

## REVIEW SUMMARY

## OCEANOGRAPHY

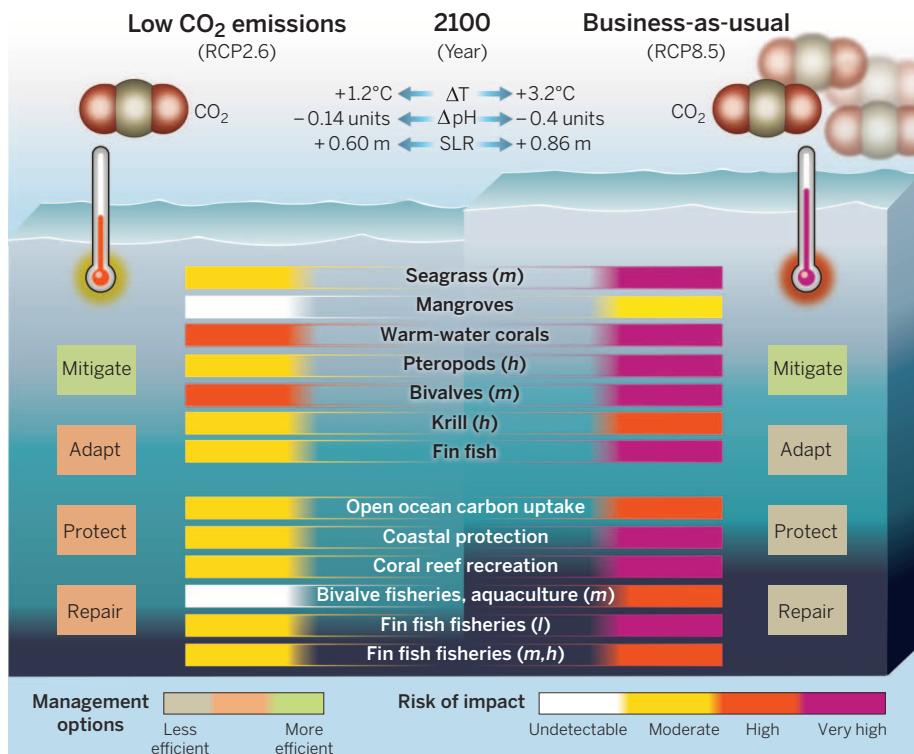
# Contrasting futures for ocean and society from different anthropogenic CO<sub>2</sub> emissions scenarios

J.-P. Gattuso\* *et al.*

**BACKGROUND:** Although the ocean moderates anthropogenic climate change, this has great impacts on its fundamental physics and chemistry, with important consequences for ecosystems and people. Yet, despite the ocean's critical role in regulating climate—and providing food security and livelihoods for millions of people—international climate negotiations have only minimally considered impacts on the ocean. Here, we evaluate changes to the ocean and its ecosystems, as well as to the goods and services they provide, under two contrasting CO<sub>2</sub> scenarios: the current high-emissions trajectory (Representative Concentration Pathway 8.5, RCP8.5)

and a stringent emissions scenario (RCP2.6) consistent with the Copenhagen Accord of keeping mean global temperature increase below 2°C in the 21st century. To do this, we draw on the consensus science in the latest assessment report of the Intergovernmental Panel on Climate Change and papers published since the assessment.

**ADVANCES:** Warming and acidification of surface ocean waters will increase proportionately with cumulative CO<sub>2</sub> emissions (see figure). Warm-water corals have already been affected, as have mid-latitude seagrass, high-latitude pteropods and krill, mid-latitude bivalves, and



**Changes in ocean physics and chemistry and impacts on organisms and ecosystem services according to stringent (RCP2.6) and high business-as-usual (RCP8.5) CO<sub>2</sub> emissions scenarios.** Changes in temperature ( $\Delta T$ ) and pH ( $\Delta \text{pH}$ ) in 2090 to 2099 are relative to preindustrial (1870 to 1899). Sea level rise (SLR) in 2100 is relative to 1901. RCP2.6 is much more favorable to the ocean, although important ecosystems, goods, and services remain vulnerable, and allows more-efficient management options. *l*, *m*, *h*: low, mid-, and high latitudes, respectively.

fin fishes. Even under the stringent emissions scenario (RCP2.6), warm-water corals and mid-latitude bivalves will be at high risk by 2100. Under our current rate of emissions, most marine organisms evaluated will have very high risk of impacts by 2100 and many by 2050. These results—derived from experiments, field observations, and modeling—are consistent with evidence from high-CO<sub>2</sub> periods in the paleorecord.

Impacts to the ocean's ecosystem services follow a parallel trajectory. Services such as coastal protection and capture fisheries are already affected by ocean warming and acidification. The risks of impacts to these services increase with continued emissions: They are

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predicted to remain moderate for the next 85 years for most services under stringent emission reductions, but the business-as-usual scenario (RCP8.5) would put all ecosystem services we considered at high or very high risk over the same time frame. These impacts will be cumulative or synergistic with other human impacts, such as overexploitation of living resources, habitat destruction, and pollution. Fin fisheries at low latitudes, which are a key source of protein and income for millions of people, will be at high risk.

**OUTLOOK:** Four key messages emerge. First, the ocean strongly influences the climate system and provides important services to humans. Second, impacts on key marine and coastal organisms, ecosystems, and services are already detectable, and several will face high risk of impacts well before 2100, even under the low-emissions scenario (RCP2.6). These impacts will occur across all latitudes, making this a global concern beyond the north/south divide. Third, immediate and substantial reduction of CO<sub>2</sub> emissions is required to prevent the massive and mostly irreversible impacts on ocean ecosystems and their services that are projected with emissions greater than those in RCP2.6. Limiting emissions to this level is necessary to meet stated objectives of the United Nations Framework Convention on Climate Change; a substantially different ocean would result from any less-stringent emissions scenario. Fourth, as atmospheric CO<sub>2</sub> increases, protection, adaptation, and repair options for the ocean become fewer and less effective.

The ocean provides compelling arguments for rapid reductions in CO<sub>2</sub> emissions and eventually atmospheric CO<sub>2</sub> drawdown. Hence, any new global climate agreement that does not minimize the impacts on the ocean will be inadequate. ■

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## REVIEW

## OCEANOGRAPHY

# Contrasting futures for ocean and society from different anthropogenic CO<sub>2</sub> emissions scenarios

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The ocean moderates anthropogenic climate change at the cost of profound alterations of its physics, chemistry, ecology, and services. Here, we evaluate and compare the risks of impacts on marine and coastal ecosystems—and the goods and services they provide—for growing cumulative carbon emissions under two contrasting emissions scenarios. The current emissions trajectory would rapidly and significantly alter many ecosystems and the associated services on which humans heavily depend. A reduced emissions scenario—consistent with the Copenhagen Accord's goal of a global temperature increase of less than 2°C—is much more favorable to the ocean but still substantially alters important marine ecosystems and associated goods and services. The management options to address ocean impacts narrow as the ocean warms and acidifies. Consequently, any new climate regime that fails to minimize ocean impacts would be incomplete and inadequate.

**A**tmospheric carbon dioxide (CO<sub>2</sub>) has increased from 278 to 400 parts per million (ppm) over the industrial period and, together with the increase of other greenhouse gases, has driven a series of major environmental changes. The global ocean (including enclosed seas) acts as a climate integrator that (i) absorbed 93% of Earth's additional heat since the 1970s, offsetting much atmospheric warming but increasing ocean temperature and sea level; (ii) captured 28% of anthropogenic CO<sub>2</sub> emissions since 1750, leading to ocean acidification; and (iii) accumulated nearly all water resulting from melting glaciers and ice sheets, hence furthering the rise in sea level. Thus, the ocean moderates anthropogenic climate change at the cost of major changes in its fundamental chemistry and physics. These changes in ocean properties profoundly affect species' biogeography and phenology, as well as ecosystem dynamics and biogeochemical cycling (1–3). Such changes inevitably affect the ecosystem services on which humans depend. The ocean represents more than 90% of Earth's habitable space, hosts 25% of eukaryotic species (4), provides 11% of global animal protein consumed by humans (5), protects coastlines, and more. Simply put, the ocean plays a particularly important role in the livelihood and food security of hundreds of millions of people.

The United Nations Framework Convention on Climate Change (UNFCCC) aims to stabilize atmospheric greenhouse gas concentrations “at a level that would prevent dangerous anthropogenic interference with the climate system ... within a time-frame sufficient to allow ecosystems to adapt

naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner” (6). According to the Copenhagen Accord (7), meeting these goals requires that the increase in average global surface temperature be less than 2°C over the preindustrial average. However, despite the ocean's critical role in global ecosystem goods and services, international climate negotiations have only minimally considered ocean impacts, especially those related to ocean acidification (8). Accordingly, highlighting ocean-related issues is now crucial, given that even achieving the +2°C target (set on global temperature) would not prevent many climate-related impacts upon the ocean (9).

This paper first summarizes the key findings of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) and, given the ongoing acceleration of climate change research, adds newer literature to assess the impacts of global change—including ocean warming, acidification, deoxygenation, and sea level rise—linking ocean physics and chemistry to biological processes, ecosystem functions, and human activities. Second, it builds on scenarios based on the range of cumulative fossil carbon emissions and the IPCC Representative Concentration Pathways (RCP) RCP2.6 and RCP8.5, contrasting two potential futures. RCP2.6 reflects the UNFCCC target of global temperature staying below +2°C, whereas RCP8.5 reflects the current trajectory of business-as-usual CO<sub>2</sub> emissions. Third, this paper provides a broad discussion of the options society has for addressing ocean impacts and ends with key messages that provide

further compelling arguments for ambitious CO<sub>2</sub> emissions reduction pathways.

## Changes in ocean physics and chemistry

Ocean changes resulting from anthropogenic emissions include long-term increase in temperature down to at least 700 m, increased sea level, and a decrease in Arctic summer sea ice (Fig. 1 and Table 1) (10). Other radiatively active agents—such as ozone, methane, nitrous oxide, and aerosols—do not affect the ocean as much as CO<sub>2</sub>. Setting it apart, CO<sub>2</sub> accounts for two or more times the warming attributed to the non-CO<sub>2</sub> greenhouse gases by 2100 (11) and causes ocean acidification. The uptake of excess anthropogenic CO<sub>2</sub> by the ocean increases the partial pressure of carbon dioxide (P<sub>CO<sub>2</sub></sub>) and dissolved inorganic carbon while decreasing pH and the saturation state of seawater with respect to the calcium carbonate minerals aragonite and calcite, both being critical drivers of solubility of shells and skeletons (12). Rising global CO<sub>2</sub> also further exacerbates the nearshore biogeochemical changes associated with land use change, nutrient inputs, aquaculture, and fishing (13).

Both the magnitude and rate of the anthropogenic carbon perturbation exceed the extent of natural variation over the last millennium and

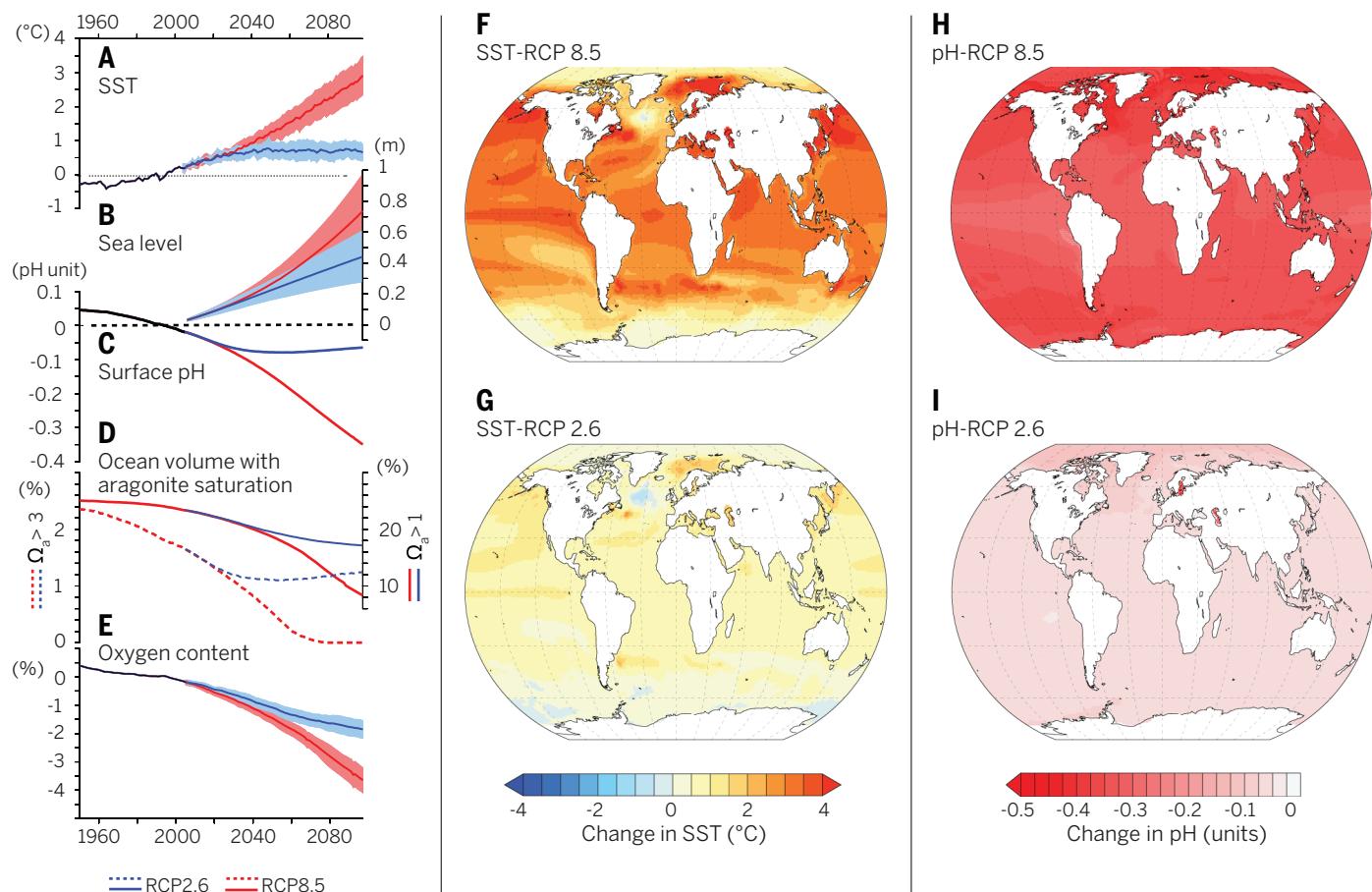
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**Fig. 1. Environmental changes over the industrial period and the 21st century for a business-as-usual scenario and a stringent emissions scenario consistent with the UNFCCC target of increase in global surface temperature by 2°C.** (A to E) Changes in globally averaged (A) SST, (B) sea level, (C) sea surface pH (total pH scale), (D) ocean volume (in % of total ocean volume) with saturation state of calcium carbonate in aragonitic form ( $\Omega_a$ ) above 1 and above 3, and (E) dissolved oxygen. RCP8.5, red lines; RCP2.6, blue lines. Maps show the 21st century changes in SST (F and G) and in sea surface pH (H and I) for RCP8.5 (top) and RCP2.6 (bottom), respectively. All projected values represent ensemble mean values from the Coupled Model Intercomparison Project 5 [CMIP5 (23)].

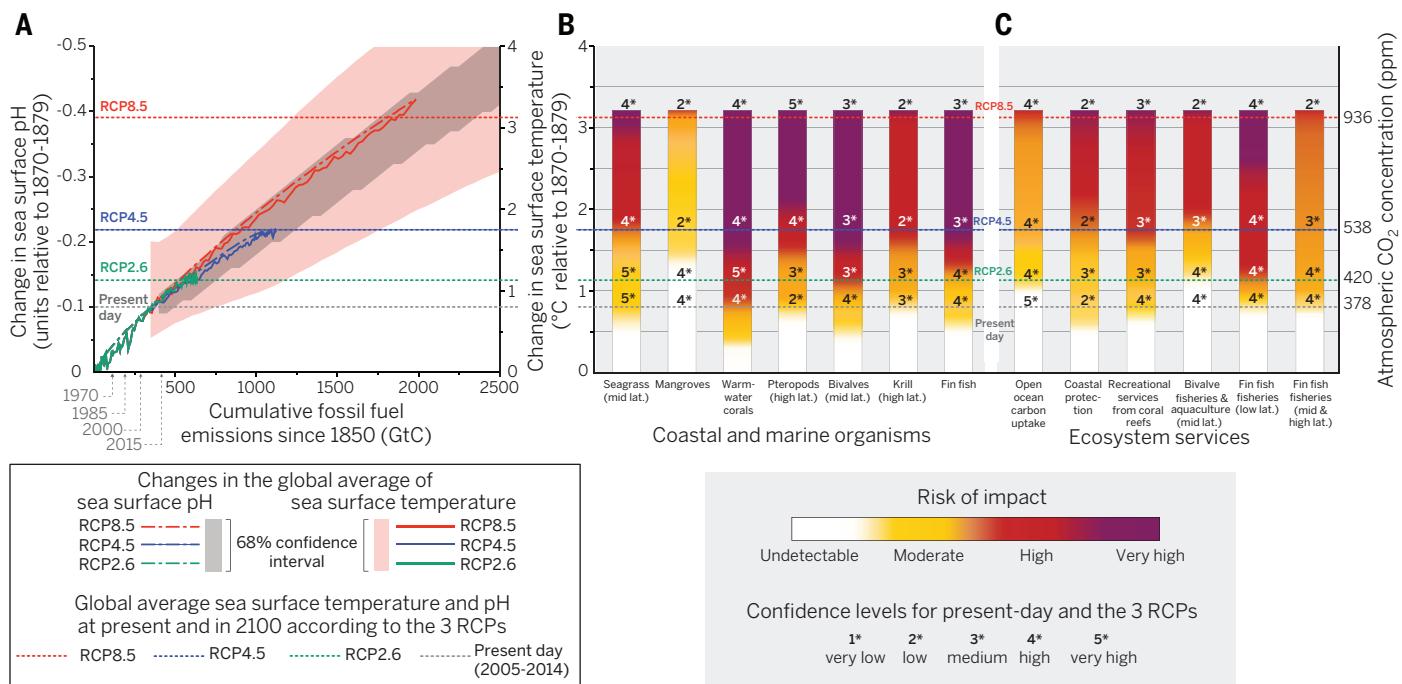
**Table 1. Changes in SST, pH, oxygen content, sea level, and ocean volume with respect to aragonite for CMIP5 models and several RCP emissions scenarios.** After Bopp et al. (23) except sea level rise (28).

	ΔSST (°C)	ΔpH (units)	ΔO <sub>2</sub> content (%)	Sea level (m)	Vol. Ω <sub>a</sub> >1 (%)	Vol. Ω <sub>a</sub> >3 (%)
<i>Changes relative to 1990–1999</i>						
2090–2099 (RCP8.5)	2.73	-0.33	-3.48	0.67	9.4	0
2090–2099 (RCP4.5)	1.28	-0.15	-2.37	0.49	15	0.57
2090–2099 (RCP2.6)	0.71	-0.07	-1.81	0.41	17.3	1.22
1990s (1990–1999)	0	0	0	0	24	1.82
Preindustrial (1870–1899)	-0.44	0.07	-	-	25.6	2.61
Preindustrial (1870–1879)	-0.38	0.07	-	-	25.6	2.67
<i>Changes relative to 1870–1899 (except sea level, relative to 1901)</i>						
2090–2099 (RCP8.5)	3.17	-0.40	-	0.86	-	-
2090–2099 (RCP4.5)	1.72	-0.22	-	0.68	-	-
2090–2099 (RCP2.6)	1.15	-0.14	-	0.60	-	-
2010s (2010–2019)	0.83	-0.11	-	-	-	-
Past 10 years (2005–2014)	0.72	-0.10	-	0.19*	-	-
1990s (1990–1999)	0.44	-0.07	-	-	-	-
Preindustrial (1870–1899)	0	0	-	0	-	-

\*Value for 2010 obtained from instrumental records.

over glacial-interglacial time scales (14–16). Variability of pH in coastal waters is considerably larger than that in the open ocean, partly driven by upwelling (17), freshwater input (18), eutrophication (19) and biogeochemical processes (20). Anthropogenic trends in biogeochemical variables—notably in pH,  $P_{CO_2}$ , and the saturation of calcite and aragonite—emerge from the noise of natural variability much faster than sea surface temperature (SST) (21). The combined changes in these parameters will be distinguishable from natural fluctuations in 41% of the global ocean within a decade (22), and the change in aragonite saturation over the industrial period has been more than five times greater than natural variability over the past millennium in many regions (15).

The condition of the future ocean depends on the amount of carbon emitted in the coming decades (Figs. 1 and 2A). The current suite of earth system models illustrate the contrast between future oceans under the high-carbon-emission, business-as-usual RCP8.5 versus the stringent emission-mitigation RCP2.6 (23, 24). The more stringent scenario allows less than one-sixth of 21st century emissions expected under business-as-usual. Between 2012 and 2100, compatible



**Fig. 2. Observed impact and risk scenarios of ocean warming and acidification for important organisms and critical ecosystem services.** “Present-day” (gray dotted line) corresponds to the period from 2005 to 2014. Impact levels are for the year 2100 under the different projections shown and do not consider genetic adaptation, acclimatization, or human risk reduction strategies (mitigation and societal adaptation). RCP4.5 is shown for illustrative purposes as an intermediate scenario between the business-as-usual high-emissions scenario (RCP8.5) and the stringent reduction scenario (RCP2.6). (A) Changes in global average SST and pH versus cumulative fossil fuel emissions. Realized fossil emissions (26) are indicated for different years below the horizontal axis, whereas the lines are based on allowable emissions estimated

from ensemble means of the CMIP5 simulations for the industrial period and the 21st century following RCP2.6, RCP4.5, and RCP8.5 (23). Cumulative emission of 1000 GtC causes a global SST change of about 1.7°C and a surface pH change of about -0.22 units. The colored shadings indicate the 68% confidence interval for pH (gray) and SST (pink) from observation-constrained, probabilistic projections using 55 multi-gas emissions scenarios (24). (B) Risk of impacts resulting from elevated CO<sub>2</sub> on key organisms that are well documented in the literature. (C) Risk of impacts resulting from elevated CO<sub>2</sub> on critical ecosystem services. The levels of confidence in the risk levels synthesize the author team’s judgments (see materials and methods) about the validity of findings as determined through evaluation of evidence and agreement (157).

cumulative carbon emissions from fossil fuel use are 1685 gigatons of carbon (GtC) and 270 GtC for the two RCPs, respectively (10, 25). This is in addition to the 375 and 180 GtC already emitted by 2011 by fossil fuel and land use, respectively (25). Because carbon emissions were 10 GtC in 2013 (26), fast and massive emission reductions are required to keep global surface temperature below the 2°C target of the Copenhagen Accord. Carbon emissions would need to be even lower if the ocean absorbs less excess CO<sub>2</sub> than is currently predicted. Indeed, the ocean’s effectiveness in absorbing CO<sub>2</sub> decreases with increasing emissions: the fraction of anthropogenic emissions absorbed by the ocean in the 21st century is projected to decline from 56% for RCP2.6 to 22% for RCP8.5 (27).

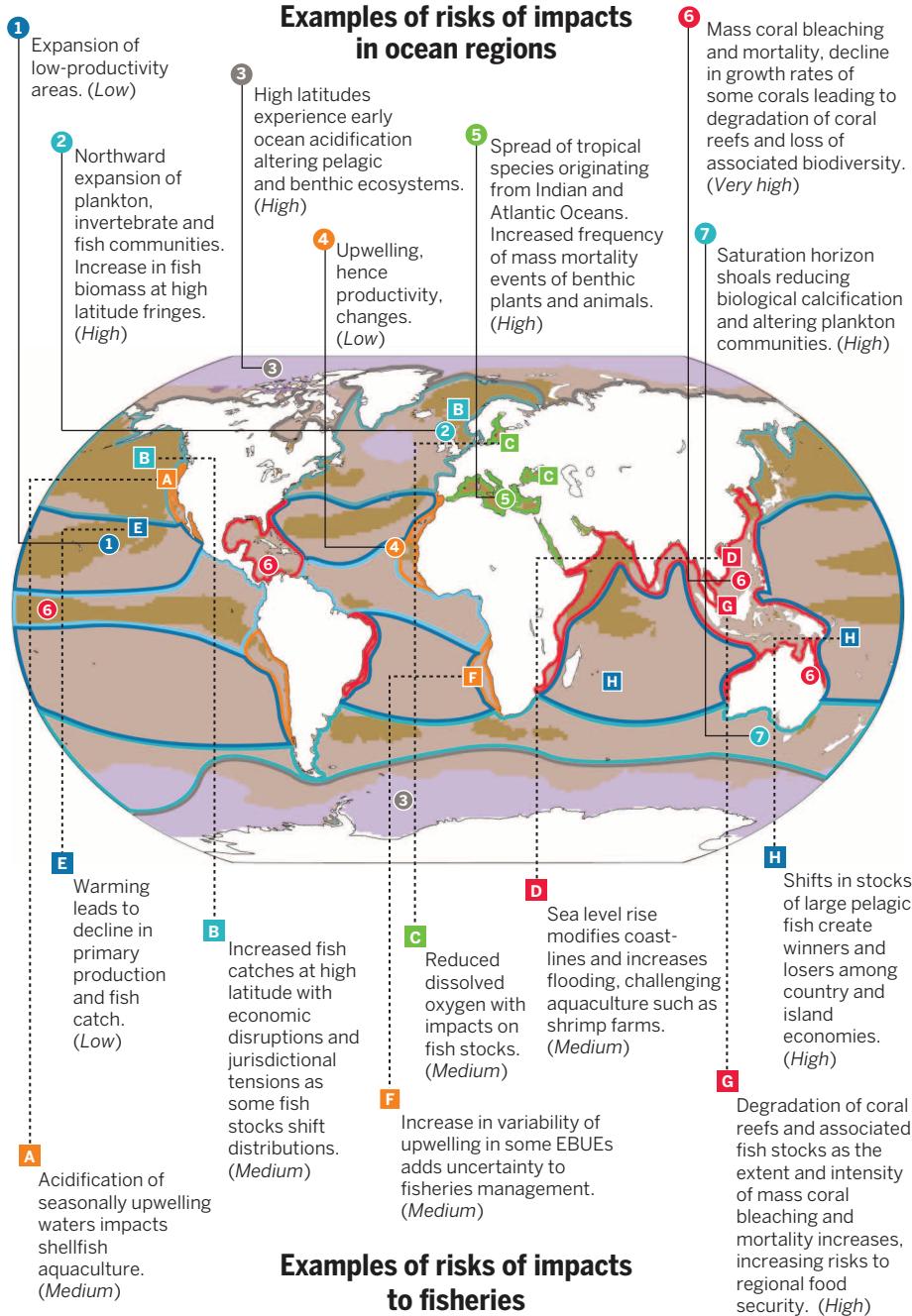
Ocean physics and chemistry will be quite different under these two emissions scenarios, although differences between the two trajectories will not be apparent until 2035. In 2100, the ocean will be much warmer and have a lower pH under RCP8.5 than under RCP2.6 (Fig. 1): The 21st century global mean change in SST differs by nearly a factor of 4 (mean  $\pm$  1 SD:  $2.73 \pm 0.72^\circ\text{C}$  versus  $0.71 \pm 0.45^\circ\text{C}$ ), whereas global surface pH changes range from  $-0.33 \pm 0.003$  units to  $-0.07 \pm 0.001$  units). By 2100, the average global

increase in mean sea level relative to preindustrial is projected to be 0.86 m for RCP8.5 and 0.60 m for RCP2.6 (28). By 2300, it will be less than 1 m for RCP2.6 and from 1 to over 3 m for RCP8.5 (10). Generally, an increase in stratification, linked to sea-surface warming and freshening, is projected; this tends to slow ocean carbon uptake and nutrient supply to the surface (29).

CO<sub>2</sub> emissions also affect the deep ocean, although the responses are delayed by the surface-to-deep transport time and continue for centuries even after carbon emissions cease (30). The volume of ocean water that is supersaturated by more than a factor of 3 with respect to aragonite ( $\Omega_a > 3$ ) is projected to completely vanish over the course of the century for RCP8.5 and to decrease from 2% to 1.25% of the ocean volume for RCP2.6 (Fig. 1 and Table 1). Conversely, the volume occupied by undersaturated water ( $\Omega_a < 1$ ) that is corrosive to unprotected calcium carbonate shells and skeletons expands from 76% of the whole ocean volume in the 1990s to 91% in 2100 with RCP8.5 and to only 83% with RCP2.6. The whole ocean oxygen inventory is consistently projected to decrease (RCP8.5:  $-3.45 \pm 0.44\%$ ; RCP2.6:  $-1.81 \pm 0.31\%$ ) with largest changes in the subsurface mid-latitude regions. However, it remains unclear whether, and to what extent,

low-oxygen regions will expand and whether the observed expansion of oxygen minimum zones over recent decades resulted from direct anthropogenic perturbation or was caused by natural variability (31, 32).

Projections of ocean warming and acidification in coastal systems follow the general trends of global and regional IPCC models but have lower confidence values because of larger contributions of processes other than CO<sub>2</sub> uptake (3). Projected regional changes vary, with the largest sea-surface warming in the North Pacific, the tropical East Pacific, and in parts of the Arctic and the largest surface pH decrease in the Arctic (Figs. 1 and 3). By 2100, 69% of the surface ocean will warm by more than 1.5°C and acidify by more than -0.2 pH units relative to preindustrial under RCP8.5 as opposed to less than 1% under RCP2.6 (Fig. 3). The largest absolute decrease in aragonite saturation is projected for the tropical ocean, partly modulated by variability within coral reef sites (33, 34). Seasonally undersaturated conditions are already present in the northeastern Pacific and the California upwelling system (17) and in the Arctic Ocean (35) and expected for the Southern Ocean (36). pH reductions at the sea floor below 500-m depth, which includes biodiversity hot spots such as deep-sea canyons and seamounts, are



**Fig. 3. Regional changes in the physical system and associated risks for natural and human-managed systems.** Projected changes in SST ( $\Delta SST$ ) and pH ( $\Delta pH$ ) in 2090–2099 relative to pre-industrial under the RCP2.6 and RCP8.5 scenarios are displayed in different colors on the map. The major ocean regions are indicated as well as examples of risks for natural systems and fisheries [modified from (1)]. Text in parentheses specifies the level of confidence (157).

projected to exceed 0.2 units (the likely bound of natural variability over the past hundreds of thousands of years) by 2100 in close to 23% of North Atlantic deep-sea canyons and 8% of seamounts under RCP8.5—including sites proposed as marine protected areas (37).

In summary, the carbon that we emit today will change the earth system irreversibly for many generations to come (10). The ocean's content of carbon, acidity, and heat as well as sea level will continue to increase long after atmospheric CO<sub>2</sub> is stabilized. These irreversible changes increase with increasing emissions (Fig. 2), underscoring the urgency of near-term carbon emission reduction if ocean warming and acidification are to be kept at moderate levels.

### Effects on biological processes and ecosystems

Organisms and ecosystems are changing in response to ocean warming, acidification, and deoxygenation. The inherent difficulty of distinguishing climate signals from natural variability (38), and of accounting for genetic adaptation (39), makes documenting these shifts challenging, but nevertheless broad anthropogenic impacts are evident (Figs. 2B and 3).

### Warming

Species' range shifts, usually following a shift in isotherms or temperature extremes, are a key consequence of ocean warming (40). Recent studies strongly reiterate that many species—including various invertebrates, commercially important fish species, and marine mammals—are undergoing phenological and geographical shifts as a result of warming (41, 42). Organisms move at different rates, up to 400 km per decade, as they track temperature changes and local climate velocities according to their ecological niches (43, 44). These shifts will continue with projected ocean warming (42, 45), causing potentially permanent changes to ecosystems, including local extinctions (42), while simultaneously producing novel assemblages (46). Responses to changing temperature depend on species' specific windows of thermal tolerance and are positively related to the degree of warming. Exceeding these limits can affect growth, body size, behavior, immune defense, feeding, and reproductive success (2), although species' individual tolerances vary. Globally, poleward range shifts of more than 800 species of exploited marine fish and invertebrates projected under RCP8.5 are 65% faster than those under RCP2.6 by mid-21st century relative to the years 2000s (42). There is medium confidence that animals adapted to a wide range of temperatures will cope better with future conditions, whereas tropical and polar specialists are at greatest risk (2). Changes are not synchronous across trophic levels; alterations in body sizes within food webs (47) and in food web composition (48) have been reported. Recent experimental studies suggest that some species may adapt to warming projected under RCP8.5 [e.g., (49, 50)], but biogeographical shifts restrict adaptive potential and the small number

of species- and population-scale studies limit the ability to generalize the importance of genetic adaptation in moderating impacts.

Reef-building corals are extremely vulnerable to warming (1, 2, 51). Warming causes mass mortality of warm-water corals through bleaching as well as through biotic diseases, resulting in declines in coral abundance and biodiversity. Coral reefs can recover from bleaching events when thermal stress is minimal and of short duration (52). However, ocean warming and acidification are expected to act synergistically to push corals and coral reefs into conditions that are unfavorable for coral reef ecosystems (53). There is limited agreement and low confidence on the potential for corals to adapt to rapid warming. Most coral species have clearly adapted to warm environments (54, 55) although the time scale of adaptation is likely to be long given the relatively lengthy generation times of corals [3 to 100 years (56)]. Recent studies have shown short-term acclimation and adaptation in some fast-growing species (57) and suggested that some genetic mechanisms may allow faster rates of change (58). It is, however, doubtful that corals will be able to adapt quickly enough to maintain populations under most emissions scenarios (56, 59, 60), especially where temperature keeps increasing over time (RCP4.5 and higher). Temperature is also an important determinant of deep-sea coral distribution, although less is known about how deep coral communities respond to thermal stress (61). The consensus is that adaptive responses of organisms will have little chance to keep current ecosystems unchanged if ocean temperature and chemistry are not stabilized, giving marine ecosystems the time needed to adapt to the new, stable environmental conditions.

### Ocean acidification

Organisms producing calcium carbonate shells and skeletons experience the strongest negative impacts from ocean acidification (62). Responses to future levels of ocean acidification expected by 2100 under RCP8.5 include reduced calcification, reduced rates of repair, and weakened calcified structures, but responses are species-specific [e.g., (63)]. Reproductive success, early life-stage survival, feeding rate, and stress-response mechanisms may also be affected (2). Most studies have investigated the effects of ocean acidification on isolated organisms; far less is known about the effects on communities and ecosystems.

Few studies measure present-day acidification effects in natural settings. However, recent field observations show a decrease in coccolith thickness over the past 12 years in the Mediterranean (64) and dissolution of live pteropod shells in the California Current system and Southern Ocean, both areas that experience significant anthropogenic acidification (65, 66). Recent investigations have also begun to report community-level responses, for example, in phytoplanktonic (67, 68), bacterial (69), seagrass (70), and algal (71) communities. Decreases in net calcification, at least partly because of ocean acidification, have also been observed in a coral reef over 1975 to 2008

(72), and conditions are already shifting some coral reefs to net erosion (73).

Most studies have investigated phenotypically plastic responses in relatively short-term, single-generation experiments and therefore did not consider the potential for transgenerational response and genetic adaptation (74). Studies published since the AR5 have expanded on the longer-term responses to ocean acidification and have found that transgenerational and evolutionary responses can partly mitigate adverse effects, for example, in phytoplankton (75), planktonic crustaceans (76), sea urchins (77), and fish (78).

### Deoxygenation

Expanding oxygen minimum zones benefits microbes and life forms adapted to hypoxia while restricting the ranges of most other species (2), with eutrophication from coastal pollution exacerbating the problem, resulting in organic matter increasing metabolic rates in deeper coastal areas (79). Moreover, higher temperatures increase species' sensitivity to hypoxia (80), limiting the depth distribution of fish and invertebrates not adapted to hypoxic conditions (81) and leading to community-level shifts to smaller Eukarya, Bacteria, and Archaea under conditions of diminished O<sub>2</sub> (82). Conversely, hypoxia-adapted species are likely to benefit, as illustrated by the range-expansion of a squid adapted to hypoxia (83).

### Multiple drivers

Investigations of single drivers can produce misleading inferences about organismal responses in a multivariate natural environment because interactive (additive, synergistic, or antagonistic) effects often are not predictable from single-driver studies. This is a major source of uncertainty for projections (39), but several recent studies have better characterized interactions among some drivers. Changes in temperature and pH, such as those projected under RCP8.5 for the year 2100, can have synergistic negative effects on species growth, survival, fitness, calcification, and development (84–88). In some cases, hypoxic conditions can mediate negative effects of ocean acidification (89, 90); however, ocean acidification and hypoxia increase heat sensitivity and vice versa (2), and oxygen loss combined with warming is projected to contract metabolically viable habitats of marine animals on a global scale (91). Growing evidence also suggests that interactions with other environmental factors—such as irradiance, nutrient availability, geographic location, and species community composition—can strongly modulate the biological effects of warming, ocean acidification, and hypoxia (68, 92–95).

Few studies addressed the potential for genetic adaptation to multiple drivers, but the phytoplankton *Emiliania huxleyi* can adapt to simultaneous warming and acidification (49). Other direct human impacts (such as fishing) can reduce the adaptive capacity of marine species and ecosystems to CO<sub>2</sub>-related impacts. For example, fishing reduces species diversity, simplifies the trophic food web, and increases ecosystem sensitivity to climate change (96). Because relatively little

is known on the interacting effects of environmental factors and the complexity of the marine food web, it is premature to make ecosystem-wide projections. However, impacts on keystone species and ecosystem engineers of three-dimensional habitats are likely to shift whole communities (97).

### Present-day impact and future risks

The observed impacts and future additional risks resulting from ocean warming and acidification vary by organism and ecosystem (Fig. 2B). Warm-water corals are already affected, as are mid-latitude seagrass, high-latitude pteropods and krill, mid-latitude bivalves, and finfish. If CO<sub>2</sub> levels are kept to the RCP2.6 scenario, by 2100 the risk of impact increases to “high” for warm-water corals and mid-latitude bivalves. Projections with RCP8.5 indicate very high risk of impact on most marine organisms considered, except mangrove. Avoiding very high levels of risk requires limiting the increase in global surface temperature between 1990 and 2100 to below 2°C and the increase in SST below ~1.2°C. These risks of impact, based on perturbation experiments, field observations, and modeling, are consistent with the paleorecord, which indicates mass extinctions triggered by carbon perturbation events such as at the Permo-Triassic boundary [at a rate slower than the present one (98)] or severe losses of deep-sea fauna during the last glaciation, attributed to oxygen depletion (99). Evolution in response to environmental changes that occurred much slower than those projected in the coming decades did not, therefore, prevent major large-scale alterations of marine ecosystems. Levels of confidence are generally medium to very high for RCP2.6 but significantly lower for RCP8.5, except for seagrass, warm-water corals, and pteropods, for which they remain high or very high (see supplementary materials).

### Effects on ecosystem services and ocean-related human activities

Ocean warming, acidification, and deoxygenation alter earth-system-regulating processes (e.g., climate, heat distribution, weather, water flow, and waste treatment), habitat provision, and cultural services [e.g., recreation and leisure, inspiration, and cultural heritage (100)]. As a consequence, CO<sub>2</sub>-driven global change is expected to result in economic impacts for humans through the alteration of ocean-derived resources and increasing risks to public health, human development, well-being, and security (101).

### Ocean carbon uptake

Ocean uptake of anthropogenic CO<sub>2</sub> is a key service to society that moderates climate change, although it comes at the cost of ocean acidification. CO<sub>2</sub> uptake depends on multiple processes, many of which are sensitive to climate change [see above (102)], and the open ocean is projected to absorb a decreasing fraction of anthropogenic CO<sub>2</sub> emissions as those emissions increase. The fraction of 21st century emissions remaining in the atmosphere consequently increases from 30% for RCP2.6 to 69% for RCP8.5 (27). The

contribution of vegetated coastal ecosystems—including seagrasses, mangrove forests, and salt marshes—to contemporary carbon sequestration (103) is an order of magnitude less than that of the land biosphere and open ocean, and the coastal carbon sequestered is likely part of the natural carbon cycle rather than related to anthropogenic emissions. The projected loss of these habitats would not only reduce this relatively small uptake of CO<sub>2</sub>, but would also release carbon previously stored and thus exacerbate CO<sub>2</sub>-driven changes.

### Coastal protection

Coastal habitats—including coral reefs, oyster beds, mangrove forests, salt marshes, kelp forests, and seagrass beds—protect human infrastructure, notably by reducing coastal wave energy, with additional benefits, such as limitation of coastal erosion and marine inundation (104, 105). Nevertheless, the projected increases in coastal human settlements and sea level will combine to expose 0.2 to 4.6% of the global population to inundation annually at a cost to global gross domestic product of 0.3 to 9.3% (106). The value of coastal protection in terms of prevented damage can be very large. Coastal wetlands in the United States were estimated to provide U.S. \$23.2 billion year<sup>-1</sup> in storm protection services (107). In contrast to human infrastructure, natural habitats can grow to keep up with sea-level rise, depending on the rate and local conditions, while offering other ecosystem services such as fish and timber (104, 108). These habitats are, however, themselves affected by ocean warming and acidification, in combination with other human disturbances such as urbanization, deforestation, and dredging, making global projections difficult.

### Capture fisheries

Ocean warming significantly affects provisioning services through its effects on marine capture fisheries (109). Warm-water species have increasingly dominated global fishery catches in recent decades, which can be attributed to a warming ocean (110–114). In addition, the maximum size of exploited fishes decreases with rising SST and decreasing oxygen level, ultimately reducing potential fish yield (115) in agreement with model predictions (111).

Human communities, especially in developing nations, that depend heavily on coastal fisheries resources for food, economic security, and traditional culture are at particular risk from shifts in ocean primary productivity and species ranges (116–120). For example, tropical fisheries yield is expected to decrease (42, 117, 121) in ways that vary among subregions and species (120). The loss of critical habitats, such as coral reefs and mangroves, will exacerbate the impacts on tropical fisheries and hence on vulnerable human communities. Substantial declines for tropical fisheries are projected, with robust evidence and strong agreement, even under RCP2.6 by mid-21st century.

Arctic fisheries may benefit from increased primary production, with projected revenue increas-

ing by 14 to 59% by mid-21st century relative to the present day under a high-emissions scenario (118). Nevertheless, the Arctic faces increasing overall risk because it is a hot spot of ocean acidification and social vulnerability [including high economic and nutritional dependence on marine resources and limited employment and nutritional alternatives (118, 122)]. Risk of impact on mid-latitude fisheries is more variable depending on the locations and exploited species, but it is expected to increase substantially under RCP8.5 because of the combination of ocean warming, acidification, and deoxygenation (2, 123, 124). Eventually, changes in the accessibility of marine resources will likely lead to increasing geopolitical and governance challenges for managing trans-boundary stocks and mitigating overexploitation (125, 126), leading to additional economic and societal costs that will be felt unequally and will place heavier burdens on less-advantaged human communities.

### Aquaculture

Climate and acidification-related impacts to aquaculture are expected to be generally negative, with impacts varying by location, species, and aquaculture method. Farmed species at higher trophic levels are expected to exhibit higher mortality rates and lower productivity under warming, with open and semi-open aquaculture and those in the tropics particularly at risk (127, 128). A reduction of mussel production by 50 or 70% is projected in the United Kingdom under the RCP2.6 or RCP8.5 scenarios, respectively (127). Projected declines in oyster production resulting from warming are much lower, but ocean acidification increases the risk in upwelling areas, such as the Northeast Pacific (129). The global economic cost of losses in the capture and aquaculture of molluscs resulting from ocean acidification based on the high-emissions scenario RCP8.5 could be higher than U.S. \$100 billion by the year 2100 (130). Sea level rise will bring saline water into deltas and estuaries, where aquaculture commonly occurs (131), driving aquaculture upstream and destroying wetlands. Infectious diseases also pose a greater threat to aquaculture in a warmer ocean, with impacts observed, for example, in oysters and abalone aquaculture (132) and coastal fish farming (133). Risks are also generated by the increased mobility of invasive species (46).

### Tourism

Decreases in the quality and abundance of coral reef cover are expected to negatively affect tourism (1, 3). Loss of coral reefs to tourism under the RCP2.6 and RCP8.5 scenarios could cost between U.S. \$1.9 billion and U.S. \$12 billion per year, respectively (134). Coral reef losses due to ocean warming and acidification on the Great Barrier Reef place up to A\$5.7 billion and 69,000 jobs in Australia at risk (135). In addition, ocean acidification may cause an annual loss of reef ecosystem services that are valued up to U.S. \$1 trillion by 2100 (136). For about a quarter of countries with reef-related tourism, mainly less-developed countries, this kind of tourism accounts for more

than 15% of gross domestic product (137) and is more sustainable than extractive livelihoods.

### Human health

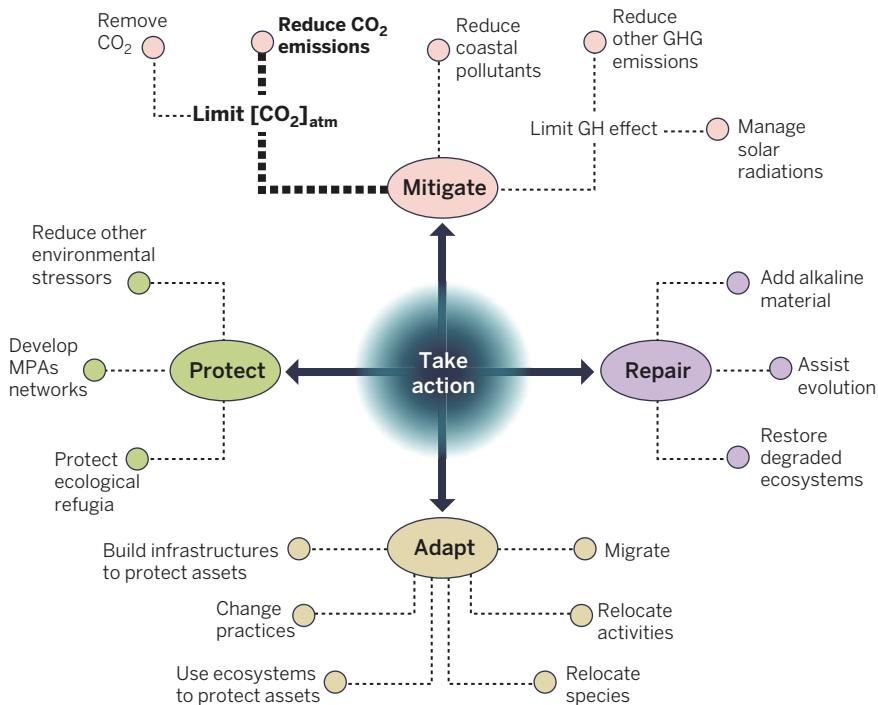
Ocean warming and acidification affect public health and security, although the impact pathways and associated costs are poorly understood. Hosts and parasites are likely to undergo poleward range shifts under climate change, and disease outbreaks of cholera (138) and other *Vibrio* infections (139) have already been linked to warmer conditions. The increased risk of pathogens and parasites in marine species and increased opportunities for pathogen transfer between hosts (140) can reduce food security (141). Increasing intensity and frequency of storm surges and sea-level rise may expand the geographical and seasonal ranges of bacteria, increasing human exposure to diseases (132). Inundation can also flood agricultural land in coastal regions, jeopardizing food security and harming human health (142).

### Present-day impact and future risks

The impacts of ocean acidification and warming have already been detected in some key ecosystem services, such as coastal protection and capture fisheries (Figs. 2C and 3). The risks of impacts increase as a function of increased temperature and decreased pH but are still moderate by 2100 for most services with the RCP2.6 scenario. However, under RCP8.5, we find that the risks of impact will become high or very high by 2100 for all seven ecosystem services considered. Fin fisheries at low latitude will be affected sooner than other services; they will face very high risk at a CO<sub>2</sub> level corresponding to RCP2.6 in 2100. In addition, cumulative or synergistic impacts with other human-induced drivers, such as over-exploitation of living resources, habitat destruction, and pollution, will likely exacerbate the risk of CO<sub>2</sub>-related impacts.

### Management options

Limiting the effects of ocean warming and acidification is critical considering the widespread risks of impacts facing natural and human systems, even under a stringent emissions scenario (RCP2.6; Fig. 2). A growing body of literature presents options for action in response to climate change and ocean acidification (143–145). Drawing on Billé *et al.* (146), these actions can be clustered in four groups (Fig. 4): reducing the drivers of climate change and ocean acidification (mitigate), building or maintaining resilience in ecosystems (protect), adapting human societies (adapt), and repairing damage that has already occurred (repair). At present, only one of these (reducing CO<sub>2</sub> emissions) addresses the fundamental problem; the others merely delay or decrease impacts (e.g., protecting reefs from major disturbances such as coral mining). Some actions rely on readily available technologies (e.g., sewage treatment plants to reduce exacerbating effects of coastal nutrient pollution) and socioeconomic mechanisms (e.g., coastal setback zones), whereas more engineering-intensive techniques are being developed and will require testing (e.g., removal of



**Fig. 4. Four clusters of actions against climate change, including ocean acidification.** For each cluster, a nonexhaustive list of actions is shown. [CO<sub>2</sub>]<sub>atm</sub> is concentration of atmospheric CO<sub>2</sub>; GH, greenhouse; GHG, greenhouse gases; MPAs, marine protected areas. The mitigation pathway leading to CO<sub>2</sub> reductions is represented in bold, consistent with the consensus view that significant reductions in CO<sub>2</sub> emissions is presently the only actual “solution” to the ocean impacts of climate change and ocean acidification (see main text).

CO<sub>2</sub> from the atmosphere). These options interact. For example, reducing secondary environmental stressors so as to retain ecosystem resilience works over some range of P<sub>CO<sub>2</sub></sub> values but is ultimately relevant only if ocean warming and acidification are drastically limited. One cannot manage coral reef resilience, for example, if there are no healthy reefs remaining (46). Importantly, some policy options are antagonistic: For example, solar radiation management could limit the increase of surface temperature but would reduce the incentive to cut greenhouse gases emissions, including CO<sub>2</sub>, thereby providing no relief from ocean acidification (147).

A positive development is that a widening range of stakeholders are testing new practices or reviving old ones, including CO<sub>2</sub> extraction from seawater (148), assisted evolution of corals (149), coral farming (150), and customary local management (151). Such field tests provide useable information and tools for decision-makers and climate negotiators as to the costs, benefits, and timing of management options. Aquaculture, for example, has shown some potential to reduce the risk of impacts from climate change and ocean acidification through societal adaptation, such as improved monitoring and changing cultured species or farm locations (127, 152). However, the cost of adaptation measures—such as real-time monitoring of water chemistry—can be prohibitive and not within the reach of most aquaculture operations, especially those in the

developing world. Ecosystem-based adaptation—or using ecosystems to reduce the vulnerability of people—appears to offer cost-efficient solutions bringing multiple co-benefits, especially for developing countries and marginalized communities (153). Stimulating ecosystem resilience by reducing the number and magnitude of local stressors and setting up marine protected areas (154) with strictly enforced no-take areas and limited pollutant inputs also stand out as tractable priorities. Moreover, some regions and local areas that are relatively less exposed to warming, hypoxia, and acidification could be climate change refugia, where more favorable environmental conditions would enable survival under CO<sub>2</sub>-driven impacts (155). Thus, identifying these climate change refugia and conserving biodiversity there contribute to building resilience to climate change (156). Nevertheless, all of these options require appropriate policy frameworks and financial commitments to cover transaction and opportunity costs, surveillance, and enforcement and monitoring and likely offer only limited protection in the face of persistent climate change and ocean acidification.

As the ocean warms and acidifies, the range of protection, adaptation, and repair options—and our confidence in those options—dwindles, while the cost of remaining options skyrockets. Lower-emissions scenarios such as RCP2.6 leave society with a greater number of effective options for safeguarding marine ecosystems and the services

they provide. Therefore, actions that do not reduce carbon emissions are meaningful ocean management options only if the future climate regime entails ambitious national contributions toward the phaseout of global CO<sub>2</sub> emissions as well as a strong funding mechanism and a relevant framework to support on-the-ground implementation of these options.

## Key messages

Maintaining ocean ecosystems and services depends in large part on the negotiation process toward a global climate agreement under the UNFCCC. In this regard, four key messages emerge from our analysis. First, the ocean strongly influences the climate system and provides important services to humans. Second, impacts on key marine and coastal organisms, ecosystems, and services from anthropogenic CO<sub>2</sub> emissions are already detectable, and several will face high risk of impacts well before 2100, even with the stringent CO<sub>2</sub> emissions scenario (RCP2.6). These impacts are occurring across all latitudes and have become a global concern that spans the traditional north/south divide. Third, the analysis shows that immediate and substantial reduction of CO<sub>2</sub> emissions is required in order to prevent the massive and effectively irreversible impacts on ocean ecosystems and their services that are projected with emissions scenarios more severe than RCP2.6. Limiting emissions to below this level is necessary to meet UNFCCC's stated objectives. Management options that overlook CO<sub>2</sub>, such as solar radiation management and control of methane emission, will only minimize impacts of ocean warming and not those of ocean acidification. Fourth, as CO<sub>2</sub> increases, the protection, adaptation, and repair options for the ocean become fewer and less effective.

Given the contrasting futures we have outlined here, the ocean provides further compelling arguments for rapid and rigorous CO<sub>2</sub> emission reduction and eventual reduction of atmospheric CO<sub>2</sub> content. As a result, any new global climate agreement that does not minimize the impacts on the ocean will be incomplete and inadequate.

## REFERENCES AND NOTES

1. O. Hoegh-Guldberg et al., “The ocean,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field et al., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 1655–1731.
2. H.-O. Pörtner et al., “Ocean systems,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field et al., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 411–484.
3. P. P. Wong et al., “Coastal systems and low-lying areas,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field et al., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 361–409.
4. C. Mora, D. P. Tittensor, S. Adl, A. G. Simpson, B. Worm, How many species are there on Earth and in the ocean? *PLOS Biol.* **9**, e1001127 (2011). doi: [10.1371/journal.pbio.1001127](https://doi.org/10.1371/journal.pbio.1001127); pmid: [21886479](https://pubmed.ncbi.nlm.nih.gov/21886479/)

5. Food and Agricultural Organization (FAO), *The State of World Fisheries and Aquaculture 2014* (FAO, Rome, 2014).
6. United Nations, *United Nations Framework Convention on Climate Change* (United Nations, New York, 1992).
7. Copenhagen Accord, *Decision 2/CP.15: Copenhagen Accord* (UNFCCC, Geneva, 2009).
8. E. R. Harrold-Kolieb, D. Herr, Ocean acidification and climate change: Synergies and challenges of addressing both under the UNFCCC. *Clim. Policy* **12**, 378–389 (2012). doi: [10.1080/14693062.2012.620788](https://doi.org/10.1080/14693062.2012.620788)
9. IPCC, "Summary for policymakers," in *Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field et al., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 1–32.
10. T. F. Stocker et al., "Technical summary," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 33–115.
11. K. M. Strassmann, G. K. Plattner, F. Joos, CO<sub>2</sub> and non-CO<sub>2</sub> radiative forcings in climate projections for twenty-first century mitigation scenarios. *Clim. Dyn.* **33**, 737–749 (2009). doi: [10.1007/s00382-008-0505-4](https://doi.org/10.1007/s00382-008-0505-4)
12. J.-P. Gattuso, L. Hansson, "Ocean acidification: Background and history," in *Ocean Acidification*, J.-P. Gattuso, L. Hansson, Eds. (Oxford Univ. Press, Oxford, 2011), pp. 1–20.
13. L. A. Levin et al., Comparative biogeochemistry-ecosystem-human interactions on dynamic continental margins. *J. Mar. Syst.* **141**, 3–17 (2015). doi: [10.1016/j.jmarsys.2014.04.016](https://doi.org/10.1016/j.jmarsys.2014.04.016)
14. D. Lüthi et al., High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* **453**, 379–382 (2008). doi: [10.1038/nature06949](https://doi.org/10.1038/nature06949); pmid: [18480821](https://pubmed.ncbi.nlm.nih.gov/18480821/)
15. T. Friedrich et al., Detecting regional anthropogenic trends in ocean acidification against natural variability. *Nat. Clim. Change* **2**, 167–171 (2012). doi: [10.1038/nclimate1372](https://doi.org/10.1038/nclimate1372)
16. F. Joos, R. Spahni, Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 1425–1430 (2008). doi: [10.1073/pnas.0707386105](https://doi.org/10.1073/pnas.0707386105); pmid: [18252830](https://pubmed.ncbi.nlm.nih.gov/18252830/)
17. R. A. Feely, C. L. Sabine, J. M. Hernandez-Ayon, D. Lanson, B. Hales, Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science* **320**, 1490–1492 (2008). doi: [10.1126/science.1155676](https://doi.org/10.1126/science.1155676); pmid: [18497259](https://pubmed.ncbi.nlm.nih.gov/18497259/)
18. J. Salisbury, M. Green, C. Hunt, J. Campbell, Coastal acidification by rivers: A new threat to shellfish? *Eos* **89**, 513 (2008). doi: [10.1029/2008EO500001](https://doi.org/10.1029/2008EO500001)
19. W.-J. Cai et al., Acidification of subsurface coastal waters enhanced by eutrophication. *Nat. Geosci.* **4**, 766–770 (2011). doi: [10.1038/ngeo1297](https://doi.org/10.1038/ngeo1297)
20. A. V. Borges, N. Gypens, Carbonate chemistry in the coastal zone responds more strongly to eutrophication than to ocean acidification. *Limnol. Oceanogr.* **55**, 346–353 (2010). doi: [10.4319/lo.2010.55.1.0346](https://doi.org/10.4319/lo.2010.55.1.0346)
21. K. M. Keller, F. Joos, C. Rable, Time of emergence of trends in ocean biogeochemistry. *Biogeosciences* **11**, 3647–3659 (2014). doi: [10.5194/bg-11-3647-2014](https://doi.org/10.5194/bg-11-3647-2014)
22. K. B. Rodgers, J. Lin, T. L. Frölicher, Emergence of multiple ocean ecosystem drivers in a large ensemble suite with an Earth system model. *Biogeosciences* **12**, 3301–3320 (2015). doi: [10.5194/bg-12-3301-2015](https://doi.org/10.5194/bg-12-3301-2015)
23. L. Bopp et al., Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences* **10**, 6225–6245 (2013). doi: [10.5194/bg-10-6225-2013](https://doi.org/10.5194/bg-10-6225-2013)
24. M. Steinacher, F. Joos, T. F. Stocker, Allowable carbon emissions lowered by multiple climate targets. *Nature* **499**, 197–201 (2013). doi: [10.1038/nature12269](https://doi.org/10.1038/nature12269); pmid: [23823728](https://pubmed.ncbi.nlm.nih.gov/23823728/)
25. P. Ciais et al., "Carbon and other biogeochemical cycles," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 465–570.
26. T. A. Boden, G. Marland, R. J. Andres, *Global, Regional, and National Fossil-Fuel CO<sub>2</sub> Emissions* (Carbon Dioxide Information Analysis Center, Oak Ridge, TN, 2013).
27. C. Jones et al., Twenty-first-century compatible CO<sub>2</sub> emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways. *J. Clim.* **26**, 4398–4413 (2013).
28. J. A. Church et al., "Sea level change," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 117–197.
29. Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T. F. Stocker et al., Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 1137–1216.
30. T. Roy et al., Regional impacts of climate change and atmospheric CO<sub>2</sub> on future ocean carbon uptake: A multimodel linear feedback analysis. *J. Clim.* **24**, 2300–2318 (2011). doi: [10.1175/2010JCLI3787.1](https://doi.org/10.1175/2010JCLI3787.1)
31. T. L. Frölicher, F. Joos, Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. *Clim. Dyn.* **35**, 1439–1459 (2010). doi: [10.1007/s00382-009-0727-0](https://doi.org/10.1007/s00382-009-0727-0)
32. S. Emerson, S. Bushinsky, Oxygen oxygen concentrations and biological fluxes in the open ocean. *Oceanography* **27**, 168–171 (2014). doi: [10.5670/oceanog.2014.20](https://doi.org/10.5670/oceanog.2014.20)
33. V. Cocco et al., Oxygen and indicators of stress for marine life in multi-model global warming projections. *Biogeosciences* **10**, 1849–1868 (2013). doi: [10.5194/bg-10-1849-2013](https://doi.org/10.5194/bg-10-1849-2013)
34. E. C. Shaw, B. I. McNeil, B. Tilbrook, R. Matear, M. L. Bates, Anthropogenic changes to seawater buffer capacity combined with natural reef metabolism induce extreme future coral reef CO<sub>2</sub> conditions. *Glob. Change Biol.* **19**, 1632–1641 (2013). doi: [10.1111/gcb.12154](https://doi.org/10.1111/gcb.12154); pmid: [23505026](https://pubmed.ncbi.nlm.nih.gov/23505026/)
35. T. Cyronak, I. R. Santos, D. V. Erler, D. T. Maher, B. D. Eyre, Drivers of pCO<sub>2</sub> variability in two contrasting coral reef lagoons: The influence of submarine groundwater discharge. *Global Biogeochem. Cycles* **28**, 398–414 (2014). doi: [10.1002/2013GB004598](https://doi.org/10.1002/2013GB004598)
36. L. L. Robbins et al., Baseline monitoring of the western Arctic Ocean estimates 20% of Canadian basin surface waters are undersaturated with respect to aragonite. *PLOS ONE* **8**, e73796 (2013). doi: [10.1371/journal.pone.0073796](https://doi.org/10.1371/journal.pone.0073796); pmid: [24040074](https://pubmed.ncbi.nlm.nih.gov/24040074/)
37. M. Mattsdotter Björk, A. Fransson, A. Torstensson, M. Chierici, Ocean acidification state in western Antarctic surface waters: Controls and interannual variability. *Biogeosciences* **11**, 57–73 (2014). doi: [10.5194/bg-11-57-2014](https://doi.org/10.5194/bg-11-57-2014)
38. M. Gehlen et al., Projected pH reductions by 2100 might put deep North Atlantic biodiversity at risk. *Biogeosciences* **11**, 6955–6967 (2014). doi: [10.5194/bg-11-6955-2014](https://doi.org/10.5194/bg-11-6955-2014)
39. P. W. Boyd, S. T. Lennartsson, D. M. Glover, S. C. Doney, Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nat. Clim. Change* **5**, 71–79 (2015). doi: [10.1038/nclimate2441](https://doi.org/10.1038/nclimate2441)
40. U. Riebesell, J.-P. Gattuso, Lessons learned from ocean acidification research. *Nat. Clim. Change* **5**, 12–14 (2015). doi: [10.1038/nclimate2456](https://doi.org/10.1038/nclimate2456)
41. E. Poloczanska, O. Hoegh-Guldberg, W. Cheung, H.-O. Pörtner, M. T. Burrows, "Observed global responses of marine biogeography, abundance, and phenology to climate change," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field et al., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 123–127.
42. L. E. Chambers et al., Phenological changes in the southern hemisphere. *PLOS ONE* **8**, e75514 (2013). doi: [10.1371/journal.pone.0075514](https://doi.org/10.1371/journal.pone.0075514); pmid: [24098389](https://pubmed.ncbi.nlm.nih.gov/24098389/)
43. M. C. Jones, W. W. L. Cheung, Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES J. Mar. Sci.* **72**, 741–752 (2015). doi: [10.1093/icesjms/fsu172](https://doi.org/10.1093/icesjms/fsu172)
44. M. L. Pinsky, B. Worm, M. J. Fogarty, J. L. Sarmiento, S. A. Levin, Marine taxa track local climate velocities. *Science* **341**, 1239–1242 (2013). doi: [10.1126/science.1239352](https://doi.org/10.1126/science.1239352); pmid: [24031017](https://pubmed.ncbi.nlm.nih.gov/24031017/)
45. J. G. Hiddink, M. T. Burrows, J. García Molinos, Temperature tracking by North Sea benthic invertebrates in response to climate change. *Glob. Change Biol.* **21**, 117–129 (2015). doi: [10.1111/gcb.12726](https://doi.org/10.1111/gcb.12726); pmid: [25179407](https://pubmed.ncbi.nlm.nih.gov/25179407/)
46. M. S. Wisz et al., Arctic warming will promote Atlantic–Pacific fish interchange. *Nat. Clim. Change* **5**, 261–265 (2015). doi: [10.1038/nclimate2500](https://doi.org/10.1038/nclimate2500)
47. O. Hoegh-Guldberg, J. F. Bruno, The impact of climate change on the world's marine ecosystems. *Science* **328**, 1523–1528 (2010). doi: [10.1126/science.1189930](https://doi.org/10.1126/science.1189930); pmid: [20558709](https://pubmed.ncbi.nlm.nih.gov/20558709/)
48. A. Vergés et al., The tropicalization of temperate marine ecosystems: Climate-mediated changes in herbivory and community phase shifts. *Proc. Biol. Sci.* **281**, 20140846 (2014). doi: [10.1098/rspb.2014.0846](https://doi.org/10.1098/rspb.2014.0846); pmid: [25009065](https://pubmed.ncbi.nlm.nih.gov/25009065/)
49. L. Schlüter et al., Adaptation of a globally important coccolithophore to ocean warming and acidification. *Nat. Clim. Change* **4**, 1024–1030 (2014). doi: [10.1038/nclimate2379](https://doi.org/10.1038/nclimate2379)
50. N. J. Muñoz, A. P. Farrell, J. W. Heath, B. D. Neff, Adaptive potential of a Pacific salmon challenged by climate change. *Nat. Clim. Change* **5**, 163–166 (2015). doi: [10.1038/nclimate2473](https://doi.org/10.1038/nclimate2473)
51. J.-P. Gattuso, O. Hoegh-Guldberg, H.-O. Pörtner, "Coral reefs," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field et al., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 97–100.
52. N. A. Graham, S. Jennings, M. A. MacNeil, D. Mouillot, S. K. Wilson, Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature* **518**, 94–97 (2015). doi: [10.1038/nature14140](https://doi.org/10.1038/nature14140); pmid: [25607371](https://pubmed.ncbi.nlm.nih.gov/25607371/)
53. O. Hoegh-Guldberg et al., Coral reefs under rapid climate change and ocean acidification. *Science* **318**, 1737–1742 (2007). doi: [10.1126/science.1152509](https://doi.org/10.1126/science.1152509); pmid: [18079392](https://pubmed.ncbi.nlm.nih.gov/18079392/)
54. B. C. Hume et al., *Symbiodinium thermophilum* sp. nov., a thermotolerant symbiotic alga prevalent in corals of the world's hottest sea, the Persian/Arabian Gulf. *Sci. Rep.* **5**, 8562 (2015). doi: [10.1038/srep08562](https://doi.org/10.1038/srep08562); pmid: [25720577](https://pubmed.ncbi.nlm.nih.gov/25720577/)
55. R. N. Silverstein, R. Cuning, A. C. Baker, Change in algal symbiont communities after bleaching, not prior heat exposure, increases heat tolerance of reef corals. *Glob. Change Biol.* **21**, 236–249 (2015). doi: [10.1111/gcb.12706](https://doi.org/10.1111/gcb.12706); pmid: [25099991](https://pubmed.ncbi.nlm.nih.gov/25099991/)
56. O. Hoegh-Guldberg, The adaptation of coral reefs to climate change: Is the Red Queen being outpaced? *Sci. Mar.* **76**, 403–408 (2012). doi: [10.3989/scimar.03660.29A](https://doi.org/10.3989/scimar.03660.29A)
57. S. R. Palumbi, D. J. Barshis, N. Taylor-Knowles, R. A. Bay, Mechanisms of reef coral resistance to future climate change. *Science* **344**, 895–898 (2014). pmid: [24762535](https://pubmed.ncbi.nlm.nih.gov/24762535/)
58. M. Schweinsberg, L. C. Weiss, S. Striewski, R. Tollrian, K. P. Lampert, More than one genotype: How common is intracolonial genetic variability in scleractinian corals? *Mol. Ecol.* **24**, 2673–2685 (2015). doi: [10.1111/mec.13200](https://doi.org/10.1111/mec.13200); pmid: [25872099](https://pubmed.ncbi.nlm.nih.gov/25872099/)
59. C. A. Logan, J. P. Dunne, C. M. Eakin, S. D. Donner, Incorporating adaptive responses into future projections of coral bleaching. *Glob. Change Biol.* **20**, 125–139 (2014). doi: [10.1111/gcb.12390](https://doi.org/10.1111/gcb.12390); pmid: [24038982](https://pubmed.ncbi.nlm.nih.gov/24038982/)
60. C. M. Eakin, Lamarck was partially right—and that is good for corals. *Science* **344**, 798–799 (2014). doi: [10.1126/science.1254136](https://doi.org/10.1126/science.1254136); pmid: [24855237](https://pubmed.ncbi.nlm.nih.gov/24855237/)
61. J. M. Roberts, A. J. Wheeler, A. Freiwald, Reefs of the deep: The biology and geology of cold-water coral ecosystems. *Science* **312**, 543–547 (2006). doi: [10.1126/science.1119861](https://doi.org/10.1126/science.1119861); pmid: [16645087](https://pubmed.ncbi.nlm.nih.gov/16645087/)
62. J. P. Gattuso et al., "Ocean acidification: Background and history," in *Ocean Acidification*, C. B. Field et al., Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 129–131.
63. J. Meyer, U. Riebesell, Reviews and Syntheses: Responses of coccolithophores to ocean acidification: A meta-analysis. *Biogeosciences* **12**, 1671–1682 (2015). doi: [10.5194/bg-12-1671-2015](https://doi.org/10.5194/bg-12-1671-2015)
64. K. J. S. Meier, L. Beaufort, S. Heussner, P. Ziveri, The role of ocean acidification in *Emiliania huxleyi* coccolith thinning in the Mediterranean Sea. *Biogeosciences* **11**, 2857–2869 (2014). doi: [10.5194/bg-11-2857-2014](https://doi.org/10.5194/bg-11-2857-2014)
65. N. Bednářek, G. A. Tarling, D. C. E. Bakker, S. Fielding, R. A. Feely, Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation. *PLOS ONE* **9**, e109183 (2014). doi: [10.1371/journal.pone.0109183](https://doi.org/10.1371/journal.pone.0109183); pmid: [25285916](https://pubmed.ncbi.nlm.nih.gov/25285916/)
66. N. Bednářek et al., Extensive dissolution of live pteropods in the Southern Ocean. *Nat. Geosci.* **5**, 881–885 (2012). doi: [10.1038/ngeo1635](https://doi.org/10.1038/ngeo1635)
67. U. Riebesell, J.-P. Gattuso, T. F. Thingstad, J. J. Middelburg, Arctic ocean acidification: Pelagic ecosystem and biogeochemical responses during a mesocosm study. *Biogeosciences* **10**, 5619–5626 (2013). doi: [10.5194/bg-10-5619-2013](https://doi.org/10.5194/bg-10-5619-2013)
68. S. Richier et al., Phytoplankton responses and associated carbon cycling during shipboard carbonate chemistry

- manipulation experiments conducted around Northwest European shelf seas. *Biogeosciences* **11**, 4733–4752 (2014). doi: [10.5194/bg-11-4733-2014](https://doi.org/10.5194/bg-11-4733-2014)
69. S. Endres, L. Galgani, U. Riebesell, K. G. Schulz, A. Engel, Stimulated bacterial growth under elevated pCO<sub>2</sub>: Results from an off-shore mesocosm study. *PLOS ONE* **9**, e99228 (2014). doi: [10.1371/journal.pone.0099228](https://doi.org/10.1371/journal.pone.0099228); pmid: [24941307](#)
70. S. L. Garrard et al., Indirect effects may buffer negative responses of seagrass invertebrate communities to ocean acidification. *J. Exp. Mar. Biol. Ecol.* **461**, 31–38 (2014). doi: [10.1016/j.jembe.2014.07.011](https://doi.org/10.1016/j.jembe.2014.07.011)
71. A. Ordóñez, C. Doropoulos, G. Diaz-Pulido, Effects of ocean acidification on population dynamics and community structure of crustose coralline algae. *Biol. Bull.* **226**, 255–268 (2014). pmid: [25070869](#)
72. J. Silverman et al., Community calcification in Lizard Island, Great Barrier Reef: A 33 year perspective. *Geochim. Cosmochim. Acta* **144**, 72–81 (2014). doi: [10.1016/j.gca.2014.09.011](https://doi.org/10.1016/j.gca.2014.09.011)
73. N. J. Silbiger, Ó. Guadayol, F. I. M. Thomas, M. J. Donahue, Reefs shift from net accretion to net erosion along a natural environmental gradient. *Mar. Ecol. Prog. Ser.* **515**, 33–44 (2014). doi: [10.3354/meps10999](https://doi.org/10.3354/meps10999)
74. J. M. Sunday et al., Evolution in an acidifying ocean. *Trends Ecol. Evol.* **29**, 117–125 (2014). doi: [10.1016/j.tree.2013.11.001](https://doi.org/10.1016/j.tree.2013.11.001); pmid: [24355315](#)
75. K. T. Lohbeck, U. Riebesell, T. B. H. Reusch, Gene expression changes in the coccolithophore *Emiliania huxleyi* after 500 generations of selection to ocean acidification. *Proc. R. Soc. London Ser. B* **281**, 20140003–20140003 (2014). doi: [10.1098/rspb.2014.0003](https://doi.org/10.1098/rspb.2014.0003); pmid: [24827439](#)
76. P. Thor, S. Dupont, Transgenerational effects alleviate severe fecundity loss during ocean acidification in a ubiquitous planktonic copepod. *Glob. Change Biol.* **21**, 2261–2271 (2015). doi: [10.1111/gcb.12815](https://doi.org/10.1111/gcb.12815); pmid: [25430823](#)
77. C. C. Suckling et al., Experimental influence of pH on the early life-stages of sea urchins II: Increasing parental exposure times gives rise to different responses. *Invertebr. Reprod. Dev.* **58**, 161–175 (2014). doi: [10.1080/07924259.2013.875951](https://doi.org/10.1080/07924259.2013.875951)
78. P. L. Munday, Transgenerational acclimation of fishes to climate change and ocean acidification. *F1000Prime Rep.* **6**, 99 (2014). doi: [10.12703/P6-99](https://doi.org/10.12703/P6-99); pmid: [25580253](#)
79. R. J. Diaz, R. Rosenberg, Spreading dead zones and consequences for marine ecosystems. *Science* **321**, 926–929 (2008). doi: [10.1126/science.1156401](https://doi.org/10.1126/science.1156401); pmid: [18703733](#)
80. H.-O. Pörtner, Oxygen- and capacity-limitation of thermal tolerance: A matrix for integrating climate-related stressor effects in marine ecosystems. *J. Exp. Biol.* **213**, 881–893 (2010). doi: [10.1242/jeb.037523](https://doi.org/10.1242/jeb.037523); pmid: [20190113](#)
81. A. Brown, S. Thatje, The effects of changing climate on faunal depth distributions determine winners and losers. *Glob. Change Biol.* **21**, 173–180 (2015). doi: [10.1111/gcb.12680](https://doi.org/10.1111/gcb.12680); pmid: [25044552](#)
82. D. Storch, L. Menzel, S. Frickenhaus, H.-O. Pörtner, Climate sensitivity across marine domains of life: Limits to evolutionary adaptation shape species interactions. *Glob. Change Biol.* **20**, 3059–3067 (2014). doi: [10.1111/gcb.12645](https://doi.org/10.1111/gcb.12645); pmid: [24890266](#)
83. J. S. Stewart et al., Combined climate- and prey-mediated range expansion of Humboldt squid (*Dosidicus gigas*), a large marine predator in the California Current System. *Glob. Change Biol.* **20**, 1832–1843 (2014). doi: [10.1111/gcb.12502](https://doi.org/10.1111/gcb.12502); pmid: [24443361](#)
84. J. D. Gaitán-Espitia et al., Interactive effects of elevated temperature and pCO<sub>2</sub> on early-life history stages of the giant kelp *Macrocystis pyrifera*. *J. Exp. Mar. Biol. Ecol.* **457**, 51–58 (2014). doi: [10.1016/j.jembe.2014.03.018](https://doi.org/10.1016/j.jembe.2014.03.018)
85. C. J. Gobler, E. L. DePasquale, A. W. Griffith, H. Baumann, Hypoxia and acidification have additive and synergistic negative effects on the growth, survival, and metamorphosis of early life stage bivalves. *PLOS ONE* **9**, e83648 (2014). doi: [10.1371/journal.pone.0083648](https://doi.org/10.1371/journal.pone.0083648); pmid: [24416169](#)
86. C. L. Mackenzie et al., Ocean warming, more than acidification, reduces shell strength in a commercial shellfish species during food limitation. *PLOS ONE* **9**, e86764 (2014). doi: [10.1371/journal.pone.0086764](https://doi.org/10.1371/journal.pone.0086764); pmid: [24489785](#)
87. D. Madeira, L. Narciso, M. S. Diniz, C. Vinagre, Synergy of environmental variables alters the thermal window and heat shock response: An experimental test with the crab *Pachygrapsus marmoratus*. *Mar. Environ. Res.* **98**, 21–28 (2014). doi: [10.1016/j.marenres.2014.03.011](https://doi.org/10.1016/j.marenres.2014.03.011); pmid: [24836643](#)
88. R. Rosa et al., Differential impacts of ocean acidification and warming on winter and summer progeny of a coastal squid (*Loligo vulgaris*). *J. Exp. Biol.* **217**, 518–525 (2014). doi: [10.1242/jeb.096081](https://doi.org/10.1242/jeb.096081); pmid: [24523499](#)
89. C. A. Frieder, J. P. Gonzalez, E. E. Bockmon, M. O. Navarro, L. A. Levin, Can variable pH and low oxygen moderate ocean acidification outcomes for mussel larvae? *Glob. Change Biol.* **20**, 754–764 (2014). doi: [10.1111/gcb.12485](https://doi.org/10.1111/gcb.12485); pmid: [24343909](#)
90. J. Mukherjee et al., Proteomic response of marine invertebrate larvae to ocean acidification and hypoxia during metamorphosis and calcification. *J. Exp. Biol.* **216**, 4580–4589 (2013). doi: [10.1242/jeb.094516](https://doi.org/10.1242/jeb.094516); pmid: [24307710](#)
91. C. Deutsch, A. Ferrel, B. Seibel, H.-O. Pörtner, R. B. Huey, Climate change tightens a metabolic constraint on marine habitats. *Science* **348**, 1132–1135 (2015). doi: [10.1126/science.aaa1605](https://doi.org/10.1126/science.aaa1605)
92. S. Comeau, R. C. Carpenter, P. J. Edmunds, Effects of irradiance on the response of the coral *Acropora pulchra* and the calcifying alga *Hydrolithon reinboldii* to temperature elevation and ocean acidification. *J. Exp. Mar. Biol. Ecol.* **453**, 28–35 (2014). doi: [10.1016/j.jembe.2013.12.013](https://doi.org/10.1016/j.jembe.2013.12.013)
93. C. J. Hoppe et al., Iron limitation modulates ocean acidification effects on southern ocean phytoplankton communities. *PLOS ONE* **8**, e79890 (2013). doi: [10.1371/journal.pone.0079890](https://doi.org/10.1371/journal.pone.0079890); pmid: [24278207](#)
94. G. W. K. Ko et al., Interactive effects of ocean acidification, elevated temperature, and reduced salinity on early-life stages of the pacific oyster. *Environ. Sci. Technol.* **48**, 10079–10088 (2014). doi: [10.1021/es50161lu](https://doi.org/10.1021/es50161lu); pmid: [25014366](#)
95. A. J. Poultney et al., Coccolithophores on the north-west European shelf: Calcification rates and environmental controls. *Biogeosciences* **11**, 3919–3940 (2014). doi: [10.5194/bg-11-3919-2014](https://doi.org/10.5194/bg-11-3919-2014)
96. R. I. Perry, R. E. Ommer, M. Barange, F. Werner, The challenge of adapting marine social–ecological systems to the additional stress of climate change. *Curr. Opin. Environ. Sustain.* **2**, 356–363 (2010). doi: [10.1016/j.cosust.2010.10.004](https://doi.org/10.1016/j.cosust.2010.10.004)
97. J. Brodie et al., The future of the northeast Atlantic benthic flora in a high CO<sub>2</sub> world. *Ecol. Evol.* **4**, 2787–2798 (2014). doi: [10.1002/ee.2105](https://doi.org/10.1002/ee.2105); pmid: [25077027](#)
98. M. O. Clarkson et al., Ocean acidification and the Permo-Triassic mass extinction. *Science* **348**, 229–232 (2015). doi: [10.1126/science.aaa0193](https://doi.org/10.1126/science.aaa0193); pmid: [25859043](#)
99. S. E. Moffitt, T. M. Hill, P. D. Roopnarine, S. J. Kennett, Response of seafloor ecosystems to abrupt global climate change. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 4684–4689 (2015). doi: [10.1073/pnas.1417130112](https://doi.org/10.1073/pnas.1417130112); pmid: [25825727](#)
100. A. Böhne-Henrichs, C. Baulcomb, R. Koss, S. S. Hussain, R. S. de Groot, Typology and indicators of ecosystem services for marine spatial planning and management. *J. Environ. Manage.* **130**, 135–145 (2013). doi: [10.1016/j.jenvman.2013.08.027](https://doi.org/10.1016/j.jenvman.2013.08.027); pmid: [24076513](#)
101. J. Meldier de Suarez, B. Cicin-Sain, K. Wowk, R. Payet, O. Hoegh-Guldberg, Ensuring survival: Oceans, climate and security. *Ocean Coast. Manage.* **90**, 27–37 (2014). doi: [10.1016/j.ocecoaman.2013.08.007](https://doi.org/10.1016/j.ocecoaman.2013.08.007)
102. U. Riebesell, A. Körtzinger, A. Oschlies, Sensitivities of marine carbon fluxes to ocean change. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 20602–20609 (2009). doi: [10.1073/pnas.0813291106](https://doi.org/10.1073/pnas.0813291106); pmid: [19995981](#)
103. C. M. Duarte, I. J. Losada, I. E. Hendriks, I. Mazarrasa, N. Marbà, The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **3**, 961–968 (2013). doi: [10.1038/nclimate1970](https://doi.org/10.1038/nclimate1970)
104. M. D. Spalding et al., The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean Coast. Manage.* **90**, 50–57 (2014). doi: [10.1016/j.ocecoaman.2013.09.007](https://doi.org/10.1016/j.ocecoaman.2013.09.007)
105. B. Ondivela et al., The role of seagrasses in coastal protection in a changing climate. *Coast. Eng.* **87**, 158–168 (2014). doi: [10.1016/j.coastalgeng.2013.11.005](https://doi.org/10.1016/j.coastalgeng.2013.11.005)
106. J. Hinkel et al., Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3292–3297 (2014). doi: [10.1073/pnas.1222469111](https://doi.org/10.1073/pnas.1222469111); pmid: [24596428](#)
107. R. Costanza et al., The value of coastal wetlands for hurricane protection. *Ambio* **37**, 241–248 (2008). doi: [10.1057/0044-7447\(2008\)37\[241\]TVOCWF2;0.CO;2](https://doi.org/10.1057/0044-7447(2008)37[241]TVOCWF2;0.CO;2); pmid: [18686502](#)
108. E. B. Barbier, Valuing the storm protection service of estuarine and coastal ecosystems. *Ecosyst. Serv.* **11**, 32–38 (2015). doi: [10.1016/j.ecoser.2014.06.010](https://doi.org/10.1016/j.ecoser.2014.06.010)
109. U. R. Sumaila, W. W. L. Cheung, V. W. Y. Lam, D. Pauly, S. Herrick, Climate change impacts on the biophysics and economics of world fisheries. *Nat. Clim. Change* **1**, 449–456 (2011). doi: [10.1038/nclimate1301](https://doi.org/10.1038/nclimate1301)
110. W. W. Cheung, R. Watson, D. Pauly, Signature of ocean warming in global fisheries catch. *Nature* **497**, 365–368 (2013). doi: [10.1038/nature12156](https://doi.org/10.1038/nature12156); pmid: [23676754](#)
111. W. W. L. Cheung et al., Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nat. Clim. Change* **3**, 254–258 (2012). doi: [10.1038/nclimate1691](https://doi.org/10.1038/nclimate1691)
112. I. Montero-Serra, M. Edwards, M. J. Genner, Warming shelf seas lead the subtropicalization of European pelagic fish communities. *Glob. Change Biol.* **21**, 144–153 (2015). doi: [10.1111/gcb.12747](https://doi.org/10.1111/gcb.12747); pmid: [25230844](#)
113. S. D. Simpson et al., Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Curr. Biol.* **21**, 1565–1570 (2011). doi: [10.1016/j.cub.2011.08.016](https://doi.org/10.1016/j.cub.2011.08.016); pmid: [21924906](#)
114. D. Yemane et al., Assessing changes in the distribution and range size of demersal fish populations in the Benguela Current Large Marine Ecosystem. *Rev. Fish Biol. Fish.* **24**, 463–483 (2014). doi: [10.1007/s11160-014-9357-7](https://doi.org/10.1007/s11160-014-9357-7)
115. A. R. Baudron, C. L. Needle, A. D. Rijnsdorp, C. T. Marshall, Warming temperatures and smaller body sizes: Synchronous changes in growth of North Sea fishes. *Glob. Change Biol.* **20**, 1023–1031 (2014). doi: [10.1111/gcb.12514](https://doi.org/10.1111/gcb.12514); pmid: [24375891](#)
116. S. R. Cooley, J. T. Mathis, Addressing ocean acidification as part of sustainable ocean development. *Ocean Yearbook Online* **27**, 29–47 (2013). doi: [10.1163/22116001-90000153](https://doi.org/10.1163/22116001-90000153)
117. M. Barange et al., Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nat. Clim. Change* **4**, 211–216 (2014). doi: [10.1038/nclimate2119](https://doi.org/10.1038/nclimate2119)
118. V. W. Y. Lam, W. W. L. Cheung, U. R. Sumaila, Marine capture fisheries in the Arctic: Winners or losers under climate change and ocean acidification? *Fish Fish.* (2014). doi: [10.1111/faf.12106](https://doi.org/10.1111/faf.12106)
119. V. W. Y. Lam, W. Cheung, W. Swartz, U. R. Sumaila, Climate change impacts on fisheries in West Africa: Implications for economic, food and nutritional security. *Afr. J. Mar. Sci.* **34**, 103–117 (2012). doi: [10.2989/1814232X.2012.673294](https://doi.org/10.2989/1814232X.2012.673294)
120. J. D. Bell et al., Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nat. Clim. Change* **3**, 591–599 (2013). doi: [10.1038/nclimate1838](https://doi.org/10.1038/nclimate1838)
121. W. W. L. Cheung et al., Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Change Biol.* **16**, 24–35 (2010). doi: [10.1111/j.1365-2486.2009.01995.x](https://doi.org/10.1111/j.1365-2486.2009.01995.x)
122. J. T. Mathis et al., Ocean acidification risk assessment for Alaska's fishery sector. *Prog. Oceanogr.* (2014). doi: [10.1016/j.pocean.2014.07.001](https://doi.org/10.1016/j.pocean.2014.07.001)
123. C. H. Ainsworth et al., Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. *ICES J. Mar. Sci.* **68**, 1217–1229 (2011). doi: [10.1093/icesjms/fsr043](https://doi.org/10.1093/icesjms/fsr043)
124. W. W. L. Cheung, J. Pinnegar, G. Merino, M. C. Jones, M. Barange, Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **22**, 368–388 (2012). doi: [10.1002/aqc.2248](https://doi.org/10.1002/aqc.2248)
125. J. S. Christiansen, C. W. Mecklenburg, O. V. Karamushko, Arctic marine fishes and their fisheries in light of global change. *Glob. Change Biol.* **20**, 352–359 (2014). doi: [10.1111/gcb.12395](https://doi.org/10.1111/gcb.12395); pmid: [24105993](#)
126. K. A. Miller, G. R. Munro, U. R. Sumaila, W. W. L. Cheung, Governing marine fisheries in a changing climate: A game-theoretic perspective. *Can. J. Agric. Econ.* **61**, 309–334 (2013). doi: [10.1111/cjag.12011](https://doi.org/10.1111/cjag.12011)
127. R. Callaway et al., Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **22**, 389–421 (2012). doi: [10.1002/aqc.2247](https://doi.org/10.1002/aqc.2247)
128. M. Ruckelshaus et al., Securing ocean benefits for society in the face of climate change. *Mar. Policy* **40**, 154–159 (2013). doi: [10.1016/j.marpol.2013.01.009](https://doi.org/10.1016/j.marpol.2013.01.009)
129. A. Barton, B. Hales, G. G. Waldbusser, C. Langdon, R. A. Feely, The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnol. Oceanogr.* **57**, 698–710 (2012). doi: [10.4319/lo.2012.57.3.0098](https://doi.org/10.4319/lo.2012.57.3.0098)
130. D. Narita, K. Rehdanz, R. S. J. Tol, Economic costs of ocean acidification: A look into the impacts on global shellfish production. *Clim. Change* **113**, 1049–1063 (2012). doi: [10.1007/s10584-011-0383-3](https://doi.org/10.1007/s10584-011-0383-3)

131. S. S. De Silva, "Climate change impacts: Challenges for aquaculture," in *Farming the Waters for People and Food*, R. P. Subasinghe *et al.*, Eds. (FAO and Network of Aquaculture Centres in Asia-Pacific, Rome and Bangkok, 2012), pp. 75–110.
132. C. A. Burge *et al.*, Climate change influences on marine infectious diseases: Implications for management and society. *Annu. Rev. Mar. Sci.* **6**, 249–277 (2014). doi: [10.1146/annurev-marine-010213-135029](https://doi.org/10.1146/annurev-marine-010213-135029); pmid: [23808894](https://pubmed.ncbi.nlm.nih.gov/23808894/)
133. J. Garai, "The impacts of climate change on the livelihoods of coastal people in Bangladesh: A sociological study," in *International Perspectives on Climate Change*, W. Leal Filho, F. Alves, S. Caerio, U. M. Azeiteiro, Eds. (Springer, Switzerland, 2014), pp. 151–163.
134. P.-Y. Chen, C.-C. Chen, L. F. Chu, B. McCarl, Evaluating the economic damage of climate change on global coral reefs. *Glob. Environ. Change* **30**, 12–20 (2015). doi: [10.1016/j.gloenvcha.2014.10.011](https://doi.org/10.1016/j.gloenvcha.2014.10.011)
135. Deloitte Access Economics, *Economic Contribution of the Great Barrier Reef* (Great Barrier Reef Marine Park Authority, Townsville, Australia, 2013).
136. L. M. Brander, K. Rehdanz, R. S. J. Tol, P. J. H. Van Beukering, The economic impact of ocean acidification on coral reefs. *Clim. Change Econ.* **03**, 1250002 (2012). doi: [10.1142/S2010007812500029](https://doi.org/10.1142/S2010007812500029)
137. L. M. Burke, K. Reydar, M. Spalding, A. Perry, *Reefs at Risk Revisited* (World Resources Institute, Washington, DC, 2011), p. 114.
138. M. Pascual, X. Rodó, S. P. Ellner, R. Colwell, M. J. Bouma, Cholera dynamics and El Niño-Southern Oscillation. *Science* **289**, 1766–1769 (2000). doi: [10.1126/science.289.5485.1766](https://doi.org/10.1126/science.289.5485.1766); pmid: [10976073](https://pubmed.ncbi.nlm.nih.gov/10976073/)
139. C. Baker-Austin *et al.*, Emerging Vibrio risk at high latitudes in response to ocean warming. *Nat. Clim. Change* **3**, 73–77 (2013). doi: [10.1038/nclimate1628](https://doi.org/10.1038/nclimate1628)
140. S. Altizer, R. S. Ostfeld, P. T. Johnson, S. Kutz, C. D. Harvell, Climate change and infectious diseases: From evidence to a predictive framework. *Science* **341**, 514–519 (2013). doi: [10.1126/science.1239401](https://doi.org/10.1126/science.1239401); pmid: [23908230](https://pubmed.ncbi.nlm.nih.gov/23908230/)
141. T. L. F. Leung, A. E. Bates, More rapid and severe disease outbreaks for aquaculture at the tropics: Implications for food security. *J. Appl. Ecol.* **50**, 215–222 (2013). doi: [10.1111/1365-2644.12017](https://doi.org/10.1111/1365-2644.12017)
142. T. Wheeler, J. von Braun, Climate change impacts on global food security. *Science* **341**, 508–513 (2013). doi: [10.1126/science.1239402](https://doi.org/10.1126/science.1239402); pmid: [23908229](https://pubmed.ncbi.nlm.nih.gov/23908229/)
143. R. P. Kelly, M. R. Caldwell, Ten ways states can combat ocean acidification (and why they should). *Harvard Environ. Law Rev.* **37**, 57–103 (2013). doi: [10.2139/ssrn.2020520](https://doi.org/10.2139/ssrn.2020520)
144. E. Mcleod *et al.*, Preparing to manage coral reefs for ocean acidification: Lessons from coral bleaching. *Front. Ecol. Environ.* **11**, 20–27 (2013). doi: [10.1890/110240](https://doi.org/10.1890/110240)
145. A. L. Strong, K. J. Kroeker, L. T. Teneva, L. A. Mease, R. P. Kelly, Ocean acidification 2.0: Managing our changing coastal ocean chemistry. *Bioscience* **64**, 581–592 (2014). doi: [10.1093/biosci/biu072](https://doi.org/10.1093/biosci/biu072)
146. R. Bille *et al.*, Taking action against ocean acidification: A review of management and policy options. *Environ. Manage.* **52**, 761–779 (2013). doi: [10.1007/s00267-013-0132-7](https://doi.org/10.1007/s00267-013-0132-7); pmid: [23897413](https://pubmed.ncbi.nlm.nih.gov/23897413/)
147. Committee on Geoengineering Climate, "Technical evaluation and discussion of impacts," in *Climate Intervention: Reflecting Sunlight to Cool Earth* (National Academy of Sciences, Washington, DC, 2015).
148. M. D. Eisaman *et al.*, CO<sub>2</sub> extraction from seawater using bipolar membrane electrodialysis. *Energy Environ. Sci.* **5**, 7346 (2012). doi: [10.1039/C2ee03393c](https://doi.org/10.1039/C2ee03393c)
149. M. J. H. van Oppen, J. K. Oliver, H. M. Putnam, R. D. Gates, Building coral reef resilience through assisted evolution. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 2307–2313 (2015). doi: [10.1073/pnas.1422301112](https://doi.org/10.1073/pnas.1422301112); pmid: [25646461](https://pubmed.ncbi.nlm.nih.gov/25646461/)
150. C. N. Young, S. A. Schopmeyer, D. Lirman, A review of reef restoration and coral propagation using the threatened genus *Acropora* in the Caribbean and Western Atlantic. *Bull. Mar. Sci.* **88**, 1075–1098 (2012). doi: [10.5343/bms.2011.1143](https://doi.org/10.5343/bms.2011.1143)
151. H. Govan *et al.*, *Status and Potential of Locally-Managed Marine Areas in the South Pacific: Meeting Nature Conservation and Sustainable Livelihood Targets Through Wide-Spread Implementation of LMMAs* (South Pacific Regional Environmental Program/WWF/WorldFish-Reefbase/Coral Reefs Initiative for the Pacific, Noumea, New Caledonia, 2009).
152. R. P. Kelly, S. R. Cooley, T. Klinger, Narratives can motivate environmental action: The Whiskey Creek ocean acidification story. *Ambio* **43**, 592–599 (2014). doi: [10.1007/s13280-013-0442-2](https://doi.org/10.1007/s13280-013-0442-2); pmid: [24081705](https://pubmed.ncbi.nlm.nih.gov/24081705/)
153. L. Weatherdon, A. Rogers, R. Sumaila, A. Magnan, W. W. L. Cheung, *The Oceans 2015 Initiative, Part II: An Updated Understanding of the Observed and Projected Impacts of Ocean Warming and Acidification on Marine and Coastal Socioeconomic Activities/Sectors* (Institut du Développement Durable et des Relations Internationales, Paris, 2015).
154. R. Murti, C. Buyck, Eds., *Safe Havens: Protected Areas for Disaster Risk Reduction and Climate Change Adaptation* (IUCN, Gland, Switzerland, 2014).
155. G. Keppel *et al.*, The capacity of refugia for conservation planning under climate change. *Front. Ecol. Environ.* **13**, 106–112 (2015). doi: [10.1890/140055](https://doi.org/10.1890/140055)
156. C. Cacciapaglia, R. van Woesik, Reef coral refugia in a rapidly changing ocean. *Glob. Change Biol.* **21**, 2272–2282 (2015). doi: [10.1111/gcb.12851](https://doi.org/10.1111/gcb.12851); pmid: [25646684](https://pubmed.ncbi.nlm.nih.gov/25646684/)
157. M. D. Mastrandrea *et al.*, *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* (IPCC, New York, 2010).

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Supplementary Text

Tables S1 and S2

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## Supplementary Materials for

### Contrasting futures for ocean and society from different anthropogenic CO<sub>2</sub> emissions scenarios

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#### This PDF file includes:

Supplementary Text  
Tables S1 and S2  
Full Reference List

## **Background information and rationale of expert judgment on the risk of impact due to CO<sub>2</sub> levels by 2100 (Fig. 2)**

This supplementary material provides the background information and rationale for the construction of the burning embers diagrams used in Figure 2 to represent the risk of impacts from CO<sub>2</sub> levels (by 2100) for keystone marine and coastal organisms and ecosystem services. This is the expert judgment of the authors on the overall risk balancing negative, neutral and positive impacts across species and regions using current literature.

Table S1- Definition of the color codes used in for the risk of impacts due to climate change, including ocean acidification, shown in Fig. 2 (after ref. 158).

Color	Risk	Definition
White	Undetectable	No risk due to climate change
Transition to yellow	Low	Notable, but low, risk of impacts due to climate change
Yellow	Moderate	Moderate risk of impacts due to climate change
Transition to red	Substantial	Substantial risk of impacts due to climate change
Red	High	Severe and widespread risk due to climate change
Purple	Very high	Even more severe/widespread, irreversibility or persistence, and substantial limitations to adaptation

Table S2. Color transitions used in Fig. 2, based upon the author team's expert judgement. N/A, denotes that level of risk of impact will not be reached by 2100.

	Color Transition	Sea surface temperature	
Seagrasses (mid latitude)	White to Yellow	Begin	0.5
		End	0.8
	Yellow to Red	Begin	1.5
		End	1.8
	Red to Purple	Begin	2.2
		End	3.0
Mangroves	White to Yellow	Begin	1.8
		End	3.0
	Yellow to Red	Begin	3.0
		End	3.2
	Red to Purple	Begin	N/A
		End	N/A
Warm water corals	White to Yellow	Begin	0.3
		End	0.4
	Yellow to Red	Begin	0.5
		End	0.8
	Red to Purple	Begin	0.8
		End	1.5
Pteropods (high latitude)	White to Yellow	Begin	0.7
		End	0.8
	Yellow to Red	Begin	0.8
		End	1.5
	Red to Purple	Begin	1.5
		End	2.0

Bivalves (mid latitude)	White to Yellow	Begin	0.4
		End	0.6
	Yellow to Red	Begin	0.9
		End	1.1
	Red to Purple	Begin	1.3
		End	1.5
Krill (high latitude)	White to Yellow	Begin	0.7
		End	0.9
	Yellow to Red	Begin	1.0
		End	1.6
	Red to Purple	Begin	1.8
		End	3.2
Finfish	White to Yellow	Begin	0.5
		End	0.7
	Yellow to Red	Begin	1.1
		End	1.3
	Red to Purple	Begin	1.4
		End	1.6
Open-ocean carbon uptake	White to Yellow	Begin	1
		End	1.5
	Yellow to Red	Begin	2
		End	3.2
	Red to Purple	Begin	N/A
		End	N/A
Coastal protection	White to Yellow	Begin	0.5
		End	0.8
	Yellow to Red	Begin	1.5
		End	1.8
	Red to Purple	Begin	2.2

		End	3.2
Recreational services from coral reefs	White to Yellow	Begin	0.6
		End	0.8
	Yellow to Red	Begin	1.0
		End	1.5
	Red to Purple	Begin	2.0
		End	3.2
Bivalve fisheries and aquaculture (mid latitude)	White to Yellow	Begin	1.1
		End	1.3
	Yellow to Red	Begin	1.7
		End	1.9
	Red to Purple	Begin	2.8
		End	3.2
Fin fisheries (low latitude)	White to Yellow	Begin	0.7
		End	0.9
	Yellow to Red	Begin	1.0
		End	1.2
	Red to Purple	Begin	2.0
		End	2.5
Fin fisheries (mid and high latitude)	White to Yellow	Begin	0.7
		End	0.9
	Yellow to Red	Begin	2.2
		End	3.2
	Red to Purple	Begin	N/A
		End	N/A

## **Seagrasses (mid latitude)**

Seagrasses, important habitats in coastal waters around the world, will be affected by climate change through a number of routes including direct effects of temperature on growth rates (159, 160), occurrence of disease (161), mortality and physiology, changes in light levels arising from sea level changes, changes in exposure to wave action (162), sometimes mediated through effects on adjacent ecosystems (163), and also by changes in the frequency and magnitude of extreme weather events. There will be changes in the distribution of seagrass communities locally and regionally. Here we take the example of temperate seagrasses including *Posidonia oceanica* from the Mediterranean, *Zostera* spp from the USA, Europe, and Australia, because the information on the effects of ocean warming and acidification for these species from several field studies is robust. Results indicate that temperate seagrass meadows have already been negatively impacted by rising sea surface temperatures (164). Models based on observations of natural populations indicate that at temperature increases of 1.5 to 3°C mortality of shoots of seagrasses will be such that populations will be unsustainable and meadows will decline to the point where their ecological functions as a habitat will cease (reduction to 10% of present density of a healthy meadow; ref. 164-167).

The confidence level is very high under RCP2.6 because of strong agreement in the literature. Confidence declines to high under RCP8.5 due to some uncertainty surrounding regional differences. For example, it has been suggested that the balance of effects on seagrass populations in the North East Atlantic could tip to positive due to the hypothetical opening of ecological niches with the decline of more sensitive species, and potential reduction of carbon limitation by elevated CO<sub>2</sub> which may help to ameliorate negative effects of other environmental drivers, such as warming, known to impact seagrass growth and survival (97).

## **Mangroves**

Mangroves are critically important coastal habitat for numerous species. Mangrove responses to increasing atmospheric CO<sub>2</sub> are complex, with some species thriving while others decline or exhibit little or no change (168). Temperature increase alone is likely to result in faster growth, reproduction, photosynthesis, and respiration, changes in community composition, diversity, and an expansion of latitudinal limits up to a certain point (169). Mangroves have already been observed to retreat with sea level rise (170). In many areas mangroves can adapt to sea level rise by landward migration, but these shifts threaten other coastal habitats such as salt marshes, which have other important biogeochemical and ecological roles. It is in areas with steep coastal inclines or coastal human infrastructure limiting landward migration that mangroves are most at risk. Climate change may lead to a maximum global loss of 10 to 15% of mangrove forest for a sea level rise of 0.6 m (high end of IPCC projections in AR4), but must be considered of secondary importance compared with current annual rates of deforestation of 1 to 2% (171). A large reservoir of below-ground nutrients, rapid rates of nutrient flux and

microbial decomposition, complex and highly efficient biotic controls, self- design and redundancy of keystone species, and numerous feedbacks, all contribute to mangrove resilience to various types of disturbance.

Mangrove response is species-specific and interacts with temperature, salinity, nutrient availability and patterns of precipitation. Many of these parameters are also subject to regional and local variation, as well as to human-induced pressures which changes over the coming decades are difficult to assess. Thus the confidence level decreases from high under RCP2.6 to low under RCP8.5.

### **Warm-water corals**

Warm-water corals form reefs that harbor great biodiversity and protect the coasts of low lying land masses. There is very high levels of confidence that impacts were undetectable up until the early 1980s, when coral reefs in the Caribbean and eastern Pacific exhibited mass coral bleaching, as well as temperature-related disease outbreaks in the Caribbean Sea (172). Given a conservative lag time of 10 years between the atmospheric concentration of CO<sub>2</sub> and changes in sea surface temperature, the atmospheric CO<sub>2</sub> level of 325 ppm reached in the early 1970s was sufficient to initiate widespread coral bleaching and decline of coral health worldwide (173). As the 1980s unfolded, visible impacts of increasing sea surface temperature were seen in a widening number of areas, with the first global event in 1997-1998 and the loss of 16% of coral reefs (high confidence; ref. 174). Further increases in atmospheric carbon dioxide and sea surface temperature have increased the risk to corals (high confidence), with multiple widespread bleaching events, including loss of a large fraction of living corals in the Caribbean in 2005 (175) and a subsequent global bleaching in 2010 (e.g. 176), and current conditions suggesting the development of a third global event in 2015-2016 (C.M. Eakin, unpublished observation). If CO<sub>2</sub> levels continue to increase, there is a very high risk that coral reefs would be negatively affected by doubled pre-industrial CO<sub>2</sub> through impacts of both warming-induced bleaching and ocean acidification (high confidence), supported by a wide array of modeling [e.g. (1, 59, 177-179)], experimental (e.g. 180), and field studies (72, 181). This leads to a very high level of confidence under RCP2.6 and a high level of confidence under RCP8.5.

### **Pteropods (high latitude)**

Pteropods are key links in ocean food webs between microscopic and larger organisms, including fish, birds and whales. Ocean acidification at levels anticipated under RCP8.5 leads to a decrease in pteropod shell production (182-184), an increase in shell degradation (185, 186), a decrease in swimming activity when ocean acidification is combined with freshening (187), and an increase in mortality that is enhanced at temperature changes smaller than those projected for RCP8.5 (184, 185). Shell dissolution has already been observed in high latitude

populations (66). Aragonite saturation ( $\Omega_a$ ) levels below 1.4 results in shell dissolution with severe shell dissolution between 0.8 and 1 (188). Despite high agreement amongst published findings, uncertainty remains surrounding the potential to adapt to environmental drivers because long-term laboratory experiments with pteropods are notoriously difficult. Hence the confidence level is medium under RCP2.6. However, confidence increases to very high under RCP8.5 because it is almost certain that genetic adaptation to such large and rapid changes in pH and temperature will not be possible.

### **Bivalves (mid latitude)**

Both cultured and wild bivalves are an important food source worldwide. Temperate bivalve shellfish, such as oysters, clams, mussels and scallops, have already been negatively impacted by ocean acidification. In the Northwest United States, Pacific oyster larval mortality has been associated with upwelling of natural CO<sub>2</sub>-rich waters acidified by additional fossil fuel CO<sub>2</sub> (high confidence; 129). Ocean acidification acts synergistically with deoxygenation (85) and warming (189, 190) to heighten physiological stress (191) on bivalve shellfish (high confidence), suggesting that future ocean conditions that include warming, deoxygenation, and acidification will be particularly difficult for members of this taxon. Archaeological/geological and modeling studies show range shifts of bivalves in response to prior and projected warming (192) and acidification (118). Model projections also anticipate decreases in mollusk body size under continued harvesting as conditions change farther from the present (193). Impacts are expected to be high to very high when CO<sub>2</sub> concentrations exceed those expected for 2100 in the RCP2.6 and 4.5 levels (medium certainty; 118, 193). The confidence level is medium both under RCP2.6 and RCP8.5 primarily due to the possibility of bivalves adapting over generations (194), or for specific species to outcompete other wild species in future conditions (*e.g.* 195).

### **Krill (high latitude)**

Krill (euphausid crustaceans) is a critical link in the food web at higher latitudes, supporting mammals and birds among many other species. Distributional changes and decreases in krill abundance have already been observed associated with temperature increase (196). The effect of changes in the extent of sea ice is considered to be an indirect effect of temperature. Temperature effects are predicted to be regional (197). If the extent of sea ice is maintained, populations in cooler waters may experience positive effects in response to small increases in temperature. In contrast, populations in warmer areas may experience some negative temperature effects by 2100 under RCP2.6. Since all life stages are associated with sea ice, decreases in krill stocks are projected to occur concurrently with the loss of sea ice habitat, potentially outweighing possible positive impacts (198). Increases in sea surface temperature of 1 to 2°C have significant impacts on krill. From Fig. 4 in Flores et al. (198) severe

disruptions of the life cycle are expected at a level of 2°C sea surface temperature rise and 500  $\mu\text{atm}$  pCO<sub>2</sub>. Therefore, high impact on populations would be reached approximately at the CO<sub>2</sub> level projected for 2100 by RCP4.5. Conditions in 2100 under the RCP2.6 scenario would be around the upper limit of the high risk range. Negative effects of ocean acidification on reproduction, larval and early life stages have been observed above 1250  $\mu\text{atm}$  pCO<sub>2</sub>, a value that is likely to be reached in parts of the Southern Ocean by 2100 under RCP8.5 (199). Figure 1 in Flores et al. (198) shows that the area with strongest sea ice decline partly overlaps with areas of high krill density (from the Peninsula to the South Orkneys). There is also a significant warming trend in this area which may force populations southwards into less productive regions. Substantial decline in the viability of major krill populations in the Southern Ocean may occur within the next 100 years (199), which could have catastrophic consequences for dependent marine mammals and birds. The genetic homogeneity of krill suggests that rapid adaptation through natural selection of more tolerant genotypes is unlikely (200). Considering uncertainties surrounding regional changes, some potentially positive effects and the relatively small number of studies, the level of confidence of future risks is medium under RCP2.6 and low under RCP8.5.

## **Finfish**

Marine fishes are important predators and prey in ocean ecosystems, contributing substantially to coastal economies, food security and livelihood. Warming-induced shifts in the abundance, geographic distribution, migration patterns, and phenology of marine species, including fishes, were reported and projected with very high confidence in the IPCC AR5 report (2). Empirical and theoretical evidence of range shifts in response to temperature gradients are reported across various taxa and many geographical locations (201-203), with observations suggesting that range shifts correspond with the rate and directionality of climate shifts —or ‘climate velocity’— across landscapes (43). Observed range shifts associated with ocean warming may result in hybridization between native and invasive species through overlapping ranges, leading to reduced fitness and thus potentially increasing the risks of genetic extinction and reducing the adaptability to environmental changes (204, 205). Some taxa are incapable of keeping pace with climate velocities, as observed with benthic invertebrates in the North Sea (44). The tropicalization of temperate marine ecosystems through poleward range shifts of tropical fish grazers increases the grazing rate of temperate macroalgae as seen in Japan and the Mediterranean (48). Such trophic impacts resulting from climate-induced range shifts are expected to affect ecosystem structure and dynamic in temperate reefs (48). Projected future changes in temperature and other physical and chemical oceanographic factors are expected to affect the distribution and abundance of marine fishes, as elaborated by species distribution models with rate of shift at present day rate under the RCP8.5 scenario (206). Limiting emissions to RCP2.6 is projected to reduce the average rate of range shift by 65% by mid 21st

century (42). Shifts in distribution of some species may be limited by the bathymetry or geographic boundaries, potentially resulting in high risk of local extinction particularly under high CO<sub>2</sub> emissions scenarios (207). While evidence suggests that adult fishes can survive high levels of CO<sub>2</sub>, behavioral studies have found significant changes in species' responses under levels of CO<sub>2</sub> elevated above those of the present day level (208). Long-term persistence of these phenomena remains unknown. Based on the above, fishes already experience medium risk of impacts at present day (high confidence). Risk increases from medium to high by end of 21<sup>st</sup> century when emissions change from RCP2.6 to RCP 4.5 and become very high under RCP8.5, highlighting the potential non-reversibility of the potential impacts.

Some evidence for direct and indirect impacts of ocean acidification on finfish is available but varies substantially between species. Also, understanding about the scope of evolutionary adaptation for marine fishes to climate change and ocean acidification are limited, although it is unlikely that majority of the species can fully adapt to expected changes in ocean properties without any impacts on their biology and ecology. Overall, we have robust evidence and high agreement (thus high confidence) from experimental data, field observations and mathematical modelling in detecting and attributing impacts for finfish in the present day and under RCP2.6. The uncertainty about the sensitivity to ocean acidification and scope for evolutionary adaptation leads to medium confidence levels for their risk under high emissions scenarios.

### **Open ocean carbon uptake**

The uptake of anthropogenic carbon by the ocean in the industrial period and in the future is a service that is predominantly provided by physico-chemical processes (209). The sensitivity of ocean carbon uptake to increasing cumulative CO<sub>2</sub> emissions, including effects of changing ocean chemistry, temperature, circulation and biology, is assessed along the following lines of quantitative evidence: (i) the fraction of total cumulative anthropogenic emissions taken up by the ocean over the industrial period and the 21st century in CMIP5 Earth System Model projections for the four RCPs (27); (ii) the fraction of additional (marginal) emissions remaining airborne or taken up by the ocean for background atmospheric CO<sub>2</sub> following the four RCPs (210). In addition, the risk of large-scale reorganization of ocean circulation, such as a collapse of the North Atlantic overturning circulation and associated reductions in allowable carbon emissions towards CO<sub>2</sub> stabilization, is increasing with the magnitude and rate of CO<sub>2</sub> emissions, in particular beyond the year 2100. Confidence level is high for both RCP 2.6 and RCP8.5 because the underlying physical and chemical process are well known.

### **Coastal protection**

Estimating the sensitivity of natural coastal protection to climate change requires to combine sensitivity across different ecosystems, especially coral reefs, mangrove forests and seagrass

beds. Other ecosystems provide coastal protection, including salt marshes, macroalgae, oyster and mussel beds, and also beaches, dunes and barrier islands (stabilized by organisms; 104, 211), but there is less understanding of the level of protection conferred by these other organisms and habitats (104). Although studies indicate some of these systems are already impacted by the effects of rising CO<sub>2</sub>, or suggest they will be in the near future, levels of sensitivity are not well established, are highly variable, and in some cases their overall influence on coastal protection may be uncertain (i.e., species are replaced by functional equivalents in this context; ref. 212).

We reason that some coastal protection has already been lost—a result of impacts on coral reefs, seagrasses and other ecosystems from sea temperature rise. In the case of corals, this began in the late 1970s. Recent papers demonstrate collapse in three-dimensional structure of reefs in the Caribbean (213) and the Seychelles (214), the second phase of which appears to be climate-related. Other studies show that some areas have not recovered from the 1997–98 and 2010 bleaching events and that some reefs have collapsed there (e.g. parts of the Seychelles). There is thus little doubt that the coastal protection function of some reefs has already been reduced. A decreasing protection may also be the case for seagrasses, although such effects have not been measured. It should also be noted that other human impacts have already largely destroyed, or are progressively destroying some of these ecosystems, through direct action (e.g. 85% oyster reefs lost globally and 1–2% of mangrove forests cut down per annum; ref. 215). It therefore appears that some impact on coastal protection has already occurred but we lack data to extrapolate globally, hence the confidence level is low in the present day.

Confidence in the loss of coastal protection decreases with increasing CO<sub>2</sub> emissions because coastal protection is conferred by a range of habitats and the co-dependency or interactions between them make projections difficult. For example, protection to seagrass beds conferred by coral reefs or the replacement of salt marsh with mangrove forest (163, 168). Additionally, human-driven pressure on these ecosystems is inherently difficult to forecast decades from now due to the possible implementation of new policies. Interacting effects of different symptoms of climate change such as increased temperature, decreasing pH, salinity, nutrient availability, patterns of precipitation and occurrence of pathogens will all influence the physiological response of individual species and ecosystems and thus further reduce the predictability of responses at higher emissions. Confidence is thus medium under RCP2.6 and low under RCP8.5.

### **Recreational services from coral reefs**

The impacts of CO<sub>2</sub> and sea surface temperature on the condition of coral reefs ultimately affect the flow of ecosystem goods and services to human communities and businesses. There is an interesting lag between the degradation of corals and coral reefs and a detectable effect on human users. For this reason, the risk of impacts on human recreation and tourism begins

significantly later than ecosystem changes are detected by marine scientists. As of 2015, atmospheric CO<sub>2</sub> concentration is 400 ppm and average sea surface temperature is 0.8°C above that of the pre-industrial period. Mass bleaching and mortality events have degraded coral populations and this has negatively impacted the recreational choices of a few, but not most, clients (high confidence; ref. 53). This impact on tourists' choice is expected to reach moderate to high-levels as CO<sub>2</sub> approaches 450 ppm, at which point reefs begin net erosion and sea level, coral cover, storms, and other environmental risks become significant considerations in destination attractiveness (medium confidence). By 600 ppm, the breakdown of the structure of most reefs becomes obvious, other changes such as reduced coral cover and increased sea level and storm damage mean that significant coastal recreation and tourism becomes difficult in most circumstances and many operations may be discarded (53). This will have a very high impact on recreational services (medium confidence). Confidence levels under RCP2.6 and RCP8.5 are medium because predicting tourists' expectations several decades from now remains relatively uncertain.

### **Bivalve fisheries and aquaculture (mid latitude)**

Ecosystem services provided by temperate bivalves include marine harvests (both from capture fisheries and aquaculture), water quality maintenance, and coastal stabilization. Of these, marine harvests are easiest to quantify, and have been the subject of several assessments. Confidence is high that ocean acidification has already jeopardized marine harvest revenues in the Northwest United States (216). Although the affected hatcheries have taken steps to enhance monitoring, alter hatchery water intake and treatment, and diversify hatchery locations (217), these adaptations will only delay the onset of ocean acidification-related problems (high confidence). Wild harvest populations are fully exposed to ocean acidification and warming, and societal adaptations like these are not applicable. Services provided by bivalves will continue even if populations migrate, decrease in size, or individuals become smaller, so effects are somewhat more delayed than those on shellfish themselves. In 2100, impacts are expected to be moderate under RCP2.6 and very high under RCP8.5. The level of confidence declines as a function of increasing CO<sub>2</sub> emissions due to uncertainty about the extent of local adaptations: medium under RCP2.6 and low under RCP8.5.

### **Fin fisheries (low latitude)**

Evidence of climate change altering species composition of tropical marine fisheries is already apparent globally (110). Simulations suggest that, as a result of range shifts and decrease in abundance of fish stocks, fisheries catch is likely to decline in tropical regions (117, 121). Projections also suggest that marine taxa in tropical regions are likely to lose critical habitat (e.g., coral reefs), leading to declines in fisheries productivity (120). Because of the magnitude

of impacts, capacity for the fisheries to reduce such risks by protection, repair or adaptation is expected to be low (2). Thus, these impacts increase with increasing CO<sub>2</sub> emissions. Risk of impacts is close to medium level in present day, and increases to high and very high when CO<sub>2</sub> concentration reaches the levels expected in 2100 under RCP4.5 and RCP8.5, respectively.

The scope of adaptation for low latitude fin fisheries is low because of the high level of impacts on ecosystems and fisheries resources, lack of new fishing opportunities from species range shifts to compensate for the impacts and relatively lower social-economic capacity of many countries to adapt changes. Thus, confidence level is high on projected impacts on low latitude fin fisheries.

### **Fin fisheries (mid and high latitude)**

Evidence that climate change effects altering species composition in mid and high latitude fisheries can already be observed globally, with increasing dominance of warmer-water species since the 1970s (110). Global-scale projections suggest substantial increases in potential fisheries catch in high latitude regions (117, 121) under RCP8.5 by mid- to end-21st century. However, ocean acidification increases uncertainty surrounding the potential fisheries gain because the Arctic is a hotspot of ocean acidification (118). Risks of impacts of warming, ocean acidification and deoxygenation on mid-latitude regions are variable (110, 117). Overall, existing fish stocks are expected to decrease in catch while new opportunities for fisheries may emerge from range expansion of warmer-water. Declines in catch have been projected for fisheries in the Northeast Pacific (123), Northwest Atlantic (218), and waters around the U.K. (219) by mid 21st century under SRES A1B and A2 scenarios (equivalent to RCP6.0 to 8.5). While it is uncertain whether small-scale fisheries will have the mobility to follow shifts in ranges of target species, those with access to multiple gears types may be able to adapt more easily to climate-related changes in stock composition. Societal adaptation to reduce the risk of impacts is expected to be relatively higher than tropical fisheries. Thus, medium risk is assigned from present day, and risk increases to high when CO<sub>2</sub> concentration is beyond level expected from RCP4.5.

Risk to fisheries at mid and high latitudes depends on how the fishers, fishing industries and fisheries management bodies respond and adapt to changes in species composition and distribution. Prediction of the scope of such adaptive response is uncertain particularly under greater changes in fisheries resources. Thus, the confidence level is high under RCP2.6 and low under RCP8.5.

## References and Notes

1. O. Hoegh-Guldberg *et al.*, “The ocean,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 1655–1731.
2. H.-O. Pörtner *et al.*, “Ocean systems,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 411–484.
3. P. P. Wong *et al.*, “Coastal systems and low-lying areas,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 361–409.
4. C. Mora, D. P. Tittensor, S. Adl, A. G. Simpson, B. Worm, How many species are there on Earth and in the ocean? *PLOS Biol.* **9**, e1001127 (2011). [Medline](#)  
[doi:10.1371/journal.pbio.1001127](https://doi.org/10.1371/journal.pbio.1001127)
5. Food and Agricultural Organization (FAO), *The State of World Fisheries and Aquaculture 2014* (FAO, Rome, 2014).
6. United Nations, *United Nations Framework Convention on Climate Change* (United Nations, New York, 1992).
7. Copenhagen Accord, *Decision 2/CP.15: Copenhagen Accord* (UNFCCC, Geneva, 2009).
8. E. R. Harrould-Kolieb, D. Herr, Ocean acidification and climate change: Synergies and challenges of addressing both under the UNFCCC. *Clim. Policy* **12**, 378–389 (2012).  
[doi:10.1080/14693062.2012.620788](https://doi.org/10.1080/14693062.2012.620788)
9. IPCC, “Summary for policymakers,” in *Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), p. 1–32.
10. T. F. Stocker *et al.*, “Technical summary,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 33–115.
11. K. M. Strassmann, G. K. Plattner, F. Joos, CO<sub>2</sub> and non-CO<sub>2</sub> radiative forcings in climate projections for twenty-first century mitigation scenarios. *Clim. Dyn.* **33**, 737–749 (2009). [doi:10.1007/s00382-008-0505-4](https://doi.org/10.1007/s00382-008-0505-4)
12. J.-P. Gattuso, L. Hansson, “Ocean acidification: Background and history,” in *Ocean Acidification*, J.-P. Gattuso, L. Hansson, Eds. (Oxford Univ. Press, Oxford, 2011), pp. 1–20.

13. L. A. Levin, K.-K. Liu, K.-C. Emeis, D. L. Breitburg, J. Cloern, C. Deutsch, M. Giani, A. Goffart, E. E. Hofmann, Z. Lachkar, K. Limburg, S.-M. Liu, E. Montes, W. Naqvi, O. Ragueneau, C. Rabouille, S. K. Sarkar, D. P. Swaney, P. Wassman, K. F. Wishner, Comparative biogeochemistry-ecosystem-human interactions on dynamic continental margins. *J. Mar. Syst.* **141**, 3–17 (2015). [doi:10.1016/j.jmarsys.2014.04.016](https://doi.org/10.1016/j.jmarsys.2014.04.016)
14. D. Lüthi, M. Le Floch, B. Bereiter, T. Blunier, J. M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, T. F. Stocker, High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* **453**, 379–382 (2008). [Medline doi:10.1038/nature06949](#)
15. T. Friedrich, A. Timmermann, A. Abe-Ouchi, N. R. Bates, M. O. Chikamoto, M. J. Church, J. E. Dore, D. K. Gledhill, M. González-Dávila, M. Heinemann, T. Ilyina, J. H. Jungclaus, E. McLeod, A. Mouchet, J. M. Santana-Casiano, Detecting regional anthropogenic trends in ocean acidification against natural variability. *Nat. Clim. Change* **2**, 167–171 (2012). [doi:10.1038/nclimate1372](https://doi.org/10.1038/nclimate1372)
16. F. Joos, R. Spahni, Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 1425–1430 (2008). [Medline doi:10.1073/pnas.0707386105](#)
17. R. A. Feely, C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, B. Hales, Evidence for upwelling of corrosive “acidified” water onto the continental shelf. *Science* **320**, 1490–1492 (2008). [Medline doi:10.1126/science.1155676](#)
18. J. Salisbury, M. Green, C. Hunt, J. Campbell, Coastal acidification by rivers: A new threat to shellfish? *Eos* **89**, 513 (2008). [doi:10.1029/2008EO500001](https://doi.org/10.1029/2008EO500001)
19. W.-J. Cai, X. Hu, W.-J. Huang, M. C. Murrell, J. C. Lehrter, S. E. Lohrenz, W.-C. Chou, W. Zhai, J. T. Hollibaugh, Y. Wang, P. Zhao, X. Guo, K. Gundersen, M. Dai, G.-C. Gong, Acidification of subsurface coastal waters enhanced by eutrophication. *Nat. Geosci.* **4**, 766–770 (2011). [doi:10.1038/ngeo1297](https://doi.org/10.1038/ngeo1297)
20. A. V. Borges, N. Gypens, Carbonate chemistry in the coastal zone responds more strongly to eutrophication than to ocean acidification. *Limnol. Oceanogr.* **55**, 346–353 (2010). [10.4319/lo.2010.55.1.0346 doi:10.4319/lo.2010.55.1.0346](https://doi.org/10.4319/lo.2010.55.1.0346)
21. K. M. Keller, F. Joos, C. C. Raible, Time of emergence of trends in ocean biogeochemistry. *Biogeosciences* **11**, 3647–3659 (2014). [doi:10.5194/bg-11-3647-2014](https://doi.org/10.5194/bg-11-3647-2014)
22. K. B. Rodgers, J. Lin, T. L. Frölicher, Emergence of multiple ocean ecosystem drivers in a large ensemble suite with an Earth system model. *Biogeosciences* **12**, 3301–3320 (2015). [doi:10.5194/bg-12-3301-2015](https://doi.org/10.5194/bg-12-3301-2015)
23. L. Bopp, L. Resplandy, J. C. Orr, S. C. Doney, J. P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra, M. Vichi, Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences* **10**, 6225–6245 (2013). [doi:10.5194/bg-10-6225-2013](https://doi.org/10.5194/bg-10-6225-2013)
24. M. Steinacher, F. Joos, T. F. Stocker, Allowable carbon emissions lowered by multiple climate targets. *Nature* **499**, 197–201 (2013). [Medline doi:10.1038/nature12269](#)

25. P. Ciais *et al.*, “Carbon and other biogeochemical cycles,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 465–570.
26. T. A. Boden, G. Marland, R. J. Andres, *Global, Regional, and National Fossil-Fuel CO<sub>2</sub> Emissions* (Carbon Dioxide Information Analysis Center, Oak Ridge, TN, 2013).
27. C. Jones *et al.*, Twenty-first-century compatible CO<sub>2</sub> emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways. *J. Clim.* **26**, 4398–4413 (2013).
28. J. A. Church *et al.*, “Sea level change,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 1137–1216.
29. T. Roy, L. Bopp, M. Gehlen, B. Schneider, P. Cadule, T. L. Frölicher, J. Segschneider, J. Tjiputra, C. Heinze, F. Joos, Regional impacts of climate change and atmospheric CO<sub>2</sub> on future ocean carbon uptake: A multimodel linear feedback analysis. *J. Clim.* **24**, 2300–2318 (2011). [doi:10.1175/2010JCLI3787.1](https://doi.org/10.1175/2010JCLI3787.1)
30. T. L. Frölicher, F. Joos, Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. *Clim. Dyn.* **35**, 1439–1459 (2010). [doi:10.1007/s00382-009-0727-0](https://doi.org/10.1007/s00382-009-0727-0)
31. S. Emerson, S. Bushinsky, Oxygen oxygen concentrations and biological fluxes in the open ocean. *Oceanography* **27**, 168–171 (2014). [doi:10.5670/oceanog.2014.20](https://doi.org/10.5670/oceanog.2014.20)
32. V. Cocco, F. Joos, M. Steinacher, T. L. Frölicher, L. Bopp, J. Dunne, M. Gehlen, C. Heinze, J. Orr, A. Oschlies, B. Schneider, J. Segschneider, J. Tjiputra, Oxygen and indicators of stress for marine life in multi-model global warming projections. *Biogeosciences* **10**, 1849–1868 (2013). [doi:10.5194/bg-10-1849-2013](https://doi.org/10.5194/bg-10-1849-2013)
33. E. C. Shaw, B. I. McNeil, B. Tilbrook, R. Matear, M. L. Bates, Anthropogenic changes to seawater buffer capacity combined with natural reef metabolism induce extreme future coral reef CO<sub>2</sub> conditions. *Glob. Change Biol.* **19**, 1632–1641 (2013). [Medline doi:10.1111/gcb.12154](https://doi.org/10.1111/gcb.12154)
34. T. Cyronak, I. R. Santos, D. V. Erler, D. T. Maher, B. D. Eyre, Drivers of pCO<sub>2</sub> variability in two contrasting coral reef lagoons: The influence of submarine groundwater discharge. *Global Biogeochem. Cycles* **28**, 398–414 (2014). [doi:10.1002/2013GB004598](https://doi.org/10.1002/2013GB004598)
35. L. L. Robbins, J. G. Wynn, J. T. Lisle, K. K. Yates, P. O. Knorr, R. H. Byrne, X. Liu, M. C. Patsavas, K. Azetsu-Scott, T. Takahashi, Baseline monitoring of the western Arctic Ocean estimates 20% of Canadian basin surface waters are undersaturated with respect to aragonite. *PLOS ONE* **8**, e73796 (2013). [Medline doi:10.1371/journal.pone.0073796](https://doi.org/10.1371/journal.pone.0073796)
36. M. Mattsdotter Björk, A. Fransson, A. Torstensson, M. Chierici, Ocean acidification state in western Antarctic surface waters: Controls and interannual variability. *Biogeosciences* **11**, 57–73 (2014). [doi:10.5194/bg-11-57-2014](https://doi.org/10.5194/bg-11-57-2014)

37. M. Gehlen, R. Séférian, D. O. B. Jones, T. Roy, R. Roth, J. Barry, L. Bopp, S. C. Doney, J. P. Dunne, C. Heinze, F. Joos, J. C. Orr, L. Resplandy, J. Segschneider, J. Tjiputra, Projected pH reductions by 2100 might put deep North Atlantic biodiversity at risk. *Biogeosciences* **11**, 6955–6967 (2014). [doi:10.5194/bg-11-6955-2014](https://doi.org/10.5194/bg-11-6955-2014)
38. P. W. Boyd, S. T. Lennartz, D. M. Glover, S. C. Doney, Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nat. Clim. Change* **5**, 71–79 (2015). [doi:10.1038/nclimate2441](https://doi.org/10.1038/nclimate2441)
39. U. Riebesell, J.-P. Gattuso, Lessons learned from ocean acidification research. *Nat. Clim. Change* **5**, 12–14 (2015). [doi:10.1038/nclimate2456](https://doi.org/10.1038/nclimate2456)
40. E. Poloczanska, O. Hoegh-Guldberg, W. Cheung, H.-O. Pörtner, M. T. Burrows, “Observed global responses of marine biogeography, abundance, and phenology to climate change,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 123–127.
41. L. E. Chambers, R. Altwegg, C. Barbraud, P. Barnard, L. J. Beaumont, R. J. Crawford, J. M. Durant, L. Hughes, M. R. Keatley, M. Low, P. C. Morellato, E. S. Poloczanska, V. Ruoppolo, R. E. Vanstreels, E. J. Woehler, A. C. Wolfaardt, Phenological changes in the southern hemisphere. *PLOS ONE* **8**, e75514 (2013). [Medline doi:10.1371/journal.pone.0075514](https://doi.org/10.1371/journal.pone.0075514)
42. M. C. Jones, W. W. L. Cheung, Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES J. Mar. Sci.* **72**, 741–752 (2015). [doi:10.1093/icesjms/fsu172](https://doi.org/10.1093/icesjms/fsu172)
43. M. L. Pinsky, B. Worm, M. J. Fogarty, J. L. Sarmiento, S. A. Levin, Marine taxa track local climate velocities. *Science* **341**, 1239–1242 (2013). [Medline doi:10.1126/science.1239352](https://doi.org/10.1126/science.1239352)
44. J. G. Hiddink, M. T. Burrows, J. García Molinos, Temperature tracking by North Sea benthic invertebrates in response to climate change. *Glob. Change Biol.* **21**, 117–129 (2015). [Medline doi:10.1111/gcb.12726](https://doi.org/10.1111/gcb.12726)
45. M. S. Wisz, O. Broennimann, P. Grönkjaer, P. R. Møller, S. M. Olsen, D. Swingedouw, R. B. Hedeholm, E. E. Nielsen, A. Guisan, L. Pellissier, Arctic warming will promote Atlantic–Pacific fish interchange. *Nat. Clim. Change* **5**, 261–265 (2015). [doi:10.1038/nclimate2500](https://doi.org/10.1038/nclimate2500)
46. O. Hoegh-Guldberg, J. F. Bruno, The impact of climate change on the world’s marine ecosystems. *Science* **328**, 1523–1528 (2010). [Medline doi:10.1126/science.1189930](https://doi.org/10.1126/science.1189930)
47. J. P. Gibert, J. P. DeLong, Temperature alters food web body-size structure. *Biol. Lett.* **10**, 20140473 (2014). [Medline doi:10.1098/rsbl.2014.0473](https://doi.org/10.1098/rsbl.2014.0473)
48. A. Vergés, P. D. Steinberg, M. E. Hay, A. G. Poore, A. H. Campbell, E. Ballesteros, K. L. Heck Jr., D. J. Booth, M. A. Coleman, D. A. Feary, W. Figueira, T. Langlois, E. M. Marzinelli, T. Mizerek, P. J. Mumby, Y. Nakamura, M. Roughan, E. van Sebille, A. S. Gupta, D. A. Smale, F. Tomas, T. Wernberg, S. K. Wilson, The tropicalization of

- temperate marine ecosystems: Climate-mediated changes in herbivory and community phase shifts. *Proc. Biol. Sci.* **281**, 20140846 (2014). [Medline](#)  
[doi:10.1098/rspb.2014.0846](#)
49. L. Schlüter, K. T. Lohbeck, M. A. Gutowska, J. P. Gröger, U. Riebesell, T. B. H. Reusch, Adaptation of a globally important coccolithophore to ocean warming and acidification. *Nat. Clim. Change* **4**, 1024–1030 (2014). [doi:10.1038/nclimate2379](#)
50. N. J. Muñoz, A. P. Farrell, J. W. Heath, B. D. Neff, Adaptive potential of a Pacific salmon challenged by climate change. *Nat. Clim. Change* **5**, 163–166 (2015).  
[doi:10.1038/nclimate2473](#)
51. J.-P. Gattuso, O. Hoegh-Guldberg, H.-O. Pörtner, “Coral reefs,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 97–100.
52. N. A. Graham, S. Jennings, M. A. MacNeil, D. Mouillot, S. K. Wilson, Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature* **518**, 94–97 (2015).  
[Medline](#) [doi:10.1038/nature14140](#)
53. O. Hoegh-Guldberg, P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, M. E. Hatziolos, Coral reefs under rapid climate change and ocean acidification. *Science* **318**, 1737–1742 (2007).  
[Medline](#) [doi:10.1126/science.1152509](#)
54. B. C. C. Hume, C. D’Angelo, E. G. Smith, J. R. Stevens, J. Burt, J. Wiedenmann, *Symbiodinium thermophilum* sp. nov., a thermotolerant symbiotic alga prevalent in corals of the world’s hottest sea, the Persian/Arabian Gulf. *Sci. Rep.* **5**, 8562 (2015).  
[Medline](#) [doi:10.1038/srep08562](#)
55. R. N. Silverstein, R. Cunning, A. C. Baker, Change in algal symbiont communities after bleaching, not prior heat exposure, increases heat tolerance of reef corals. *Glob. Change Biol.* **21**, 236–249 (2015). [Medline](#) [doi:10.1111/gcb.12706](#)
56. O. Hoegh-Guldberg, The adaptation of coral reefs to climate change: Is the Red Queen being outpaced? *Sci. Mar.* **76**, 403–408 (2012). [doi:10.3989/scimar.03660.29A](#)
57. S. R. Palumbi, D. J. Barshis, N. Traylor-Knowles, R. A. Bay, Mechanisms of reef coral resistance to future climate change. *Science* **344**, 895–898 (2014). [Medline](#)
58. M. Schweinsberg, L. C. Weiss, S. Striewski, R. Tollrian, K. P. Lampert, More than one genotype: How common is intracolonial genetic variability in scleractinian corals? *Mol. Ecol.* **24**, 2673–2685 (2015). [Medline](#) [doi:10.1111/mec.13200](#)
59. C. A. Logan, J. P. Dunne, C. M. Eakin, S. D. Donner, Incorporating adaptive responses into future projections of coral bleaching. *Glob. Change Biol.* **20**, 125–139 (2014).  
10.1111/gcb.12390 [Medline](#) [doi:10.1111/gcb.12390](#)

60. C. M. Eakin, Lamarck was partially right—and that is good for corals. *Science* **344**, 798–799 (2014). [Medline](#) [doi:10.1126/science.1254136](https://doi.org/10.1126/science.1254136)
61. J. M. Roberts, A. J. Wheeler, A. Freiwald, Reefs of the deep: The biology and geology of cold-water coral ecosystems. *Science* **312**, 543–547 (2006). [Medline](#) [doi:10.1126/science.1119861](https://doi.org/10.1126/science.1119861)
62. J.-P. Gattuso *et al.*, “Ocean acidification: Background and history,” in *Ocean Acidification*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 129–131.
63. J. Meyer, U. Riebesell, Reviews and Syntheses: Responses of coccolithophores to ocean acidification: A meta-analysis. *Biogeosciences* **12**, 1671–1682 (2015). [doi:10.5194/bg-12-1671-2015](https://doi.org/10.5194/bg-12-1671-2015)
64. K. J. S. Meier, L. Beaufort, S. Heussner, P. Ziveri, The role of ocean acidification in *Emiliania huxleyi* coccolith thinning in the Mediterranean Sea. *Biogeosciences* **11**, 2857–2869 (2014). [doi:10.5194/bg-11-2857-2014](https://doi.org/10.5194/bg-11-2857-2014)
65. N. Bednaršek, G. A. Tarling, D. C. E. Bakker, S. Fielding, R. A. Feely, Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation. *PLOS ONE* **9**, e109183 (2014). [Medline](#) [doi:10.1371/journal.pone.0109183](https://doi.org/10.1371/journal.pone.0109183)
66. N. Bednaršek, G. A. Tarling, D. C. E. Bakker, S. Fielding, E. M. Jones, H. J. Venables, P. Ward, A. Kuzirian, B. Lézé, R. A. Feely, E. J. Murphy, Extensive dissolution of live pteropods in the Southern Ocean. *Nat. Geosci.* **5**, 881–885 (2012). [doi:10.1038/ngeo1635](https://doi.org/10.1038/ngeo1635)
67. U. Riebesell, J.-P. Gattuso, T. F. Thingstad, J. J. Middelburg, Arctic ocean acidification: Pelagic ecosystem and biogeochemical responses during a mesocosm study. *Biogeosciences* **10**, 5619–5626 (2013). [doi:10.5194/bg-10-5619-2013](https://doi.org/10.5194/bg-10-5619-2013)
68. S. Richier, E. P. Achterberg, C. Dumousseaud, A. J. Poulton, D. J. Suggett, T. Tyrrell, M. V. Zubkov, C. M. Moore, Phytoplankton responses and associated carbon cycling during shipboard carbonate chemistry manipulation experiments conducted around Northwest European shelf seas. *Biogeosciences* **11**, 4733–4752 (2014). [doi:10.5194/bg-11-4733-2014](https://doi.org/10.5194/bg-11-4733-2014)
69. S. Endres, L. Galgani, U. Riebesell, K. G. Schulz, A. Engel, Stimulated bacterial growth under elevated pCO<sub>2</sub>: Results from an off-shore mesocosm study. *PLOS ONE* **9**, e99228 (2014). [Medline](#) [doi:10.1371/journal.pone.0099228](https://doi.org/10.1371/journal.pone.0099228)
70. S. L. Garrard, M. C. Gambi, M. B. Scipione, F. P. Patti, M. Lorenti, V. Zupo, D. M. Paterson, M. C. Buia, Indirect effects may buffer negative responses of seagrass invertebrate communities to ocean acidification. *J. Exp. Mar. Biol. Ecol.* **461**, 31–38 (2014). [doi:10.1016/j.jembe.2014.07.011](https://doi.org/10.1016/j.jembe.2014.07.011)
71. A. Ordoñez, C. Doropoulos, G. Diaz-Pulido, Effects of ocean acidification on population dynamics and community structure of crustose coralline algae. *Biol. Bull.* **226**, 255–268 (2014). [Medline](#)

72. J. Silverman, K. Schneider, D. I. Kline, T. Rivlin, A. Rivlin, S. Hamylton, B. Lazar, J. Erez, K. Caldeira, Community calcification in Lizard Island, Great Barrier Reef: A 33 year perspective. *Geochim. Cosmochim. Acta* **144**, 72–81 (2014). [doi:10.1016/j.gca.2014.09.011](https://doi.org/10.1016/j.gca.2014.09.011)
73. N. J. Silbiger, Ò. Guadayol, F. I. M. Thomas, M. J. Donahue, Reefs shift from net accretion to net erosion along a natural environmental gradient. *Mar. Ecol. Prog. Ser.* **515**, 33–44 (2014). [doi:10.3354/meps10999](https://doi.org/10.3354/meps10999)
74. J. M. Sunday, P. Calosi, S. Dupont, P. L. Munday, J. H. Stillman, T. B. Reusch, Evolution in an acidifying ocean. *Trends Ecol. Evol.* **29**, 117–125 (2014). [Medline](#) [doi:10.1016/j.tree.2013.11.001](https://doi.org/10.1016/j.tree.2013.11.001)
75. K. T. Lohbeck, U. Riebesell, T. B. H. Reusch, Gene expression changes in the coccolithophore *Emiliania huxleyi* after 500 generations of selection to ocean acidification. *Proc. R. Soc. London Ser. B* **281**, 20140003–20140003 (2014). [Medline](#) [doi:10.1098/rspb.2014.0003](https://doi.org/10.1098/rspb.2014.0003)
76. P. Thor, S. Dupont, Transgenerational effects alleviate severe fecundity loss during ocean acidification in a ubiquitous planktonic copepod. *Glob. Change Biol.* **21**, 2261–2271 (2015). [Medline](#) [doi:10.1111/gcb.12815](https://doi.org/10.1111/gcb.12815)
77. C. C. Suckling, M. S. Clark, C. Beveridge, L. Brunner, A. D. Hughes, E. M. Harper, E. J. Cook, A. J. Davies, L. S. Peck, Experimental influence of pH on the early life-stages of sea urchins II: Increasing parental exposure times gives rise to different responses. *Invertebr. Reprod. Dev.* **58**, 161–175 (2014). [doi:10.1080/07924259.2013.875951](https://doi.org/10.1080/07924259.2013.875951)
78. P. L. Munday, Transgenerational acclimation of fishes to climate change and ocean acidification. *F1000Prime Rep.* **6**, 99 (2014). [Medline](#) [doi:10.12703/P6-99](https://doi.org/10.12703/P6-99)
79. R. J. Diaz, R. Rosenberg, Spreading dead zones and consequences for marine ecosystems. *Science* **321**, 926–929 (2008). [Medline](#) [doi:10.1126/science.1156401](https://doi.org/10.1126/science.1156401)
80. H.-O. Pörtner, Oxygen- and capacity-limitation of thermal tolerance: A matrix for integrating climate-related stressor effects in marine ecosystems. *J. Exp. Biol.* **213**, 881–893 (2010). [Medline](#) [doi:10.1242/jeb.037523](https://doi.org/10.1242/jeb.037523)
81. A. Brown, S. Thatje, The effects of changing climate on faunal depth distributions determine winners and losers. *Glob. Change Biol.* **21**, 173–180 (2015). [Medline](#) [doi:10.1111/gcb.12680](https://doi.org/10.1111/gcb.12680)
82. D. Storch, L. Menzel, S. Frickenhaus, H.-O. Pörtner, Climate sensitivity across marine domains of life: Limits to evolutionary adaptation shape species interactions. *Glob. Change Biol.* **20**, 3059–3067 (2014). [Medline](#) [doi:10.1111/gcb.12645](https://doi.org/10.1111/gcb.12645)
83. J. S. Stewart, E. L. Hazen, S. J. Bograd, J. E. Byrnes, D. G. Foley, W. F. Gilly, B. H. Robison, J. C. Field, Combined climate- and prey-mediated range expansion of Humboldt squid (*Dosidicus gigas*), a large marine predator in the California Current System. *Glob. Change Biol.* **20**, 1832–1843 (2014). [Medline](#) [doi:10.1111/gcb.12502](https://doi.org/10.1111/gcb.12502)
84. J. D. Gaitán-Espitia, J. R. Hancock, J. L. Padilla-Gamiño, E. B. Rivest, C. A. Blanchette, D. C. Reed, G. E. Hofmann, Interactive effects of elevated temperature and pCO<sub>2</sub> on

- early-life-history stages of the giant kelp *Macrocystis pyrifera*. *J. Exp. Mar. Biol. Ecol.* **457**, 51–58 (2014). [doi:10.1016/j.jembe.2014.03.018](https://doi.org/10.1016/j.jembe.2014.03.018)
85. C. J. Gobler, E. L. DePasquale, A. W. Griffith, H. Baumann, Hypoxia and acidification have additive and synergistic negative effects on the growth, survival, and metamorphosis of early life stage bivalves. *PLOS ONE* **9**, e83648 (2014). [Medline doi:10.1371/journal.pone.0083648](https://doi.org/10.1371/journal.pone.0083648)
86. C. L. Mackenzie, G. A. Ormondroyd, S. F. Curling, R. J. Ball, N. M. Whiteley, S. K. Malham, Ocean warming, more than acidification, reduces shell strength in a commercial shellfish species during food limitation. *PLOS ONE* **9**, e86764 (2014). [Medline doi:10.1371/journal.pone.0086764](https://doi.org/10.1371/journal.pone.0086764)
87. D. Madeira, L. Narciso, M. S. Diniz, C. Vinagre, Synergy of environmental variables alters the thermal window and heat shock response: An experimental test with the crab *Pachygrapsus marmoratus*. *Mar. Environ. Res.* **98**, 21–28 (2014). [Medline doi:10.1016/j.marenvres.2014.03.011](https://doi.org/10.1016/j.marenvres.2014.03.011)
88. R. Rosa, K. Trübenbach, M. S. Pimentel, J. Boavida-Portugal, F. Faleiro, M. Baptista, G. Dionísio, R. Calado, H. O. Pörtner, T. Repolho, Differential impacts of ocean acidification and warming on winter and summer progeny of a coastal squid (*Loligo vulgaris*). *J. Exp. Biol.* **217**, 518–525 (2014). [Medline doi:10.1242/jeb.096081](https://doi.org/10.1242/jeb.096081)
89. C. A. Frieder, J. P. Gonzalez, E. E. Bockmon, M. O. Navarro, L. A. Levin, Can variable pH and low oxygen moderate ocean acidification outcomes for mussel larvae? *Glob. Change Biol.* **20**, 754–764 (2014). [Medline doi:10.1111/gcb.12485](https://doi.org/10.1111/gcb.12485)
90. J. Mukherjee, K. K. Wong, K. H. Chandramouli, P. Y. Qian, P. T. Leung, R. S. Wu, V. Thiagarajan, Proteomic response of marine invertebrate larvae to ocean acidification and hypoxia during metamorphosis and calcification. *J. Exp. Biol.* **216**, 4580–4589 (2013). [Medline doi:10.1242/jeb.094516](https://doi.org/10.1242/jeb.094516)
91. C. Deutsch, A. Ferrel, B. Seibel, H.-O. Pörtner, R. B. Huey, Climate change tightens a metabolic constraint on marine habitats. *Science* **348**, 1132–1135 (2015). [doi:10.1126/science.aaa1605](https://doi.org/10.1126/science.aaa1605)
92. S. Comeau, R. C. Carpenter, P. J. Edmunds, Effects of irradiance on the response of the coral *Acropora pulchra* and the calcifying alga *Hydrolithon reinboldii* to temperature elevation and ocean acidification. *J. Exp. Mar. Biol. Ecol.* **453**, 28–35 (2014). [doi:10.1016/j.jembe.2013.12.013](https://doi.org/10.1016/j.jembe.2013.12.013)
93. C. J. Hoppe, C. S. Hassler, C. D. Payne, P. D. Tortell, B. Rost, S. Trimborn, Iron limitation modulates ocean acidification effects on southern ocean phytoplankton communities. *PLOS ONE* **8**, e79890 (2013). [Medline doi:10.1371/journal.pone.0079890](https://doi.org/10.1371/journal.pone.0079890)
94. G. W. K. Ko, R. Dineshram, C. Campanati, V. B. Chan, J. Havenhand, V. Thiagarajan, Interactive effects of ocean acidification, elevated temperature, and reduced salinity on early-life stages of the pacific oyster. *Environ. Sci. Technol.* **48**, 10079–10088 (2014). [Medline doi:10.1021/es501611u](https://doi.org/10.1021/es501611u)
95. A. J. Poulton, M. C. Stinchcombe, E. P. Achterberg, D. C. E. Bakker, C. Dumousseaud, H. E. Lawson, G. A. Lee, S. Richier, D. J. Suggett, J. R. Young, Coccolithophores on the

- north-west European shelf: Calcification rates and environmental controls. *Biogeosciences* **11**, 3919–3940 (2014). [doi:10.5194/bg-11-3919-2014](https://doi.org/10.5194/bg-11-3919-2014)
96. R. I. Perry, R. E. Ommer, M. Barange, F. Werner, The challenge of adapting marine social–ecological systems to the additional stress of climate change. *Curr. Opin. Environ. Sustain.* **2**, 356–363 (2010). [doi:10.1016/j.cosust.2010.10.004](https://doi.org/10.1016/j.cosust.2010.10.004)
97. J. Brodie, C. J. Williamson, D. A. Smale, N. A. Kamenos, N. Mieszkowska, R. Santos, M. Cunliffe, M. Steinke, C. Yesson, K. M. Anderson, V. Asnaghi, C. Brownlee, H. L. Burdett, M. T. Burrows, S. Collins, P. J. Donohue, B. Harvey, A. Foggo, F. Noisette, J. Nunes, F. Ragazzola, J. A. Raven, D. N. Schmidt, D. Suggett, M. Teichberg, J. M. Hall-Spencer, The future of the northeast Atlantic benthic flora in a high CO<sub>2</sub> world. *Ecol. Evol.* **4**, 2787–2798 (2014). [Medline doi:10.1002/ece3.1105](#)
98. M. O. Clarkson, S. A. Kasemann, R. A. Wood, T. M. Lenton, S. J. Daines, S. Richoz, F. Ohnemueller, A. Meixner, S. W. Poulton, E. T. Tipper, Ocean acidification and the Permo-Triassic mass extinction. *Science* **348**, 229–232 (2015). [Medline doi:10.1126/science.aaa0193](#)
99. S. E. Moffitt, T. M. Hill, P. D. Roopnarine, J. P. Kennett, Response of seafloor ecosystems to abrupt global climate change. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 4684–4689 (2015). [Medline doi:10.1073/pnas.1417130112](#)
100. A. Böhnke-Henrichs, C. Baulcomb, R. Koss, S. S. Hussain, R. S. de Groot, Typology and indicators of ecosystem services for marine spatial planning and management. *J. Environ. Manage.* **130**, 135–145 (2013). [Medline doi:10.1016/j.jenvman.2013.08.027](#)
101. J. Mendler de Suarez, B. Cicin-Sain, K. Wowk, R. Payet, O. Hoegh-Guldberg, Ensuring survival: Oceans, climate and security. *Ocean Coast. Manage.* **90**, 27–37 (2014). [doi:10.1016/j.ocecoaman.2013.08.007](#)
102. U. Riebesell, A. Körtzinger, A. Oschlies, Sensitivities of marine carbon fluxes to ocean change. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 20602–20609 (2009). [Medline doi:10.1073/pnas.0813291106](#)
103. C. M. Duarte, I. J. Losada, I. E. Hendriks, I. Mazarrasa, N. Marbà, The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **3**, 961–968 (2013). [doi:10.1038/nclimate1970](#)
104. M. D. Spalding, S. Ruffo, C. Lacambra, I. Meliane, L. Z. Hale, C. C. Shepard, M. W. Beck, The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean Coast. Manage.* **90**, 50–57 (2014). [doi:10.1016/j.ocecoaman.2013.09.007](#)
105. B. Ondiviela, I. J. Losada, J. L. Lara, M. Maza, C. Galván, T. J. Bouma, J. van Belzen, The role of seagrasses in coastal protection in a changing climate. *Coast. Eng.* **87**, 158–168 (2014). [doi:10.1016/j.coastaleng.2013.11.005](#)
106. J. Hinkel, D. Lincke, A. T. Vafeidis, M. Perrette, R. J. Nicholls, R. S. Tol, B. Marzeion, X. Fettweis, C. Ionescu, A. Levermann, Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3292–3297 (2014). [Medline doi:10.1073/pnas.1222469111](#)

107. R. Costanza, O. Pérez-Maqueo, M. L. Martinez, P. Sutton, S. J. Anderson, K. Mulder, The value of coastal wetlands for hurricane protection. *Ambio* **37**, 241–248 (2008). [Medline](#) [doi:10.1579/0044-7447\(2008\)37\[241:TVOCWF\]2.0.CO;2](#)
108. E. B. Barbier, Valuing the storm protection service of estuarine and coastal ecosystems. *Ecosyst. Serv.* **11**, 32–38 (2015). [doi:10.1016/j.ecoser.2014.06.010](#)
109. U. R. Sumaila, W. W. L. Cheung, V. W. Y. Lam, D. Pauly, S. Herrick, Climate change impacts on the biophysics and economics of world fisheries. *Nat. Clim. Change* **1**, 449–456 (2011). [doi:10.1038/nclimate1301](#)
110. W. W. Cheung, R. Watson, D. Pauly, Signature of ocean warming in global fisheries catch. *Nature* **497**, 365–368 (2013). [Medline](#) [doi:10.1038/nature12156](#)
111. W. W. L. Cheung, J. L. Sarmiento, J. Dunne, T. L. Frölicher, V. W. Y. Lam, M. L. Deng Palomares, R. Watson, D. Pauly, Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nat. Clim. Change* **3**, 254–258 (2012). [doi:10.1038/nclimate1691](#)
112. I. Montero-Serra, M. Edwards, M. J. Genner, Warming shelf seas drive the subtropicalization of European pelagic fish communities. *Glob. Change Biol.* **21**, 144–153 (2015). [Medline](#) [doi:10.1111/gcb.12747](#)
113. S. D. Simpson, S. Jennings, M. P. Johnson, J. L. Blanchard, P. J. Schön, D. W. Sims, M. J. Genner, Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Curr. Biol.* **21**, 1565–1570 (2011). [Medline](#) [doi:10.1016/j.cub.2011.08.016](#)
114. D. Yemane, S. P. Kirkman, J. Kathena, S. E. N'siangango, B. E. Axelsen, T. Samaai, Assessing changes in the distribution and range size of demersal fish populations in the Benguela Current Large Marine Ecosystem. *Rev. Fish Biol. Fish.* **24**, 463–483 (2014). [doi:10.1007/s11160-014-9357-7](#)
115. A. R. Baudron, C. L. Needle, A. D. Rijnsdorp, C. T. Marshall, Warming temperatures and smaller body sizes: Synchronous changes in growth of North Sea fishes. *Glob. Change Biol.* **20**, 1023–1031 (2014). [Medline](#) [doi:10.1111/gcb.12514](#)
116. S. R. Cooley, J. T. Mathis, Addressing ocean acidification as part of sustainable ocean development. *Ocean Yearbook Online* **27**, 29–47 (2013). [doi:10.1163/22116001-90000153](#)
117. M. Barange, G. Merino, J. L. Blanchard, J. Scholtens, J. Harle, E. H. Allison, J. I. Allen, J. Holt, S. Jennings, Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nat. Clim. Change* **4**, 211–216 (2014). [doi:10.1038/nclimate2119](#)
118. V. W. Y. Lam, W. W. L. Cheung, U. R. Sumaila, Marine capture fisheries in the Arctic: Winners or losers under climate change and ocean acidification? *Fish Fish.*, 10.1111/faf.12106 (2014).
119. V. W. Y. Lam, W. Cheung, W. Swartz, U. R. Sumaila, Climate change impacts on fisheries in West Africa: Implications for economic, food and nutritional security. *Afr. J. Mar. Sci.* **34**, 103–117 (2012). [doi:10.2989/1814232X.2012.673294](#)

120. J. D. Bell *et al.*, Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nat. Clim. Change* **3**, 591–599 (2013). [doi:10.1038/nclimate1838](https://doi.org/10.1038/nclimate1838)
121. W. W. L. Cheung, V. W. Lam, J. L. Sarmiento, K. Kearney, R. Watson, D. Zeller, D. Pauly, Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Change Biol.* **16**, 24–35 (2010). [doi:10.1111/j.1365-2486.2009.01995.x](https://doi.org/10.1111/j.1365-2486.2009.01995.x)
122. J. T. Mathis *et al.*, Ocean acidification risk assessment for Alaska’s fishery sector. *Prog. Oceanogr.*, 10.1016/j.pocean.2014.07.001 (2014).
123. C. H. Ainsworth, J. F. Samhouri, D. S. Busch, W. W. L. Cheung, J. Dunne, T. A. Okey, Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. *ICES J. Mar. Sci.* **68**, 1217–1229 (2011). [doi:10.1093/icesjms/fsr043](https://doi.org/10.1093/icesjms/fsr043)
124. W. W. L. Cheung, J. Pinnegar, G. Merino, M. C. Jones, M. Barange, Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **22**, 368–388 (2012). [doi:10.1002/aqc.2248](https://doi.org/10.1002/aqc.2248)
125. J. S. Christiansen, C. W. Mecklenburg, O. V. Karamushko, Arctic marine fishes and their fisheries in light of global change. *Glob. Change Biol.* **20**, 352–359 (2014). [Medline doi:10.1111/gcb.12395](https://doi.org/10.1111/gcb.12395)
126. K. A. Miller, G. R. Munro, U. R. Sumaila, W. W. L. Cheung, Governing marine fisheries in a changing climate: A game-theoretic perspective. *Can. J. Agric. Econ.* **61**, 309–334 (2013). [doi:10.1111/cjag.12011](https://doi.org/10.1111/cjag.12011)
127. R. Callaway, A. P. Shinn, S. E. Grenfell, J. E. Bron, G. Burnell, E. J. Cook, M. Crumlish, S. Culloty, K. Davidson, R. P. Ellis, K. J. Flynn, C. Fox, D. M. Green, G. C. Hays, A. D. Hughes, E. Johnston, C. D. Lowe, I. Lupatsch, S. Malham, A. F. Mendzil, T. Nickell, T. Pickerell, A. F. Rowley, M. S. Stanley, D. R. Tocher, J. F. Turnbull, G. Webb, E. Wootton, R. J. Shields, Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **22**, 389–421 (2012). [doi:10.1002/aqc.2247](https://doi.org/10.1002/aqc.2247)
128. M. Ruckelshaus, S. C. Doney, H. M. Galindo, J. P. Barry, F. Chan, J. E. Duffy, C. A. English, S. D. Gaines, J. M. Grebmeier, A. B. Hollowed, N. Knowlton, J. Polovina, N. N. Rabalais, W. J. Sydeman, L. D. Talley, Securing ocean benefits for society in the face of climate change. *Mar. Policy* **40**, 154–159 (2013). [doi:10.1016/j.marpol.2013.01.009](https://doi.org/10.1016/j.marpol.2013.01.009)
129. A. Barton, B. Hales, G. G. Waldbusser, C. Langdon, R. A. Feely, The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnol. Oceanogr.* **57**, 698–710 (2012). [doi:10.4319/lo.2012.57.3.0698](https://doi.org/10.4319/lo.2012.57.3.0698)
130. D. Narita, K. Rehdanz, R. S. J. Tol, Economic costs of ocean acidification: A look into the impacts on global shellfish production. *Clim. Change* **113**, 1049–1063 (2012). [doi:10.1007/s10584-011-0383-3](https://doi.org/10.1007/s10584-011-0383-3)

131. S. S. De Silva, “Climate change impacts: Challenges for aquaculture,” in *Farming the Waters for People and Food*, R. P. Subasinghe *et al.*, Eds. (FAO and Network of Aquaculture Centres in Asia-Pacific, Rome and Bangkok, 2012), pp. 75–110.
132. C. A. Burge, C. Mark Eakin, C. S. Friedman, B. Froelich, P. K. Hershberger, E. E. Hofmann, L. E. Petes, K. C. Prager, E. Weil, B. L. Willis, S. E. Ford, C. D. Harvell, Climate change influences on marine infectious diseases: Implications for management and society. *Annu. Rev. Mar. Sci.* **6**, 249–277 (2014). [Medline doi:10.1146/annurev-marine-010213-135029](#)
133. J. Garai, “The impacts of climate change on the livelihoods of coastal people in Bangladesh: A sociological study,” in *International Perspectives on Climate Change*, W. Leal Filho, F. Alves, S. Caeiro, U. M. Azeiteiro, Eds. (Springer, Switzerland, 2014), pp. 151–163.
134. P.-Y. Chen, C.-C. Chen, L. F. Chu, B. McCarl, Evaluating the economic damage of climate change on global coral reefs. *Glob. Environ. Change* **30**, 12–20 (2015). [doi:10.1016/j.gloenvcha.2014.10.011](#)
135. Deloitte Access Economics, *Economic Contribution of the Great Barrier Reef* (Great Barrier Reef Marine Park Authority, Townsville, Australia, 2013).
136. L. M. Brander, K. Rehdanz, R. S. J. Tol, P. J. H. Van Beukering, The economic impact of ocean acidification on coral reefs. *Clim. Change Econ.* **03**, 1250002 (2012). [10.1142/S2010007812500029 doi:10.1142/S2010007812500029](#)
137. L. M. Burke, K. Reytar, M. Spalding, A. Perry, *Reefs at Risk Revisited* (World Resources Institute, Washington, DC, 2011), p. 114.
138. M. Pascual, X. Rodó, S. P. Ellner, R. Colwell, M. J. Bouma, Cholera dynamics and El Niño-Southern Oscillation. *Science* **289**, 1766–1769 (2000). [10.1126/science.289.5485.1766 Medline doi:10.1126/science.289.5485.1766](#)
139. C. Baker-Austin, J. A. Trinanes, N. G. H. Taylor, R. Hartnell, A. Siitonen, J. Martinez-Urtaza, Emerging Vibrio risk at high latitudes in response to ocean warming. *Nat. Clim. Change* **3**, 73–77 (2013). [10.1038/nclimate1628 doi:10.1038/nclimate1628](#)
140. S. Altizer, R. S. Ostfeld, P. T. Johnson, S. Kutz, C. D. Harvell, Climate change and infectious diseases: From evidence to a predictive framework. *Science* **341**, 514–519 (2013). [10.1126/science.1239401 Medline doi:10.1126/science.1239401](#)
141. T. L. F. Leung, A. E. Bates, More rapid and severe disease outbreaks for aquaculture at the tropics: Implications for food security. *J. Appl. Ecol.* **50**, 215–222 (2013). [10.1111/1365-2644.12017 doi:10.1111/1365-2644.12017](#)
142. T. Wheeler, J. von Braun, Climate change impacts on global food security. *Science* **341**, 508–513 (2013). [10.1126/science.1239402 Medline doi:10.1126/science.1239402](#)
143. R. P. Kelly, M. R. Caldwell, Ten ways states can combat ocean acidification (and why they should). *Harvard Environ. Law Rev.* **37**, 57–103 (2013). [doi:10.2139/ssrn.2020520](#)
144. E. Mcleod, K. R. N. Anthony, A. Andersson, R. Beeden, Y. Golbuu, J. Kleypas, K. Kroeker, D. Manzello, R. V. Salm, H. Schuttenberg, J. E. Smith, Preparing to manage

- coral reefs for ocean acidification: Lessons from coral bleaching. *Front. Ecol. Environ* **11**, 20–27 (2013). 10.1890/110240 [doi:10.1890/110240](https://doi.org/10.1890/110240)
145. A. L. Strong, K. J. Kroeker, L. T. Teneva, L. A. Mease, R. P. Kelly, Ocean acidification 2.0: Managing our changing coastal ocean chemistry. *Bioscience* **64**, 581–592 (2014). 10.1093/biosci/biu072 [doi:10.1093/biosci/biu072](https://doi.org/10.1093/biosci/biu072)
146. R. Billé, R. Kelly, A. Biastoch, E. Harrould-Kolieb, D. Herr, F. Joos, K. Kroeker, D. Laffoley, A. Oschlies, J. P. Gattuso, Taking action against ocean acidification: A review of management and policy options. *Environ. Manage.* **52**, 761–779 (2013). 10.1007/s00267-013-0132-7 [Medline doi:10.1007/s00267-013-0132-7](https://doi.org/10.1007/s00267-013-0132-7)
147. Committee on Geoengineering Climate, “Technical evaluation and discussion of impacts,” in *Climate Intervention: Reflecting Sunlight to Cool Earth* (National Academy of Sciences, Washington, DC, 2015).
148. M. D. Eisaman, K. Parajuly, A. Tuganov, C. Eldershaw, N. Chang, K. A. Littau, CO<sub>2</sub> extraction from seawater using bipolar membrane electrodialysis. *Energy Environ. Sci.* **5**, 7346 (2012). [doi:10.1039/c2ee03393c](https://doi.org/10.1039/c2ee03393c)
149. M. J. H. van Oppen, J. K. Oliver, H. M. Putnam, R. D. Gates, Building coral reef resilience through assisted evolution. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 2307–2313 (2015). [Medline doi:10.1073/pnas.1422301112](https://doi.org/10.1073/pnas.1422301112)
150. C. N. Young, S. A. Schopmeyer, D. Lirman, A review of reef restoration and coral propagation using the threatened genus *Acropora* in the Caribbean and Western Atlantic. *Bull. Mar. Sci.* **88**, 1075–1098 (2012). [doi:10.5343/bms.2011.1143](https://doi.org/10.5343/bms.2011.1143)
151. H. Govan *et al.*, *Status and Potential of Locally-Managed Marine Areas in the South Pacific: Meeting Nature Conservation and Sustainable Livelihood Targets Through Wide-Spread Implementation of LMMA*s (South Pacific Regional Environmental Program/WWF/WorldFish-Reefbase/Coral Reefs Initiative for the Pacific, Noumea, New Caledonia, 2009).
152. R. P. Kelly, S. R. Cooley, T. Klinger, Narratives can motivate environmental action: The Whiskey Creek ocean acidification story. *Ambio* **43**, 592–599 (2014). 10.1007/s13280-013-0442-2 [Medline doi:10.1007/s13280-013-0442-2](https://doi.org/10.1007/s13280-013-0442-2)
153. L. Weatherdon, A. Rogers, R. Sumaila, A. Magnan, W. W. L. Cheung, *The Oceans 2015 Initiative, Part II: An Updated Understanding of the Observed and Projected Impacts of Ocean Warming and Acidification on Marine and Coastal Socioeconomic Activities/Sectors* (Institut du Développement Durable et des Relations Internationales, Paris, 2015).
154. R. Murti, C. Buyck, Eds., *Safe Havens: Protected Areas for Disaster Risk Reduction and Climate Change Adaptation* (IUCN, Gland, Switzerland, 2014).
155. G. Keppel, K. Mokany, G. W. Wardell-Johnson, B. L. Phillips, J. A. Welbergen, A. E. Reside, The capacity of refugia for conservation planning under climate change. *Front. Ecol. Environ* **13**, 106–112 (2015). 10.1890/140055 [doi:10.1890/140055](https://doi.org/10.1890/140055)

156. C. Cacciapaglia, R. van Woesik, Reef-coral refugia in a rapidly changing ocean. *Glob. Change Biol.* **21**, 2272–2282 (2015). 10.1111/gcb.12851 [Medline](#) [doi:10.1111/gcb.12851](#)
157. M. D. Mastrandrea *et al.*, *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* (IPCC, New York, 2010).
158. M. Oppenheimer *et al.*, “Emergent risks and key vulnerabilities,” in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 1039–1099.
159. L. B. Nejrup, M. F. Pedersen, Effects of salinity and water temperature on the ecological performance of the *Zostera marina*. *Aquat. Bot.* **88**, 239–246 (2008). [doi:10.1016/j.aquabot.2007.10.006](#)
160. H. Höffle, M. S. Thomsen, M. Holmer, High mortality of *Zostera marina* under high temperature regimes but minor effects of the invasive macroalgae *Gracilaria vermiculophylla*. *Estuar. Coast. Shelf Sci.* **92**, 35–46 (2011). [doi:10.1016/j.ecss.2010.12.017](#)
161. C. A. Burge, C. J. S. Kim, J. M. Lyles, C. D. Harvell, Special issue Oceans and Humans Health: The ecology of marine opportunists. *Microb. Ecol.* **65**, 869–879 (2013). [Medline](#) [doi:10.1007/s00248-013-0190-7](#)
162. F. T. Short, H. A. Neckles, The effects of global climate change on seagrasses. *Aquat. Bot.* **63**, 169–196 (1999). [doi:10.1016/S0304-3770\(98\)00117-X](#)
163. M. I. Saunders, J. X. Leon, D. P. Callaghan, C. M. Roelfsema, S. Hamylton, C. J. Brown, T. Baldock, A. Golshani, S. R. Phinn, C. E. Lovelock, O. Hoegh-Guldberg, C. D. Woodroffe, P. J. Mumby, Interdependency of tropical marine ecosystems in response to climate change. *Nat. Clim. Change* **4**, 724–729 (2014). [doi:10.1038/nclimate2274](#)
164. N. Marbà, C. M. Duarte, Mediterranean warming triggers seagrass (*Posidonia oceanica*) shoot mortality. *Glob. Change Biol.* **16**, 2366–2375 (2010). [doi:10.1111/j.1365-2486.2009.02130.x](#)
165. G. Jordà, N. Marbà, C. M. Duarte, Mediterranean seagrass vulnerable to regional climate warming. *Nat. Clim. Change* **2**, 821–824 (2012). [doi:10.1038/nclimate1533](#)
166. J. A. Carr, P. D’Odorico, K. J. McGlathery, P. L. Wiberg, Modeling the effects of climate change on eelgrass stability and resilience: Future scenarios and leading indicators of collapse. *Mar. Ecol. Prog. Ser.* **448**, 289–301 (2012).
167. P. H. York, R. K. Gruber, R. Hill, P. J. Ralph, D. J. Booth, P. I. Macreadie, Physiological and morphological responses of the temperate seagrass *Zostera muelleri* to multiple stressors: Investigating the interactive effects of light and temperature. *PLOS ONE* **8**, e76377 (2013). [Medline](#) [doi:10.1371/journal.pone.0076377](#)
168. D. M. Alongi, The impact of climate change on mangrove forests. *Curr. Clim. Change Rep.* **1**, 30–39 (2015). [doi:10.1007/s40641-015-0002-x](#)

169. D. P. Tittensor, C. Mora, W. Jetz, H. K. Lotze, D. Ricard, E. V. Berghe, B. Worm, Global patterns and predictors of marine biodiversity across taxa. *Nature* **466**, 1098–1101 (2010). [Medline doi:10.1038/nature09329](#)
170. K. McKee, K. Rogers, N. Saintilan, “Response of salt marsh and mangrove wetlands to changes in atmospheric CO<sub>2</sub>, climate, and sea level,” in *Global Change and the Function and Distribution of Wetlands*, B. A. Middleton, Ed. (Springer, Dordrecht, 2012), pp. 63–96.
171. D. M. Alongi, Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuar. Coast. Shelf Sci.* **76**, 1–13 (2008). [doi:10.1016/j.ecss.2007.08.024](#)
172. P. W. Glynn, Widespread coral mortality and the 1982-83 El Niño warming event. *Environ. Conserv.* **11**, 133–146 (1984). [doi:10.1017/S0376892900013825](#)
173. J. E. Veron, O. Hoegh-Guldberg, T. M. Lenton, J. M. Lough, D. O. Obura, P. Pearce-Kelly, C. R. Sheppard, M. Spalding, M. G. Stafford-Smith, A. D. Rogers, The coral reef crisis: The critical importance of <350 ppm CO<sub>2</sub>. *Mar. Pollut. Bull.* **58**, 1428–1436 (2009). [Medline doi:10.1016/j.marpolbul.2009.09.009](#)
174. C. R. Wilkinson, *Status of Coral Reefs of the World: 2000* (Australian Institute of Marine Science, Townsville, Australia, 2000), p. 363.
175. C. M. Eakin, J. A. Morgan, S. F. Heron, T. B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, E. Bartels, C. Bastidas, C. Bouchon, M. Brandt, A. W. Bruckner, L. Bunkley-Williams, A. Cameron, B. D. Causey, M. Chiappone, T. R. Christensen, M. J. Crabbe, O. Day, E. de la Guardia, G. Díaz-Pulido, D. DiResta, D. L. Gil-Agudelo, D. S. Gilliam, R. N. Ginsburg, S. Gore, H. M. Guzmán, J. C. Hendee, E. A. Hernández-Delgado, E. Husain, C. F. Jeffrey, R. J. Jones, E. Jordán-Dahlgren, L. S. Kaufman, D. I. Kline, P. A. Kramer, J. C. Lang, D. Lirman, J. Mallela, C. Manfrino, J. P. Maréchal, K. Marks, J. Mihaly, W. J. Miller, E. M. Mueller, E. M. Muller, C. A. Orozco Toro, H. A. Oxenford, D. Ponce-Taylor, N. Quinn, K. B. Ritchie, S. Rodríguez, A. R. Ramírez, S. Romano, J. F. Samhouri, J. A. Sánchez, G. P. Schmahl, B. V. Shank, W. J. Skirving, S. C. Steiner, E. Villamizar, S. M. Walsh, C. Walter, E. Weil, E. H. Williams, K. W. Roberson, Y. Yusuf, Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. *PLOS ONE* **5**, e13969 (2010). [Medline doi:10.1371/journal.pone.0013969](#)
176. J. A. Y. Moore, L. M. Bellchambers, M. R. Depczynski, R. D. Evans, S. N. Evans, S. N. Field, K. J. Friedman, J. P. Gilmour, T. H. Holmes, R. Middlebrook, B. T. Radford, T. Ridgway, G. Shedrawi, H. Taylor, D. P. Thomson, S. K. Wilson, Unprecedented mass bleaching and loss of coral across 12° of latitude in Western Australia in 2010-11. *PLOS ONE* **7**, e51807 (2012). [Medline doi:10.1371/journal.pone.0051807](#)
177. O. Hoegh-Guldberg, Climate change, coral bleaching, and the future of the world's coral reefs. *Mar. Freshw. Res.* **50**, 839–866 (1999). [doi:10.1071/MF99078](#)
178. S. D. Donner, W. J. Skirving, C. M. Little, M. Oppenheimer, O. Hoegh Guldberg, Global assessment of coral bleaching and required rates of adaptation under climate change. *Glob. Change Biol.* **11**, 2251–2265 (2005). [doi:10.1111/j.1365-2486.2005.01073.x](#)

179. R. van Hooijdonk, J. A. Maynard, D. Manzello, S. Planes, Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Glob. Change Biol.* **20**, 103–112 (2014). [Medline doi:10.1111/gcb.12394](#)
180. S. G. Dove, D. I. Kline, O. Pantos, F. E. Angly, G. W. Tyson, O. Hoegh-Guldberg, Future reef decalcification under a business-as-usual CO<sub>2</sub> emission scenario. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 15342–15347 (2013). [Medline doi:10.1073/pnas.1302701110](#)
181. G. De'ath, K. E. Fabricius, H. Sweatman, M. Puotinen, The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 17995–17999 (2012). [Medline doi:10.1073/pnas.1208909109](#)
182. S. Comeau, G. Gorsky, R. Jeffree, J.-L. Teyssié, J.-P. Gattuso, Impact of ocean acidification on a key Arctic pelagic mollusc (*Limacina helicina*). *Biogeosciences* **6**, 1877–1882 (2009). [doi:10.5194/bg-6-1877-2009](#)
183. S. Comeau, R. Jeffree, J.-L. Teyssié, J.-P. Gattuso, Response of the Arctic pteropod *Limacina helicina* to projected future environmental conditions. *PLOS ONE* **5**, e11362 (2010). [Medline doi:10.1371/journal.pone.0011362](#)
184. S. Lischka, J. Büdenbender, T. Boxhammer, U. Riebesell, Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: Mortality, shell degradation, and shell growth. *Biogeosciences* **8**, 919–932 (2011). [doi:10.5194/bg-8-919-2011](#)
185. S. Lischka, U. Riebesell, Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. *Glob. Change Biol.* **18**, 3517–3528 (2012). [doi:10.1111/gcb.12020](#)
186. S. Comeau, S. Alliouane, J.-P. Gattuso, Effects of ocean acidification on overwintering juvenile Arctic pteropods *Limacina helicina*. *Mar. Ecol. Prog. Ser.* **456**, 279–284 (2012). [doi:10.3354/meps09696](#)
187. C. Manno, N. Morata, R. Primicerio, *Limacina retroversa*'s response to combined effects of ocean acidification and sea water freshening. *Estuar. Coast. Shelf Sci.* **113**, 163–171 (2012). [doi:10.1016/j.ecss.2012.07.019](#)
188. N. Bednaršek, M. D. Ohman, Changes in pteropod distributions and shell dissolution across a frontal system in the California Current System. *Mar. Ecol. Prog. Ser.* **523**, 93–103 (2015). [doi:10.3354/meps11199](#)
189. C. L. Mackenzie, S. A. Lynch, S. C. Culloty, S. K. Malham, Future oceanic warming and acidification alter immune response and disease status in a commercial shellfish species, *Mytilus edulis* L. *PLOS ONE* **9**, e99712 (2014). [Medline doi:10.1371/journal.pone.0099712](#)
190. K. J. Kroeker, R. L. Kordas, R. Crim, I. E. Hendriks, L. Ramajo, G. S. Singh, C. M. Duarte, J. P. Gattuso, Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Glob. Change Biol.* **19**, 1884–1896 (2013). [Medline doi:10.1111/gcb.12179](#)

191. A. C. Wittmann, H.-O. Pörtner, Sensitivities of extant animal taxa to ocean acidification. *Nat. Clim. Change* **3**, 995–1001 (2013). [doi:10.1038/nclimate1982](https://doi.org/10.1038/nclimate1982)
192. V. Raybaud, G. Beaugrand, J.-M. Dewarumez, C. Luczak, Climate-induced range shifts of the American jackknife clam *Ensis directus* in Europe. *Biol. Invasions* **17**, 725–741 (2015). [doi:10.1007/s10530-014-0764-4](https://doi.org/10.1007/s10530-014-0764-4)
193. S. R. Cooley, J. E. Rheuban, D. R. Hart, V. Luu, D. M. Glover, J. A. Hare, S. C. Doney, An integrated assessment model for helping the United States sea scallop (*Placopecten magellanicus*) fishery plan ahead for ocean acidification and warming. *PLOS ONE* **10**, e0124145 (2015). [Medline doi:10.1371/journal.pone.0124145](https://doi.org/10.1371/journal.pone.0124145)
194. M. H. Pespeni, E. Sanford, B. Gaylord, T. M. Hill, J. D. Hosfelt, H. K. Jaris, M. LaVigne, E. A. Lenz, A. D. Russell, M. K. Young, S. R. Palumbi, Evolutionary change during experimental ocean acidification. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 6937–6942 (2013). [Medline doi:10.1073/pnas.1220673110](https://doi.org/10.1073/pnas.1220673110)
195. A. W. Miller, A. C. Reynolds, C. Sobrino, G. F. Riedel, Shellfish face uncertain future in high CO<sub>2</sub> world: Influence of acidification on oyster larvae calcification and growth in estuaries. *PLOS ONE* **4**, e5661–e5661 (2009). [Medline](#)
196. A. Atkinson, V. Siegel, E. Pakhomov, P. Rothery, Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature* **432**, 100–103 (2004). [Medline doi:10.1038/nature02996](https://doi.org/10.1038/nature02996)
197. S. L. Hill, T. Phillips, A. Atkinson, Potential climate change effects on the habitat of antarctic krill in the weddell quadrant of the southern ocean. *PLOS ONE* **8**, e72246 (2013). [Medline doi:10.1371/journal.pone.0072246](https://doi.org/10.1371/journal.pone.0072246)
198. H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss, G. A. Tarling, R. Werner, E. Bravo Rebollo, V. Cirelli, J. Cuzin-Roudy, S. Fielding, J. A. van Franeker, J. J. Groeneveld, M. Haraldsson, A. Lombana, E. Marschoff, B. Meyer, E. A. Pakhomov, A. P. Van de Putte, E. Rombolá, K. Schmidt, V. Siegel, M. Teschke, H. Tonkes, J. Y. Toullec, P. N. Trathan, N. Tremblay, T. Werner, Impact of climate change on Antarctic krill. *Mar. Ecol. Prog. Ser.* **458**, 1–19 (2012). [doi:10.3354/meps09831](https://doi.org/10.3354/meps09831)
199. S. Kawaguchi, A. Ishida, R. King, B. Raymond, N. Waller, A. Constable, S. Nicol, M. Wakita, A. Ishimatsu, Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nat. Clim. Change* **3**, 843–847 (2013). [doi:10.1038/nclimate1937](https://doi.org/10.1038/nclimate1937)
200. E. Bortolotto, A. Bucklin, M. Mezzavilla, L. Zane, T. Patarnello, Gone with the currents: Lack of genetic differentiation at the circum-continental scale in the Antarctic krill *Euphausia superba*. *BMC Genet.* **12**, 32 (2011). [Medline doi:10.1186/1471-2156-12-32](https://doi.org/10.1186/1471-2156-12-32)
201. A. E. Bates, G. T. Pecl, S. Frusher, A. J. Hobday, T. Wernberg, D. A. Smale, J. M. Sunday, N. A. Hill, N. K. Dulvy, R. K. Colwell, N. J. Holbrook, E. A. Fulton, D. Slawinski, M. Feng, G. J. Edgar, B. T. Radford, P. A. Thompson, R. A. Watson, Defining and observing stages of climate-mediated range shifts in marine systems. *Glob. Environ. Change* **26**, 27–38 (2014). [doi:10.1016/j.gloenvcha.2014.03.009](https://doi.org/10.1016/j.gloenvcha.2014.03.009)

202. E. S. Poloczanska, C. J. Brown, W. J. Sydeman, W. Kiessling, D. S. Schoeman, P. J. Moore, K. Brander, J. F. Bruno, L. B. Buckley, M. T. Burrows, C. M. Duarte, B. S. Halpern, J. Holding, C. V. Kappel, M. I. O'Connor, J. M. Pandolfi, C. Parmesan, F. Schwing, S. A. Thompson, A. J. Richardson, Global imprint of climate change on marine life. *Nat. Clim. Change* **3**, 919–925 (2013). [doi:10.1038/nclimate1958](https://doi.org/10.1038/nclimate1958)
203. E. Couce, A. Ridgwell, E. J. Hendy, Future habitat suitability for coral reef ecosystems under global warming and ocean acidification. *Glob. Change Biol.* **19**, 3592–3606 (2013). [Medline doi:10.1111/gcb.12335](https://doi.org/10.1111/gcb.12335)
204. C. C. Muhlfeld, R. P. Kovach, L. A. Jones, R. Al-Chokhachy, M. C. Boyer, R. F. Leary, W. H. Lowe, G. Luikart, F. W. Allendorf, Invasive hybridization in a threatened species is accelerated by climate change. *Nat. Clim. Change* **4**, 620–624 (2014). [doi:10.1038/nclimate2252](https://doi.org/10.1038/nclimate2252)
205. W. M. Potts, R. Henriques, C. V. Santos, K. Munnik, I. Ansorge, F. Dufois, A. J. Booth, C. Kirchner, W. H. Sauer, P. W. Shaw, Ocean warming, a rapid distributional shift, and the hybridization of a coastal fish species. *Glob. Change Biol.* **20**, 2765–2777 (2014). [Medline doi:10.1111/gcb.12612](https://doi.org/10.1111/gcb.12612)
206. W. W. L. Cheung, V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, D. Pauly, Projecting global marine biodiversity impacts under climate change scenarios. *Fish Fish.* **10**, 235–251 (2009). [doi:10.1111/j.1467-2979.2008.00315.x](https://doi.org/10.1111/j.1467-2979.2008.00315.x)
207. F. Ben Rais Lasram, F. Guilhaumon, C. Albouy, S. Somot, W. Thuiller, D. Mouillot, The Mediterranean Sea as a ‘cul-de-sac’ for endemic fishes facing climate change. *Glob. Change Biol.* **16**, 3233–3245 (2010). [doi:10.1111/j.1365-2486.2010.02224.x](https://doi.org/10.1111/j.1365-2486.2010.02224.x)
208. P. L. Munday, A. J. Cheal, D. L. Dixson, J. L. Rummer, K. E. Fabricius, Behavioural impairment in reef fishes caused by ocean acidification at CO<sub>2</sub> seeps. *Nat. Clim. Change* **4**, 487–492 (2014). [doi:10.1038/nclimate2195](https://doi.org/10.1038/nclimate2195)
209. C. Prentice *et al.*, “The carbon cycle and atmospheric carbon dioxide,” in *Climate Change 2001: the Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 183–237.
210. F. Joos, R. Roth, J. S. Fuglestvedt, G. P. Peters, I. G. Enting, W. von Bloh, V. Brovkin, E. J. Burke, M. Eby, N. R. Edwards, T. Friedrich, T. L. Frölicher, P. R. Halloran, P. B. Holden, C. Jones, T. Kleinen, F. T. Mackenzie, K. Matsumoto, M. Meinshausen, G.-K. Plattner, A. Reisinger, J. Segschneider, G. Shaffer, M. Steinacher, K. Strassmann, K. Tanaka, A. Timmermann, A. J. Weaver, Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis. *Atmos. Chem. Phys.* **13**, 2793–2825 (2013). [doi:10.5194/acp-13-2793-2013](https://doi.org/10.5194/acp-13-2793-2013)
211. O. Defeo, A. McLachlan, D. S. Schoeman, T. A. Schlacher, J. Dugan, A. Jones, M. Lastra, F. Scapini, Threats to sandy beach ecosystems: A review. *Estuar. Coast. Shelf Sci.* **81**, 1–12 (2009). [doi:10.1016/j.ecss.2008.09.022](https://doi.org/10.1016/j.ecss.2008.09.022)

212. K. B. Gedan, M. D. Bertness, Experimental warming causes rapid loss of plant diversity in New England salt marshes. *Ecol. Lett.* **12**, 842–848 (2009). [Medline](#)  
[doi:10.1111/j.1461-0248.2009.01337.x](https://doi.org/10.1111/j.1461-0248.2009.01337.x)
213. L. Alvarez-Filip, N. K. Dulvy, J. A. Gill, I. M. Côté, A. R. Watkinson, Flattening of Caribbean coral reefs: Region-wide declines in architectural complexity. *Proc. Biol. Sci.* **276**, 3019–3025 (2009). [Medline](#) [doi:10.1098/rspb.2009.0339](https://doi.org/10.1098/rspb.2009.0339)
214. C. Sheppard, D. J. Dixon, M. Gourlay, A. Sheppard, R. Payet, Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. *Estuar. Coast. Shelf Sci.* **64**, 223–234 (2005). [doi:10.1016/j.ecss.2005.02.016](https://doi.org/10.1016/j.ecss.2005.02.016)
215. M. W. Beck, R. D. Brumbaugh, L. Aioldi, A. Carranza, L. D. Coen, C. Crawford, O. Defeo, G. J. Edgar, B. Hancock, M. C. Kay, H. S. Lenihan, M. W. Luckenbach, C. L. Toropova, G. Zhang, X. Guo, Oyster reefs at risk and recommendations for conservation, restoration, and management. *Bioscience* **61**, 107–116 (2011).  
[doi:10.1525/bio.2011.61.2.5](https://doi.org/10.1525/bio.2011.61.2.5)
216. Washington State Blue Ribbon Panel on Ocean Acidification, *Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response* (Washington Department of Ecology, Olympia, WA, 2012).
217. A. Barton, G. G. Waldbusser, R. A. Feely, S. B. Weisberg, J. A. Newton, B. Hales, S. Cudd, B. Eudeline, C. J. Langdon, I. Jefferds, T. King, A. Suurbier, K. McLaughlin, Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography* **28**, 146–159 (2015).
218. S. Guénette, J. N. Araújo, A. Bundy, Exploring the potential effects of climate change on the Western Scotian Shelf ecosystem, Canada. *J. Mar. Syst.* **134**, 89–100 (2014).  
[doi:10.1016/j.jmarsys.2014.03.001](https://doi.org/10.1016/j.jmarsys.2014.03.001)
219. M. C. Jones, S. R. Dye, J. K. Pinnegar, R. Warren, W. W. L. Cheung, Using scenarios to project the changing profitability of fisheries under climate change. *Fish Fish.*, 10.1111/faf.12081 (2014).