can also significantly improve flood resilience, while at the same time enhancing water quality and supporting estuarine biodiversity (Bevacqua and others, 2019; Maiolo and others, 2020). Furthermore, adopting integrated watershed management approaches can prove highly beneficial by controlling erosion, run-off and pollutant loads travelling downstream (Ge and others, 2021), while climate-adaptive infrastructure and planning in coastal cities can enhance the resilience of coastal communities (Wang and others, 2021). Improvements in monitoring, forecasting and early warning system development, along with strategic investment in community preparedness and response, will always be integral to coastal resilience (Figlus, 2022; Shen and others, 2019).

Droughts and saltwater intrusion

Droughts and saltwater intrusion are closely associated in terms of their impacts and therefore call for aligned strategies to strengthen ocean and coastal resilience. In general, aligning water management, land use policies and coastal zone management should be a key requirement for effective water resources management from catchment to coast. Water conservation measures and efficient crop selection and irrigation practices can alleviate stress on water resources during drought periods (Cook and others, 2018; Tabari and Willems, 2023), while sustainable groundwater management and coastal infrastructure, such as barriers and subsurface dams, can mitigate saltwater intrusion (Werner and others, 2013; Ferguson and Gleeson, 2012). Coastal land use zoning in vulnerable areas and managed aquifer recharge can also be

reliable management strategies (Chong and others, 2014), as can the controlled release of freshwater from upstream reservoirs (Moore and Joye, 2021). Furthermore, ecosystem-based adaptation (restoring and conserving coastal ecosystems), a shift towards drought- and salinity-tolerant crops in agriculture, and community engagement and education on sustainable water use and irrigation practices can all contribute to resilient coastal ecosystems and communities (Vissschers and others, 2022; Mafi-Gholami and others, 2020).

Ocean acidification and ocean deoxygenation

Ocean acidification and ocean deoxygenation generate extensive impacts across ocean-related sectors, including coastal communities, fisheries, mariculture and tourism, and adversely affect all categories of marine ecosystem services – regulating, provisioning and supporting (IPCC, 2022). Adapting to ocean acidification requires enhancing the resilience of marine ecosystems, supporting affected industries and developing adaptive management practices (Pelletier and others, 2020; Trebilco and others, 2022; Woods and others, 2022). With regard to marine heatwaves, the protection and restoration of resilient ecosystems, such as seagrass, mangroves, kelp forests, and other benthic habitats can help to buffer the effects of acidification by absorbing CO₂ and creating more stable local conditions (Falkenberg and others 2021; Voolstra and others, 2023). Evidence-based support for marine species adaptation, such as selective breeding and diversification of the major aquaculture species, also plays an increasing role (Boudry and others, 2021, Tan and others, 2020). Ocean acidification also affects human health and well-being in the context of malnutrition and poisoning, respiratory issues, mental health impacts and the development of medical resources (Falkenberg and others, 2020). Adapting to ocean changes will require efforts to manage socioecological systems adaptively (Cinner and others, 2019), including for fisheries and aquaculture, by iteratively changing management practices through biodiversity conservation and local management (Doubleday and Connell, 2018; Arkhipkin and others, 2015; Billé and others, 2013; Arafah-Dalmau and others, 2023).

Figure XVII

Pathways connecting the “impacts-disasters” and “mitigation-management-adaptation” components contained in figure I

		Risk Reduction								Governance / Institutional / Social Transformation						
Mitigation-Management-Adaptation		Monitoring, Forecasting and Early Warning Systems	Warning Dissemination & Communication	Preparedness & Response	Sectoral medium to long term planning (zoning, infrastructure)	Nature-Based Solutions	Digital Twins	Managed Retreat	Infrastructure Upgrading / Climate-proofing / Building Codes	Marine and Maritime Spatial Planning	Governance Framework	Disaster Recovery Planning	Equitable Coastal Resilience	Government Investments, Financing & Insurance	Capacity Building	Corporate Social Responsibility
Impacts -Disasters	Loss of land	●	●	●	●	●	●	●	●			●		●		
	Loss of life	●	●	●	●	●	●	●	●			●		●	●	
	Infrastructure damage	●	●	●	●	●	●	●	●	●		●		●		●
	Property damage	●	●	●	●	●	●	●	●	●		●	●	●		
	Livelihood disruption	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Navig./Shipp. challenges	●	●				●		●	●				●		
	Tourism disruption				●		●	●	●	●		●		●	●	●
	Cultural heritage LD ¹					●	●		●			●	●	●	●	
	Habitat LD ¹					●	●	●		●	●	●		●		●
	Biodiversity LD ¹	●				●	●	●		●	●	●		●		●
	Saltwater intrusion	●		●	●	●	●		●	●		●		●		
	Water quality issues	●	●	●	●	●	●		●	●	●	●	●	●	●	●
	Food systems disruption		●	●	●	●	●		●	●	●	●	●	●	●	●
	Coastal Erosion	●			●	●	●	●	●	●		●		●	●	●
Coastal Flooding	●	●	●	●	●	●	●	●			●		●	●		

¹ Loss/Destruction or Loss/Disruption

● Weak connection & expected impact

● Medium/Strong connection & expected impact

Source: Prepared by the writing team.

Note: Division by “risk reduction” and governance/institutional/social transformation” adopted from [Pinardi and others, 2024](#).

Table 1

Extended literature by chapter part

Sub-Section	Extended Literature
5B4.3.1	Doocy and others (2013), Espinosa and others (2017)
5B4.3.2	Daniel (2014), Jaiswal and Wald (2013), Skufina and others (2019)
5B4.3.3	-
5B4.3.4	-
5B4.3.5	Nawarat and others (2024)
5B4.3.6	Wang and Lin (2020), Earl-Spurr and others (2023), Lamers and others (2023), Heidarzadeh and Rabinovich (2021), Kim and Omira (2024), Raible and others (2021), Gaertner and others (2018), Hoque and others (2017), Catto (2016), Leroux and others (2018), Heming and others (2019), Wang and others (2016), Catto and others (2019), Knutson and others (2019), Hart (2003)
5B4.3.7	Dusek and others (2019), Vilibic and others (2016), Huang and others (2022), Angove and others (2021)
5B4.3.8	-
5B4.3.9	Xu and Perrie (2012), Wong and others (2019), Dissanayake and others (2021), Hemer and others (2010, 2013), Meucci and others (2023), Shimura and other (2015), Young and others (2011), Hsu and others (2023), Lee and others (2022)
5B4.3.10	-
5B4.3.11	Harris and others (2018)
5B4.3.12	Zemp and others (2020), Sraneo and Heimbach (2023), Khan and others (2022), Zhou and others (2021), Cape and others (2019), Sejr and others (2022)
5B4.3.13	Wood and others (2024), Yuan and others (2024), Couasnon and others (2020), Wang and others (2021), Howley and others (2018), Cardoso and others (2008), Shore and others (2021), Draut and others (2009), Milner and others (2018), Dankers and others (2014), Eccles and others (2019)
5B4.3.14	Fakhruddin and Eslamian (2017), Thomsen and Green (2019), Lake (2011), Ravindra and others (2010), Oh and others (2023), Dai (2011, 2013)
5B4.3.15	Chong and others (2014), Hu and others (2024), Bui and others (2024), Vu and others (2024), Datta and others (2009), Ferguson and Gleeson (2012)
5B4.3.16	-
5B4.3.17	Levin (2003), Sperling and others (2016), Orio and others (2021)
5B4.4.1	-
5B4.4.2	Lewis and others (2023), Angove and others (2021), Lamers and others (2023)
5B4.4.3	Huss and others (2021), Xie and others (2023)
5B4.4.4	Vousdoukas and others (2018, 2020), Dedekorkut-Howes and others (2020), Casella and others (2014), Polk and Eulie (2018)
5B4.4.5	-
5B4.4.6	Dankers and others (2014), Barbier and others (2011), Howley and others (2018), Mansour Abdelkareem (2024), Ward and others (2018), Wahl and others (2015)
5B4.4.7	Hingst and others (2024), Bhattachan and others (2018), Chang and others (2019), Hu and others (2024), Murgulet and Tick (2008), Miyan (2015), Ravindra and others (2010), Osemwegie and Boko-Koiadia (2019)
5B4.4.8	-

Source: Prepared by the writing team.

Table 2

Links to other sections and chapters of the third *World Ocean Assessment*

		Links to WOA III Chapters/Sections					
Pressures	Ocean temperature	S4.C1	S4.C2	S4.C3			
	Air temperature	S4.C1	S4.C2	S4.C3			
	Wind	S4.C1	S4.C2	S4.C3			
	Precipitation	S4.C1	S4.C2	S4.C3			
	CO2	S4.C1	S4.C2	S4.C3			
Ocean Hazards	Tsunamis		S4.C3				
	Earthquakes		S4.C3				
	Volc. Eruptions		S4.C3				
	Subsidence		S4.C3				
	Coastal Erosion	S4.C1	S4.C3				
	Cyclones / Meteotsunamis	S4.C1	S4.C3				
	Sea-level rise	S4.C1	S4.C3				
	Waves /	S4.C1	S4.C3				
	Storm Surge /	S4.C1	S4.C3				
	Marine heatwaves	S4.C1	S4.C3				
	Glacial melt	S4.C1	S4.C3				
	Heavy rainfall /	S4.C1	S4.C3				
	Droughts	S4.C1	S4.C3				
	Saltwater intrusion	S4.C1	S4.C3				
Acidification / Deoxygenation	S4.C1	S4.C3					
Impacts -Disasters	Loss of land	S4.C1	S4.C3	S5A.C9			
	Loss of life	S4.C1	S4.C3	S5B.C2			
	Infrastructure damage	S4.C1	S4.C3	S5A.C3	S5A.C9		
	Property damage	S4.C1	S4.C3	S5A.C9			
	Livelihood disruption	S4.C1	S4.C3	S5A.C3	S5B.C3		
	Navig./Shipp. challenges	S4.C1	S4.C3	S5A.C6	S5A.C9		
	Tourism disruption	S4.C1	S4.C3	S5A.C2	S5A.C4	S5A.C9	S5B.C3
	Cultural heritage Loss/Destruction	S4.C1	S4.C3	S5A.C7	S5A.C9		
	Habitat Loss/Destruction	S4.C1	S4.C3	S4.C5	S5A.C9	S5B.C1	S5B.C2
	Biodiversity Loss/Disruption	S4.C1	S4.C3	S4.C4	S5A.C5	S5B.C1	S5B.C2
	Saltwater intrusion	S4.C1	S4.C3				
	Water quality issues	S4.C1	S4.C3	S5A.C8	S5B.C2		
	Food systems disruption	S4.C1	S4.C3	S5A.C1	S5A.C5	S5B.C2	
	Coastal Erosion	S4.C1	S4.C3	S5A.C9			
Coastal Flooding	S4.C1	S4.C3	S5A.C9				
Mitigation-Management-Adaptation	Monitoring, Forecasting and Early Warning Systems						
	Warning Dissemination & Communication						
	Preparedness & Response						
	Sectoral medium to long term planning						
	Nature-Based Solutions						
	Digital Twins						
	Managed Retreat						
	Infrastructure Upgrading / Climate-proofing / Building Codes	S4.C2	S5A.C*	S5B.C*			
	Marine and Maritime Spatial Planning						
	Governance Framework						
	Disaster Recovery Planning						
	Equitable Coastal Resilience						
	Government Investments, Financing & Insurance						
	Capacity Building						
Corporate Social Responsibility							

* Potential link to all Chapters of this Section

Source: Prepared by the writing team.

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