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Oceans and Coastal Ecosystems and Their Services

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Executive Summary

Ocean and coastal ecosystems support life on Earth and many aspects of human well-being. Covering two-thirds of the planet, the ocean hosts vast biodiversity and modulates the global climate system by regulating cycles of heat, water and elements, including carbon. Marine systems are central to many cultures, and they also provide food, minerals, energy and employment to people. Since previous assessments[1], new laboratory studies, field observations and process studies, a wider range of model simulations, Indigenous knowledge, and local knowledge have provided increasing evidence on the impacts of climate change on ocean and coastal systems, how human communities are experiencing these impacts, and the potential solutions for ecological and human adaptation.

Observations: vulnerabilities and impacts

Anthropogenic climate change has exposed ocean and coastal ecosystems to conditions that are unprecedented over millennia (*high confidence*[2]), and this has greatly impacted life in the ocean and along its coasts (*very high confidence*). Fundamental changes in the physical and chemical characteristics of the ocean acting individually and together are changing the timing of seasonal activities (*very high confidence*), distribution (*very high confidence*) and abundance (*very high confidence*) of oceanic and coastal organisms, from microbes to mammals and from individuals to ecosystems, in every region. Evidence of these changes is apparent from multi-decadal observations, laboratory studies and mesocosms, as well as meta-analyses of published data. Geographic range shifts of marine species generally follow the pace and direction of climate warming (*high confidence*): surface warming since the 1950s has shifted marine taxa and communities poleward at an average (mean ± *very likely*[3] range) of 59.2 ± 15.5 km per decade (*high confidence*), with substantial variation in responses among taxa and regions. Seasonal events occur 4.3 ± 1.8 d to 7.5 ± 1.5 d earlier per decade among planktonic organisms (*very high confidence*) and on average 3 ± 2.1 d earlier per decade for fish (*very high confidence*). Warming, acidification and deoxygenation are altering ecological communities by increasing the spread of physiologically suboptimal conditions for many marine fish and invertebrates (*medium confidence*). These and other responses have subsequently driven habitat loss (*very high confidence*), population declines (*high confidence*), increased risks of species extirpations and extinctions (*medium confidence*) and rearrangement of marine food webs (*medium to high confidence*, depending on ecosystem). {3.2, 3.3, 3.3.2, 3.3.3, 3.3.3.2, 3.4.2.1, 3.4.2.3–3.4.2.8, 3.4.2.10, 3.4.3.1, 3.4.3.2, 3.4.3.3, Box 3.2}

Marine heatwaves lasting weeks to several months are exposing species and ecosystems to environmental conditions beyond their tolerance and acclimation limits (*very high confidence*). WGI AR6 concluded that marine heatwaves are more frequent (*high confidence*), more intense and longer (*medium confidence*) since the 1980s, and since at least 2006 *very likely* attributable to anthropogenic climate change. Open-ocean, coastal and shelf-sea ecosystems, including coral reefs, rocky shores, kelp forests, seagrasses, mangroves, the Arctic Ocean and semi-enclosed seas, have recently undergone mass mortalities from marine heatwaves (*very high confidence*). Marine heatwaves, including well-documented events along the west coast of North America (2013–2016) and east coast of Australia (2015–2016, 2016–2017 and 2020), drive abrupt shifts in community composition that may persist for years (*very high confidence*), with associated biodiversity loss (*very high confidence*), collapse of regional fisheries and aquaculture (*high confidence*) and reduced capacity of habitat-forming species to protect shorelines (*high confidence*). {WGI AR6 Chapter 9, 3.2.2.1, 3.4.2.1–3.4.2.5, 3.4.2.7, 3.4.2.10, 3.4.2.3, 3.4.3.3.3, 3.5.3}

At local to regional scales, climate change worsens the impacts on marine life of non-climate anthropogenic drivers, such as habitat degradation, marine pollution, overfishing and overharvesting, nutrient enrichment and introduction of non-indigenous species (*very high confidence*). Although impacts of multiple climate and non-climate drivers can be beneficial or neutral to marine life, most are detrimental (*high confidence*). Warming exacerbates coastal eutrophication and associated hypoxia, causing 'dead zones' (*very high confidence*), which drive severe impacts on coastal and shelf-sea ecosystems (*very high confidence*), including mass mortalities, habitat reduction and fisheries disruptions (*medium confidence*). Overfishing exacerbates effects of multiple climate-induced drivers on predators at the top of the marine food chain (*medium confidence*). Urbanisation and associated changes in freshwater and sediment dynamics increase the vulnerability of coastal ecosystems like sandy beaches, salt marshes and mangrove forests to sea level rise and changes in wave energy (*very high confidence*). Although these non-climate drivers confound attribution of impacts to climate change, adaptive, inclusive and evidence-based management reduces the cumulative pressure on ocean and coastal ecosystems, which will decrease their vulnerability to climate change (*high confidence*). {3.3, 3.3.3, 3.4.2.4–3.4.2.8, 3.4.3.4, 3.5.3, 3.6.2, Cross-Chapter Box SLR in Chapter 3}

Climate-driven impacts on ocean and coastal environments have caused measurable changes in specific industries, economic losses, emotional harm and altered cultural and recreational activities around the world (*high confidence*). Climate-driven movement of fish stocks is causing commercial, small-scale, artisanal

1 Previous IPCC assessments include the IPCC Fifth Assessment Report (AR5) (IPCC, 2013; IPCC, 2014b; IPCC, 2014c; IPCC, 2014d), the Special Report on Global Warming of 1.5°C (SR1.5) (IPCC, 2018), the Special Report on Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2019b) and the IPCC Sixth Assessment Report Working Group I (WGI AR6).

2 In this Report, the following summary terms are used to describe the available evidence: limited, medium or robust; and for the degree of agreement: low, medium or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and is typeset in italics (e.g., *medium confidence*). For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

3 In this Report, the following terms are used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10% and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100% and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics (e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.

and recreational fishing activities to shift poleward and diversify harvests (*high confidence*). Climate change is increasing the geographic spread and risk of marine-borne pathogens like *Vibrio* sp. (*very high confidence*), which endanger human health and decrease provisioning and cultural ecosystem services (*high confidence*). Interacting climate-induced drivers and non-climate drivers are enhancing movement and bioaccumulation of toxins and contaminants into marine food webs (*medium evidence, high agreement*), and increasing salinity of coastal waters, aquifers and soils (*very high confidence*), which endangers human health (*very high confidence*). Combined climate-induced drivers and non-climate drivers also expose densely populated coastal zones to flooding (*high confidence*) and decrease physical protection of people, property and culturally important sites (*very high confidence*). {3.4.2.10, 3.5.3, 3.5.5, 3.5.5.3, 3.5.6, Cross-Chapter Box SLR in Chapter 3}

Projections: vulnerabilities, risks and impacts

Ocean conditions are projected to continue diverging from a pre-industrial state (*virtually certain*), with the magnitude of warming, acidification, deoxygenation, sea level rise and other climate-induced drivers depending on the emission scenario (*very high confidence*), and to increase risk of regional extirpations and global extinctions of marine species (*medium confidence*). Marine species richness near the equator and in the Arctic is projected to continue declining, even with less than 2°C warming by the end of the century (*medium confidence*). In the deep ocean, all global warming levels will cause faster movements of temperature niches by 2100 than those that have driven extensive reorganisation of marine biodiversity at the ocean surface over the past 50 years (*medium confidence*). At warming levels beyond 2°C by 2100, risks of extirpation, extinction and ecosystem collapse escalate rapidly (*high confidence*). Paleorecords indicate that at extreme global warming levels (>5.2°C), mass extinction of marine species may occur (*medium confidence*). {Box 3.2, 3.2.2.1, 3.4.2.5, 3.4.2.10, 3.4.3.3, Cross-Chapter Box PALEO in Chapter 1}

Climate impacts on ocean and coastal ecosystems will be exacerbated by increases in intensity, reoccurrence and duration of marine heatwaves (*high confidence*), in some cases, leading to species extirpation, habitat collapse or surpassing ecological tipping points (*very high confidence*). Some habitat-forming coastal ecosystems including many coral reefs, kelp forests and seagrass meadows, will undergo irreversible phase shifts due to marine heatwaves with global warming levels >1.5°C and are at high risk this century even in <1.5°C scenarios that include periods of temperature overshoot beyond 1.5°C (*high confidence*). Under SSP1-2.6, coral reefs are at risk of widespread decline, loss of structural integrity and transitioning to net erosion by mid-century due to increasing intensity and frequency of marine heatwaves (*very high confidence*). Due to these impacts, the rate of sea level rise is *very likely* to exceed that of reef growth by 2050, absent adaptation. Other coastal ecosystems, including kelp forests, mangroves and seagrasses, are vulnerable to phase shifts towards alternate states as marine heatwaves intensify (*high confidence*). Loss of kelp forests are expected to be greatest at the low-latitude warm edge of species' ranges (*high confidence*). {3.4.2.1, 3.4.2.3, 3.4.2.5, 3.4.4}

Escalating impacts of climate change on marine life will further alter biomass of marine animals (*medium confidence*), the timing of seasonal ecological events (*medium confidence*) and the geographic ranges of coastal and ocean taxa (*medium confidence*), disrupting life cycles (*medium confidence*), food webs (*medium confidence*) and ecological connectivity throughout the water column (*medium confidence*). Multiple lines of evidence suggest that climate-change responses are *very likely* to amplify up marine food webs over large regions of the ocean. Modest projected declines in global phytoplankton biomass translate into larger declines of total animal biomass (by 2080–2099 relative to 1995–2014) ranging from (mean ± *very likely* range) –5.7 ± 4.1% to –15.5 ± 8.5% under SSP1-2.6 and SSP5-8.5, respectively (*medium confidence*). Projected declines in upper-ocean nutrient concentrations, *likely* associated with increases in stratification, will reduce carbon export flux to the mesopelagic and deep-sea ecosystems (*medium confidence*). This will lead to a decline in the biomass of abyssal meio- and macrofauna (by 2081–2100 relative to 1995–2014) by –9.8% and –13.0% under SSP1-2.6 and SSP5-8.5, respectively (*limited evidence*). By 2100, 18.8 ± 19.0% to 38.9 ± 9.4% of the ocean will *very likely* undergo a change of more than 20 d (advances and delays) in the start of the phytoplankton growth period under SSP1-2.6 and SSP5-8.5, respectively (*low confidence*). This altered timing increases the risk of temporal mismatches between plankton blooms and fish spawning seasons (*medium to high confidence*) and increases the risk of fish-recruitment failure for species with restricted spawning locations, especially in mid-to-high latitudes of the Northern Hemisphere (*low confidence*). Projected range shifts among marine species (*medium confidence*) suggest extirpations and strongly decreasing tropical biodiversity. At higher latitudes, range expansions will drive increased homogenisation of biodiversity. The projected loss of biodiversity ultimately threatens marine ecosystem resilience (*medium to high confidence*), with subsequent effects on service provisioning (*medium to high confidence*). {3.2.2.3, 3.4.2.10, 3.4.3.1–3.4.3.5, 3.5, WGI AR6 Section 2.3.4.2.3}

Risks from sea level rise for coastal ecosystems and people are *very likely* to increase tenfold well before 2100 without adaptation and mitigation action as agreed by Parties to the Paris Agreement (*very high confidence*). Sea level rise under emission scenarios that do not limit warming to 1.5°C will increase the risk of coastal erosion and submergence of coastal land (*high confidence*), loss of coastal habitat and ecosystems (*high confidence*) and worsen salinisation of groundwater (*high confidence*), compromising coastal ecosystems and livelihoods (*high confidence*). Under SSP1-2.6, most coral reefs (*very high confidence*), mangroves (*likely*, *medium confidence*) and salt marshes (*likely*, *medium confidence*) will be unable to keep up with sea level rise by 2050, with ecological impacts escalating rapidly beyond 2050, especially for scenarios coupling high emissions with aggressive coastal development (*very high confidence*). Resultant decreases in natural shoreline protection will place increasing numbers of people at risk (*very high confidence*). The ability to adapt to current coastal impacts, cope with future coastal risks and prevent further acceleration of sea level rise beyond 2050 depends on immediate implementation of mitigation and adaptation actions (*very high confidence*). {3.4.2.1, 3.4.2.4, 3.4.2.5, 3.4.2.6, 3.5.5.3, Cross-Chapter Box SLR in Chapter 3}

Climate change will alter many ecosystem services provided by marine systems (*high confidence*), but impacts to human communities will depend on people's overall vulnerability, which is strongly influenced by local context and development pathways (*very high confidence*). Catch composition and diversity of regional fisheries will change (*high confidence*), and fishers who are able to move, diversify and leverage technology to sustain harvests decrease their own vulnerability (*medium confidence*). Management that eliminates overfishing facilitates successful future adaptation of fisheries to climate change (*very high confidence*). Marine-dependent communities, including Indigenous Peoples and local peoples, will be at increased risk of losing cultural heritage and traditional seafood-sourced nutrition (*medium confidence*). Without adaptation, seafood-dependent people face increased risk of exposure to toxins, pathogens and contaminants (*high confidence*), and coastal communities face increasing risk from salinisation of groundwater and soil (*high confidence*). Early-warning systems and public education about environmental change, developed and implemented within the local and cultural context, can decrease those risks (*high confidence*). Coastal development and management informed by sea level rise projections will reduce the number of people and amount of property at risk (*high confidence*), but historical coastal development and policies impede change (*high confidence*). Current financial flows are globally uneven and overall insufficient to meet the projected costs of climate impacts on coastal and marine social–ecological systems (*very high confidence*). Inclusive governance that (a) accommodates geographically shifting marine life, (b) financially supports needed human transformations, (c) provides effective public education and (d) incorporates scientific evidence, Indigenous knowledge and local knowledge to manage resources sustainably shows greatest promise for decreasing human vulnerability to all of these projected changes in ocean and coastal ecosystem services (*very high confidence*). {3.5.3, 3.5.5, 3.5.6, 3.6.3, Box 3.4, Cross-Chapter Box ILLNESS in Chapter 2, Cross-Chapter Box SLR in Chapter 3}

Solutions, trade-offs, residual risk, decisions and governance

Humans are already adapting to climate-driven changes in marine systems, and while further adaptations are required even under low-emission scenarios (*high confidence*), transformative adaptation will be essential under high-emission scenarios (*high confidence*). Low-emission scenarios permit a wider array of feasible, effective and low-risk nature-based adaptation options (e.g., restoration, revegetation, conservation, early-warning systems for extreme events and public education) (*high confidence*). Under high-emission scenarios, adaptation options (e.g., hard infrastructure for coastal protection, assisted migration or evolution, livelihood diversification, migration and relocation of people) are more uncertain and require transformative governance changes (*high confidence*). Transformative climate adaptation will reinvent institutions to overcome obstacles arising from historical precedents, reducing current barriers to climate adaptation in cultural, financial and governance sectors (*high confidence*). Without transformation, global inequities will *likely* increase between regions (*high confidence*) and conflicts between jurisdictions may emerge and escalate. {3.5, 3.5.2, 3.5.5.3, 3.6, 3.6.2.1, 3.6.3.1, 3.6.3.2, 3.6.3.3, 3.6.4.1, 3.6.4.2, 3.6.5, Cross-Chapter Box SLR in Chapter 3, Cross-Chapter Box ILLNESS in Chapter 2}

Available adaptation options are unable to offset climate-change impacts on marine ecosystems and the services they provide (*high confidence*). Adaptation solutions implemented at appropriate scales, when combined with ambitious and urgent mitigation measures, can meaningfully reduce impacts (*high confidence*). Increasing evidence from implemented adaptations indicates that multi-level governance, early-warning systems for climate-associated marine hazards, seasonal and dynamic forecasts, habitat restoration, ecosystem-based management, climate-adaptive management and sustainable harvesting tend to be both feasible and effective (*high confidence*). Marine protected areas (MPAs), as currently implemented, do not confer resilience against warming and heatwaves (*medium confidence*) and are not expected to provide substantial protection against climate impacts past 2050 (*high confidence*). However, MPAs can contribute substantially to adaptation and mitigation if they are designed to address climate change, strategically implemented and well governed (*high confidence*). Habitat restoration limits climate-change-related loss of ecosystem services, including biodiversity, coastal protection, recreational use and tourism (*medium confidence*), provides mitigation benefits on local to regional scales (e.g., via carbon-storing 'blue carbon' ecosystems) (*high confidence*) and may safeguard fish-stock production in a warmer climate (*limited evidence*). Ambitious and swift global mitigation offers more adaptation options and pathways to sustain ecosystems and their services (*high confidence*). {3.4.2, 3.4.3.3, 3.5, 3.5.2, 3.5.3, 3.5.5.4, 3.5.5.5, 3.6.2.1, 3.6.2.2, 3.6.2.3, 3.6.3.1, 3.6.3.2, 3.6.3.3, 3.6.5, Figure 3.24, Figure 3.25}

Nature-based solutions for adaptation of ocean and coastal ecosystems can achieve multiple benefits when well designed and implemented (*high confidence*), but their effectiveness declines without ambitious and urgent mitigation (*high confidence*). Nature-based solutions, such as ecosystem-based management, climate-smart conservation approaches (i.e., climate-adaptive fisheries and conservation) and coastal habitat restoration, can be cost-effective and generate social, economic and cultural co-benefits while contributing to the conservation of marine biodiversity and reducing cumulative anthropogenic drivers (*high confidence*). The effectiveness of nature-based solutions declines with warming; conservation and restoration alone will be insufficient to protect coral reefs beyond 2030 (*high confidence*) and to protect mangroves beyond the 2040s (*high confidence*). The multidimensionality of climate-change impacts and their interactions with other anthropogenic stressors calls for integrated approaches that identify trade-offs and synergies across sectors and scales in space and time to build resilience of ocean and coastal ecosystems and the services they deliver (*high confidence*). {3.4.2, 3.5.2, 3.5.3, 3.5.5.3, 3.5.5.4, 3.5.5.5, 3.6.2.2, 3.6.3.2, 3.6.5, Figure 3.25, Table 3.SM.6}

Ocean-focused adaptations, especially those that employ nature-based solutions, address existing inequalities, and incorporate just and inclusive decision-making and implementation processes, support the UN Sustainable Development Goals (SDGs) (*high confidence*). There are predominantly positive synergies between adaptation options for Life Below Water (SDG14), Climate Action (SDG13) and social, economic and governance SDGs (SDG1–12, 16–17) (*high confidence*), but the ability of ocean adaptation to contribute to the

SDGs is constrained by the degree of mitigation action (*high confidence*). Furthermore, existing inequalities and entrenched practices limit effective and just responses to climate change in coastal communities (*high confidence*). Momentum is growing towards transformative international and regional governance that will support comprehensive, equitable ocean and coastal adaptation while also achieving SDG14 (*robust evidence*), without compromising achievement of other SDGs. {3.6.4.0, 3.6.4.2, 3.6.4.3, Figure 3.26}.