

REVIEW SUMMARY

OCEANOGRAPHY

Contrasting futures for ocean and society from different anthropogenic CO₂ 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 CO₂ 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 CO₂ emissions (see figure). Warm-water corals have already been affected, as have mid-latitude seagrass, high-latitude pteropods and krill, mid-latitude bivalves, and

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-CO₂ 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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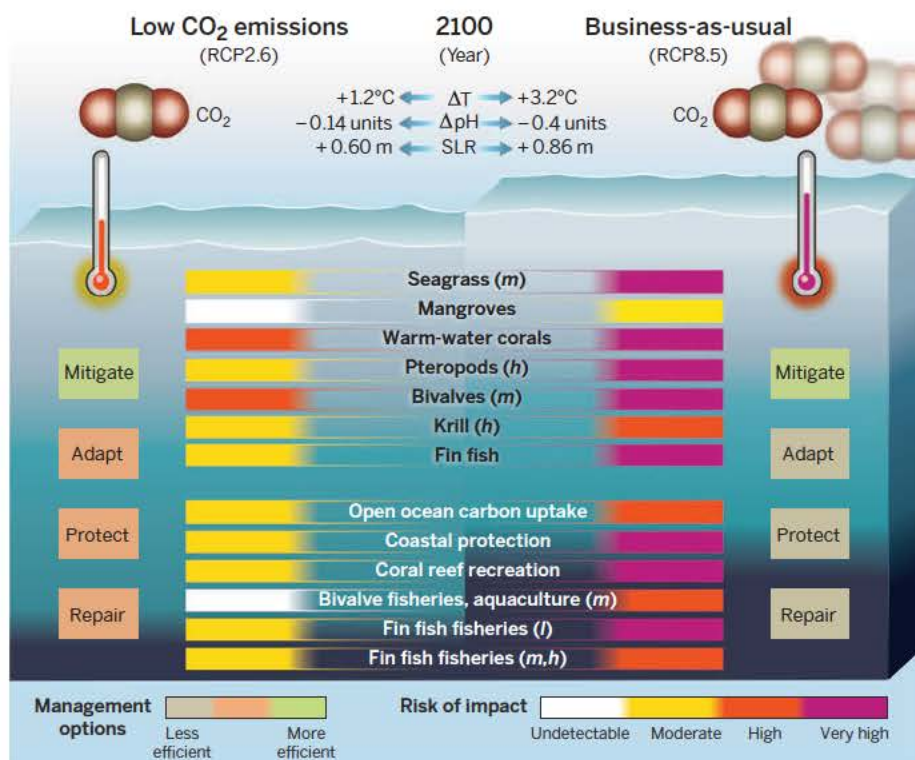
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predicted to remain moderate for the next 85 years for most services under stringent emission reductions, but the business-as-usual scenario (RCP8.5) would put all ecosystem

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 CO₂ 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 CO₂ increases, protection, adaptation, and repair options for the ocean become fewer and less effective.

The ocean provides compelling arguments for rapid reductions in CO₂ emissions and eventually atmospheric CO₂ drawdown. Hence, any new global climate agreement that does not minimize the impacts on the ocean will be inadequate. ■



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) CO₂ emissions scenarios. Changes in temperature (ΔT) and pH (ΔpH) 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.

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REVIEW

OCEANOGRAPHY

Contrasting futures for ocean and society from different anthropogenic CO₂ 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.

Atmospheric carbon dioxide (CO₂) 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂. Setting it apart, CO₂ accounts for two or more times the warming attributed to the non CO₂ greenhouse gases by 2100 (11) and causes ocean acidification. The uptake of excess anthropogenic CO₂ by the ocean increases the partial pressure of carbon dioxide (P_{CO₂}) 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 CO₂ 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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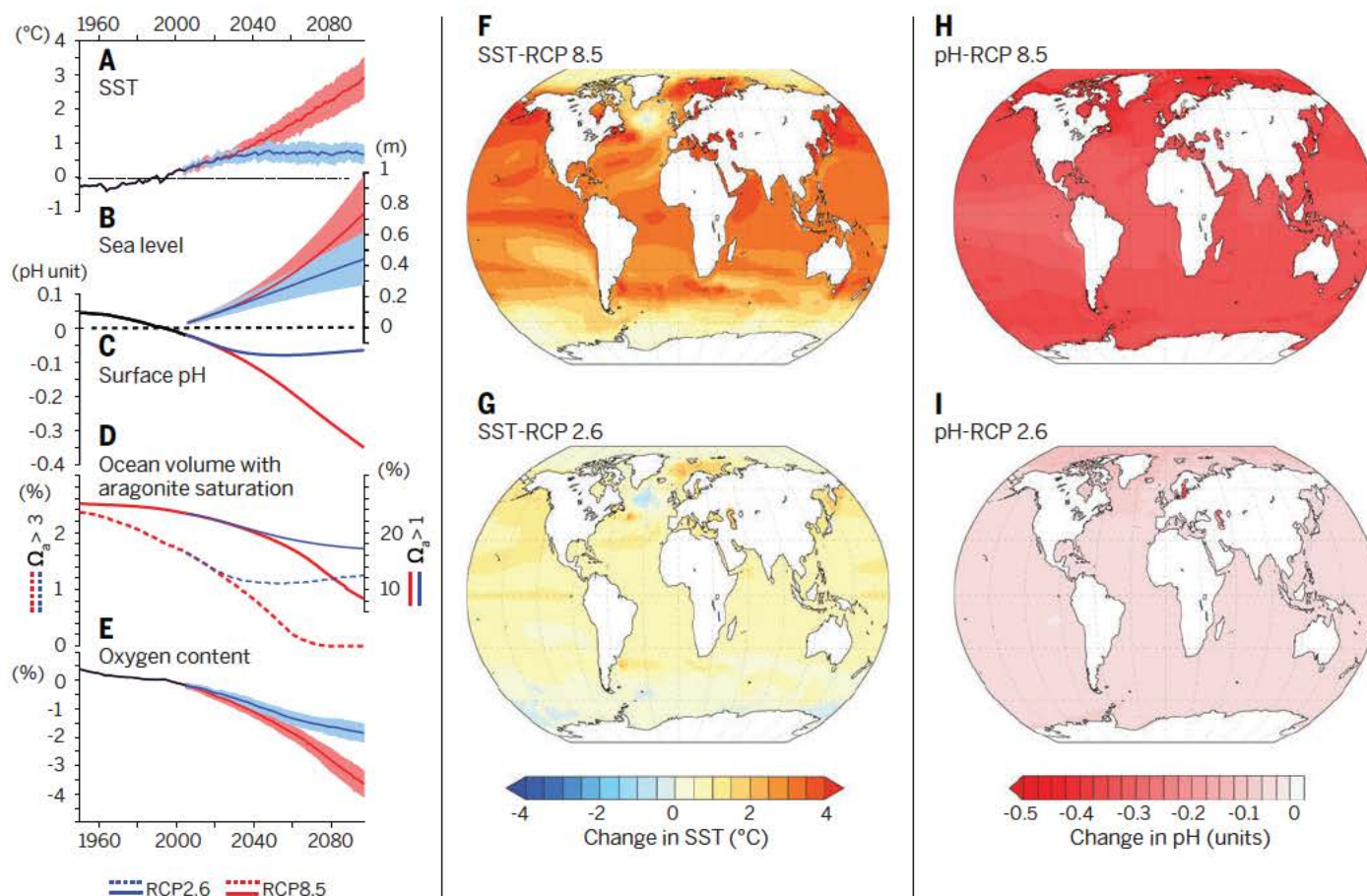


Fig. 1. Environmental changes over the industrial period and the 21st century for a business-as-usual scenario and a stringent emissions scenario consistent with the UNFCCC target of increase in global surface temperature by 2°C. (A to E) Changes in globally averaged (A) SST, (B) sea level, (C) sea surface pH (total pH scale), (D) ocean volume (in % of total ocean volume) with saturation state of calcium carbonate in aragonitic form (Ω_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).

	Δ SST (°C)	Δ pH (units)	Δ O ₂ content (%)	Sea level (m)	Vol. Ω_a >1 (%)	Vol. Ω_a >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

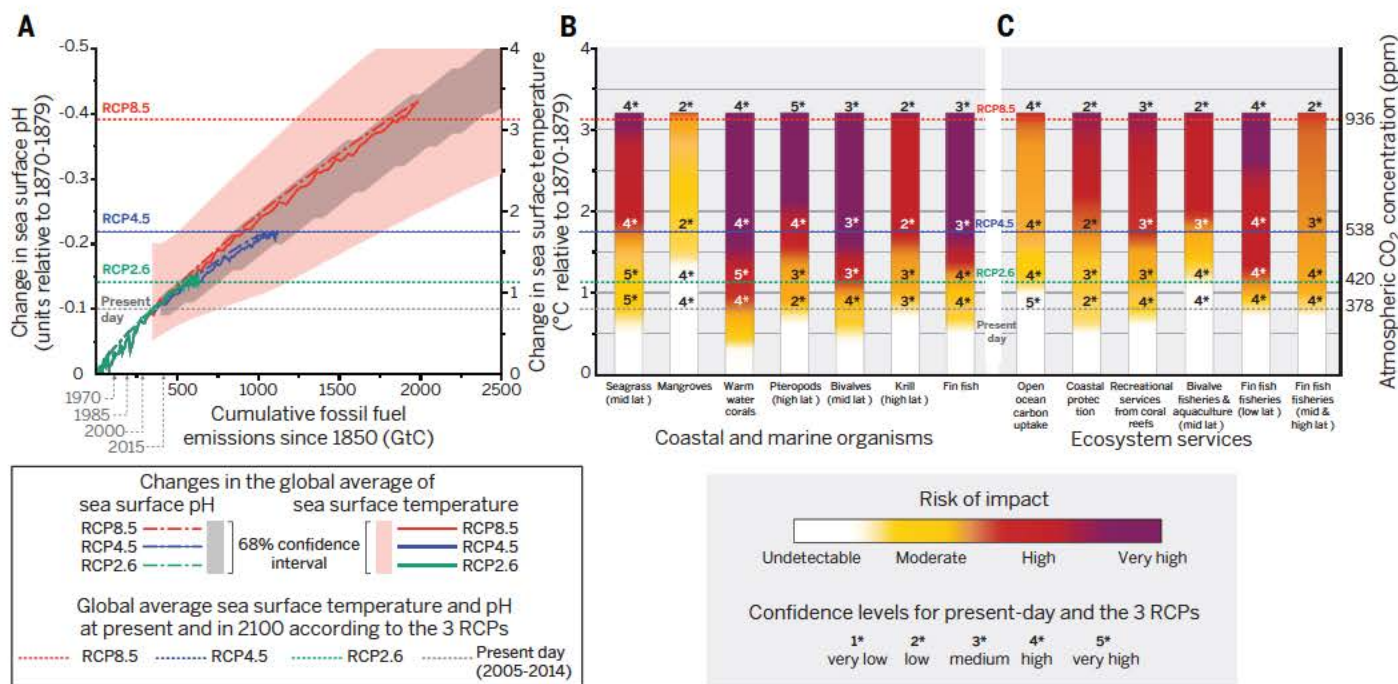


Fig. 2. Observed impact and risk scenarios of ocean warming and acidification for important organisms and critical ecosystem services. “Present-day” (gray dotted line) corresponds to the period from 2005 to 2014. Impact levels are for the year 2100 under the different projections shown and do not consider 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 CO₂ on key organisms that are well documented in the literature. (C) Risk of impacts resulting from elevated CO₂ 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 CO₂ than is currently predicted. Indeed, the ocean’s effectiveness in absorbing CO₂ 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 ± 0.003 units to 0.07 ± 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).

CO₂ 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 CO₂ 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

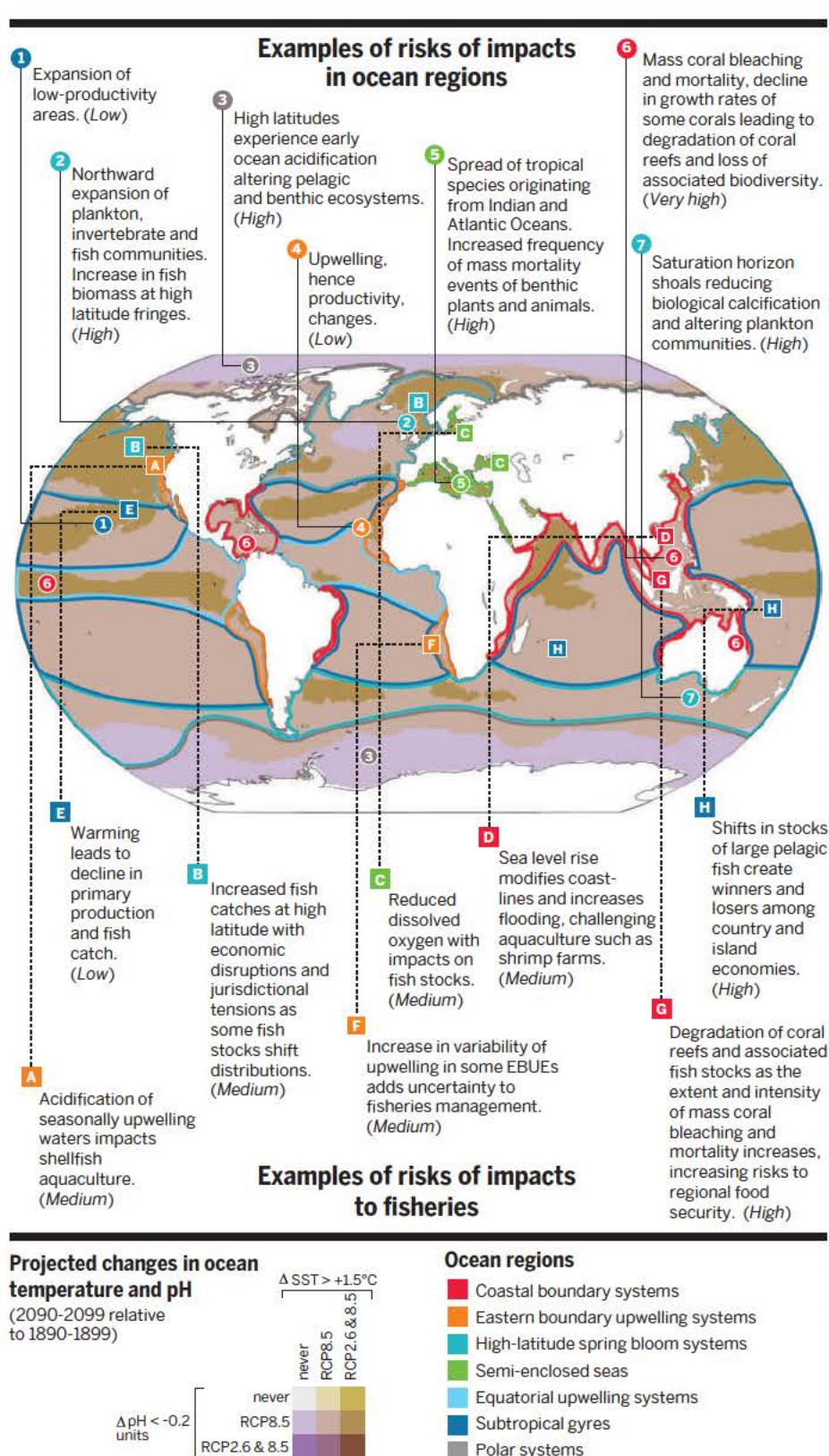


Fig. 3. Regional changes in the physical system and associated risks for natural and human-managed systems. Projected changes in SST (Δ SST) and pH (Δ pH) in 2090–2099 relative to pre-industrial under the RCP2.6 and RCP8.5 scenarios are displayed in different colors on the map. The major ocean regions 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_2 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 O₂ (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 CO₂ 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 CO₂ 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, CO₂ 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 CO₂ is a key service to society that moderates climate change, although it comes at the cost of ocean acidification. CO₂ 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 CO₂ 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 CO₂, but would also release carbon previously stored and thus exacerbate CO₂ 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⁻¹ 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 CO₂ 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 CO₂ 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 CO₂ 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

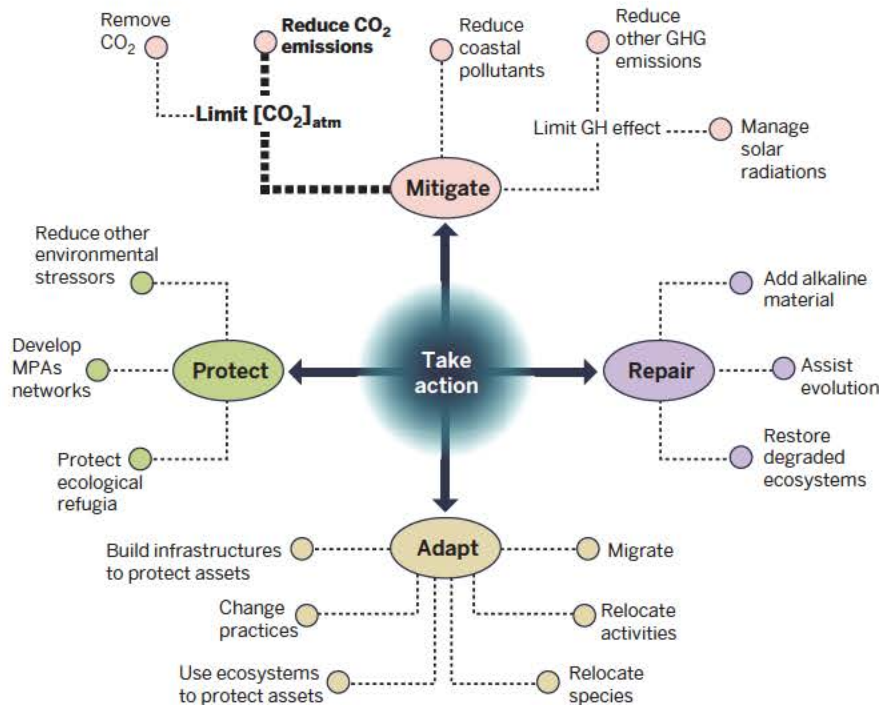


Fig. 4. Four clusters of actions against climate change, including ocean acidification. For each cluster, a nonexhaustive list of actions is shown. [CO₂]_{atm} is concentration of atmospheric CO₂; GH, greenhouse; GHG, greenhouse gases; MPAs, marine protected areas. The mitigation pathway leading to CO₂ reductions is represented in bold, consistent with the consensus view that significant reductions in CO₂ emissions is presently the only actual “solution” to the ocean impacts of climate change and ocean acidification (see main text).

CO₂ from the atmosphere). These options interact. For example, reducing secondary environmental stressors so as to retain ecosystem resilience works over some range of P_{CO_2} 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 CO₂, 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 CO₂ 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 CO₂ 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 dwindle, 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 CO₂ 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 CO₂ emissions are already detectable, and several will face high risk of impacts well before 2100, even with the stringent CO₂ 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 CO₂ 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 CO₂, 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 CO₂ 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 CO₂ emission reduction and eventual reduction of atmospheric CO₂ 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 I 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 I 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; pmid: 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. Harrould Kolbe, 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, CO₂ and non CO₂ 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. 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. Ianson, 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.2010.55.10346](https://doi.org/10.4319/lo.2010.55.10346)
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 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 CO₂ Emissions* (Carbon Dioxide Information Analysis Center, Oak Ridge, TN, 2013).
27. C. Jones et al., Twenty first century compatible CO₂ 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 et al., Regional impacts of climate change and atmospheric CO₂ 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 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)
33. E. C. Shaw, B. I. McNeil, B. Tibbrook, R. Matear, M. L. Bates, Anthropogenic changes to seawater buffer capacity combined with natural reef metabolism induce extreme future coral reef CO₂ 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/)
34. T. Cironak, I. R. Santos, D. V. Erler, D. T. Maher, B. D. Eyre, Drivers of pCO₂ 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 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: [24004074](https://pubmed.ncbi.nlm.nih.gov/24004074/)
36. M. Mätzdotter 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 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)
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 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/)
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/fsv172](https://doi.org/10.1093/icesjms/fsv172)
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). doi: [10.1126/science.1239352](https://doi.org/10.1126/science.1239352); pmid: [24031017](https://pubmed.ncbi.nlm.nih.gov/24031017/)
44. J. G. Hiddink, M. T. Burrows, J. Garcia 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/)
45. 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)
46. 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/)
47. J. P. Gilbert, J. P. DeLong, Temperature alters food web body size structure. *Biol. Lett.* **10**, 20140473 (2014). doi: [10.1098/rsbl.2014.0473](https://doi.org/10.1098/rsbl.2014.0473); pmid: [25165457](https://pubmed.ncbi.nlm.nih.gov/25165457/)
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. 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. Cunniff, 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.0366029A](https://doi.org/10.3989/scimar.0366029A)
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). pmid: [24762535](https://pubmed.ncbi.nlm.nih.gov/24762535/)
58. M. Schweinsberg, L. C. Weiss, S. Striessnig, R. Tollrian, K. P. Lampert, More than one genotype: How common is intracolony 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. 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). 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. Bednaršek 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 pCO₂: 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. 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). 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, O. Guadalupe, 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 pCO₂ 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.1256055](https://doi.org/10.1126/science.1256055)
 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/es501611u](https://doi.org/10.1021/es501611u); pmid: 25014366
 95. A. J. Poulton 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.coust.2010.10.004](https://doi.org/10.1016/j.coust.2010.10.004)
 97. J. Brodie et al., The future of the northeast Atlantic benthic flora in a high CO₂ world. *Ecol. Evol.* **4**, 2787–2798 (2014). doi: [10.1002/ece3.1105](https://doi.org/10.1002/ece3.1105); pmid: 25077027
 98. M. O. Clarkson et al., Ocean acidification and the Permian Triassic mass extinction. *Science* **348**, 229–232 (2015). doi: [10.1126/science.1256093](https://doi.org/10.1126/science.1256093); pmid: 25859043
 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). 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. Mender de Suarez, B. C. Sain Cacin, 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. Ondiviela et al., 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](https://doi.org/10.1016/j.coastaleng.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: [10.1579/0044-7447\(2008\)37\[241:TVOOCWF\]2.0.CO;2](https://doi.org/10.1579/0044-7447(2008)37[241:TVOOCWF]2.0.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 drive 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: [10.1163/2211600190000153](https://doi.org/10.1163/2211600190000153)
 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.pocan.2014.07.001](https://doi.org/10.1016/j.pocan.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. Waldburger, 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/lm.2012.57.3.0698](https://doi.org/10.4319/lm.2012.57.3.0698)
 130. D. Narita, K. Rehndanz, 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
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](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. Reyter, M. Spalding, A. Perry, *Reefs at Risk Revisited* (World Resources Institute, Washington, DC, 2011), p. 114.
138. M. Pascual, X. Rodó, S. P. Elner, R. Colwell, M. J. Boura, Chlora 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
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
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
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. Billé 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
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., "CO₂ 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
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
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. Murri, 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
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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