REVIEW SUMMARY

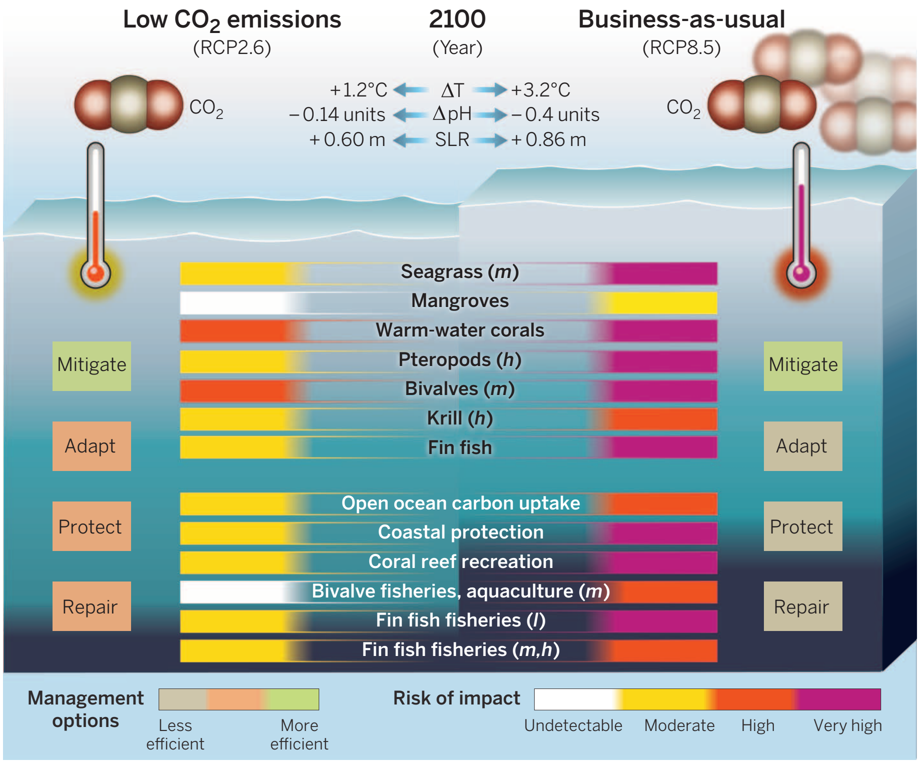
OCEANOGRAPHY

Contrasting futures for ocean and society from different anthropogenic CO_2 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_2 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_2 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-CO_2 periods in the paleorecord.



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_2 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.

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 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.

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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_2 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_2 increases, protection, adaptation, and repair options for the ocean become fewer and less effective.

The ocean provides compelling arguments for rapid reductions in CO_2 emissions and eventually atmospheric CO_2 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_2 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 (CO_2) 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_2 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_2 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_2 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_2. Setting it apart, CO_2 accounts for two or more times the warming attributed to the non-CO_2 greenhouse gases by 2100 (*11*) and causes ocean acidification. The uptake of excess anthropogenic CO_2 by the ocean increases the partial pressure of carbon dioxide (P_{CO_2}) 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_2 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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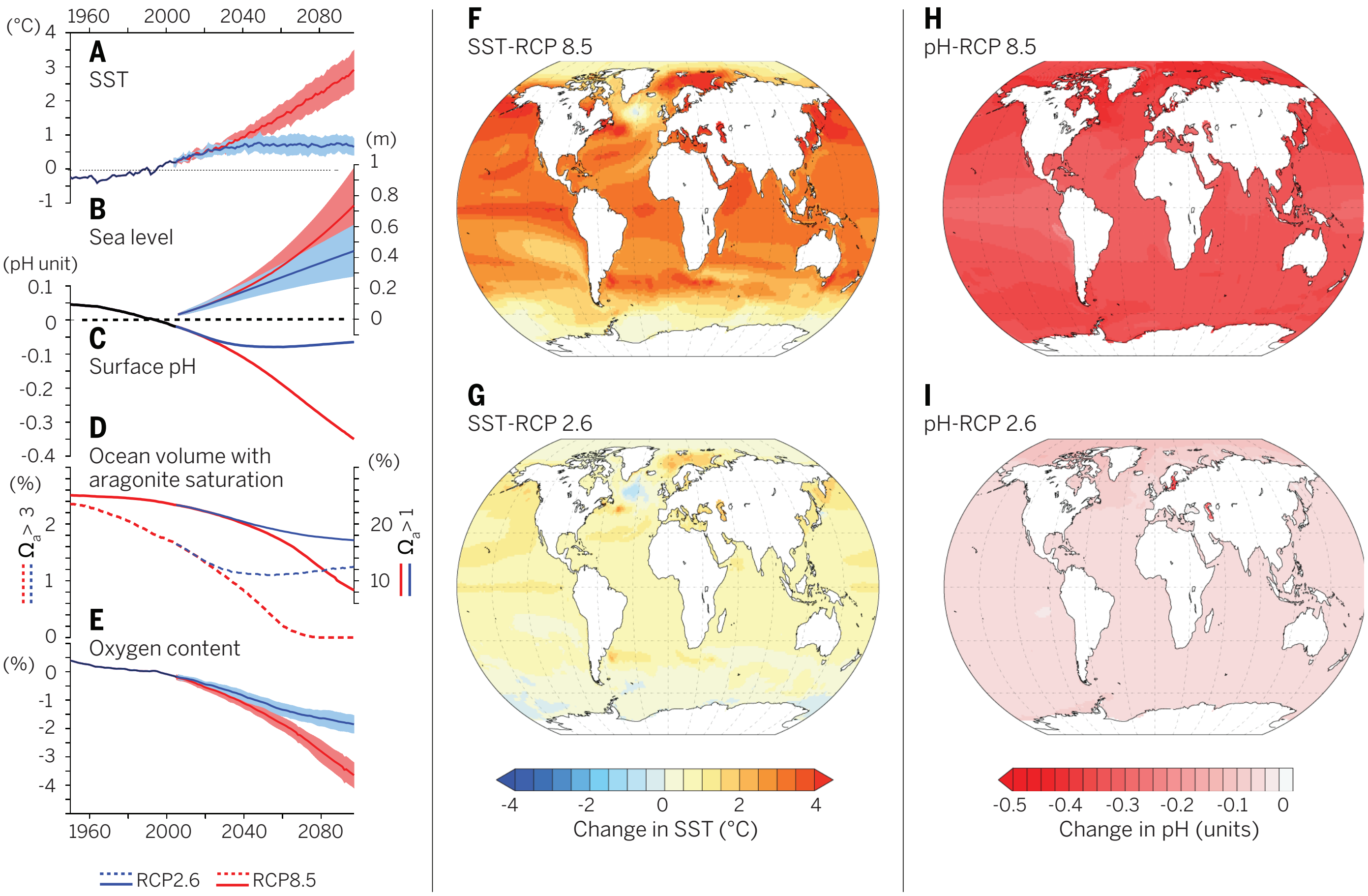


Fig. 1. Environmental changes over the industrial period and the 21st century for a business-as-usual scenario and a stringent emissions scenario consistent with the UNFCCC target of increase in global surface temperature by 2°C. (**A** to **E**) Changes in globally averaged (A) SST, (B) sea level, (C) 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).

	ΔSST (°C)	ΔpH (units)	ΔO_2 content (%)	Sea level (m)	Vol. Ω_a >1 (%)	Vol. Ω_a >3 (%)
Changes relative to 1990–1999						
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
Changes relative to 1870–1899 (except sea level, relative to 1901)						
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

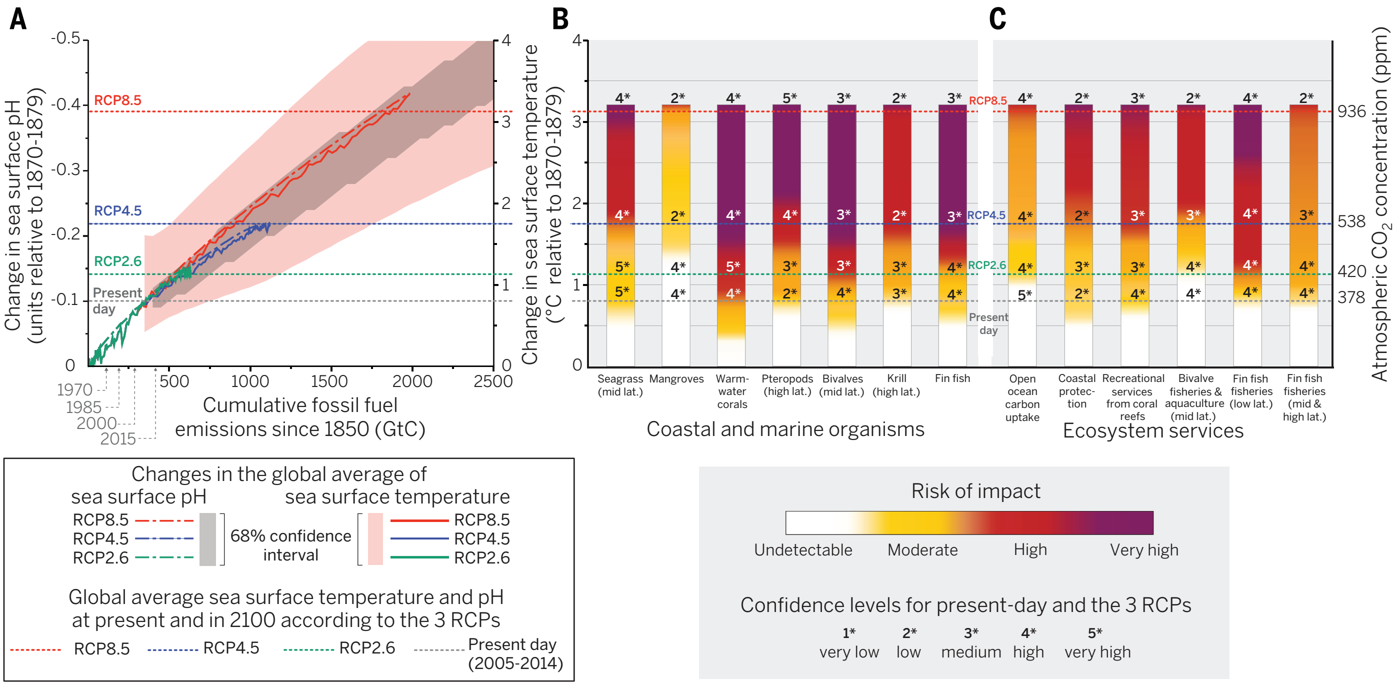


Fig. 2. Observed impact and risk scenarios of ocean warming and acidification for important organisms and critical ecosystem services. "Present-day" (gray dotted line) corresponds to the period from 2005 to 2014. Impact levels are for the year 2100 under the different projections shown and do not consider 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_2 on key organisms that are well documented in the literature. (**C**) Risk of impacts resulting from elevated CO_2 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*).

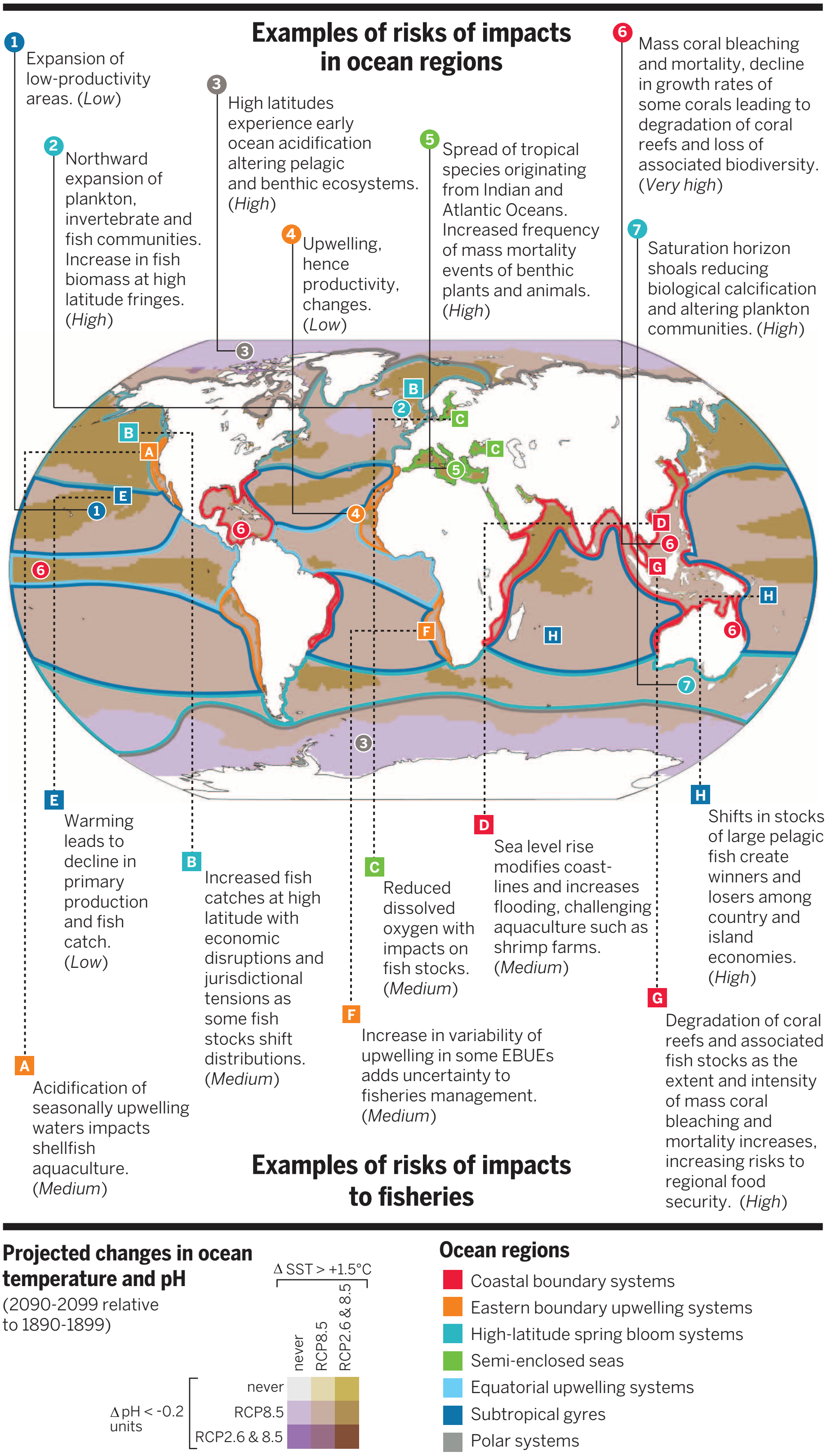
cumulative carbon emissions from fossil fuel use are 1685 gigatons of carbon (GtC) and 270 GtC for the two RCPs, respectively (*10*, *25*). This is in addition to the 375 and 180 GtC already emitted by 2011 by fossil fuel and land use, respectively (*25*). Because carbon emissions were 10 GtC in 2013 (*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_2 than is currently predicted. Indeed, the ocean's effectiveness in absorbing CO_2 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 ± 1 SD: 2.73 ± 0.72°C versus 0.71 ± 0.45°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*).

CO_2 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 ± 0.44%; RCP2.6: –1.81 ± 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_2 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 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.



Examples of risks of impacts in ocean regions

1 Expansion of low-productivity areas. (*Low*)

2 Northward expansion of plankton, invertebrate and fish communities. Increase in fish biomass at high latitude fringes. (*High*)

3 High latitudes experience early ocean acidification altering pelagic and benthic ecosystems. (*High*)

4 Upwelling, hence productivity, changes. (*Low*)

5 Spread of tropical species originating from Indian and Atlantic Oceans. Increased frequency of mass mortality events of benthic plants and animals. (*High*)

6 Mass coral bleaching and mortality, decline in growth rates of some corals leading to degradation of coral reefs and loss of associated biodiversity. (*Very high*)

7 Saturation horizon shoals reducing biological calcification and altering plankton communities. (*High*)

Examples of risks of impacts to fisheries

A Acidification of seasonally upwelling waters impacts shellfish aquaculture. (*Medium*)

E Warming leads to decline in primary production and fish catch. (*Low*)

B Increased fish catches at high latitude with economic disruptions and jurisdictional tensions as some fish stocks shift distributions. (*Medium*)

F Increase in variability of upwelling in some EBUEs adds uncertainty to fisheries management. (*Medium*)

C Reduced dissolved oxygen with impacts on fish stocks. (*Medium*)

D Sea level rise modifies coastlines and increases flooding, challenging aquaculture such as shrimp farms. (*Medium*)

G Degradation of coral reefs and associated fish stocks as the extent and intensity of mass coral bleaching and mortality increases, increasing risks to regional food security. (*High*)

H Shifts in stocks of large pelagic fish create winners and losers among country and island economies. (*High*)

Projected changes in ocean temperature and pH

(2090-2099 relative to 1890-1899)

Ocean regions

- 🟥 Coastal boundary systems
- 🟧 Eastern boundary upwelling systems
- 🟦 High-latitude spring bloom systems
- 🟩 Semi-enclosed seas
- 🟦 Equatorial upwelling systems
- 🟦 Subtropical gyres
- ⬜ Polar systems

Fig. 3. Regional changes in the physical system and associated risks for natural and human-managed systems. Projected changes in SST (ΔSST) and pH (ΔpH) in 2090–2099 relative to preindustrial 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*).

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_2 (*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_2-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_2 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_2-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_2 is a key service to society that moderates climate change, although it comes at the cost of ocean acidification. CO_2 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_2 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_2, but would also release carbon previously stored and thus exacerbate CO_2-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 increasing 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_2 level corresponding to RCP2.6 in 2100. In addition, cumulative or synergistic impacts with other human-induced drivers, such as overexploitation of living resources, habitat destruction, and pollution, will likely exacerbate the risk of CO_2-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_2 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

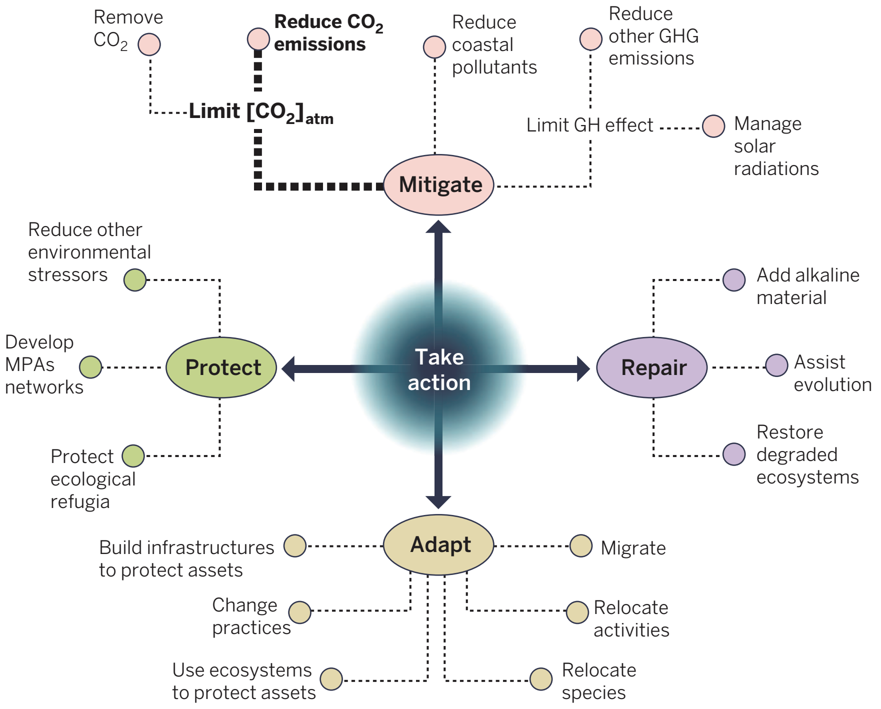


Fig. 4. Four clusters of actions against climate change, including ocean acidification. For each cluster, a nonexhaustive list of actions is shown. $[CO_2]_{atm}$ is concentration of atmospheric CO_2; GH, greenhouse; GHG, greenhouse gases; MPAs, marine protected areas. The mitigation pathway leading to CO_2 reductions is represented in bold, consistent with the consensus view that significant reductions in CO_2 emissions is presently the only actual "solution" to the ocean impacts of climate change and ocean acidification (see main text).

CO_2 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 CO_2, 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_2 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_2-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_2 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_2 emissions are already detectable, and several will face high risk of impacts well before 2100, even with the stringent CO_2 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_2 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_2, 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_2 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_2 emission reduction and eventual reduction of atmospheric CO_2 content. As a result, any new global climate agreement that does not minimize the impacts on the ocean will be incomplete and inadequate.

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SUPPLEMENTARY MATERIALS

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Contrasting futures for ocean and society from different anthropogenic CO $_2$ emissions scenarios

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