

# OA

## Ocean Acidification

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Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO<sub>2</sub> (Figure OA-1A; WGI, Section 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulfur all exacerbate ocean acidification locally (Sections 5.3.3.6, 6.1.1, 30.3.2.2).

### Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO<sub>2</sub> result in an increased flux of CO<sub>2</sub> into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO<sub>2</sub> levels (Figure CC-OA-1B). Observations of changing upper ocean CO<sub>2</sub> chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30-8, 30-9). Projected changes in open ocean, surface water chemistry for the year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to pre-industrial values range from a pH change of  $-0.14$  units with Representative Concentration Pathway (RCP)2.6 (421 ppm CO<sub>2</sub>,  $+1^{\circ}\text{C}$ , 22% reduction of carbonate ion concentration) to a pH change of  $-0.43$  units with RCP8.5 (936 ppm CO<sub>2</sub>,  $+3.7^{\circ}\text{C}$ , 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (Sections 5.3.3.5, 30.3.2.2), in polar regions (WGI Section 6.4.4), and at depth are more difficult but generally follow similar trends.

### Biological, Ecological, and Biogeochemical Impacts

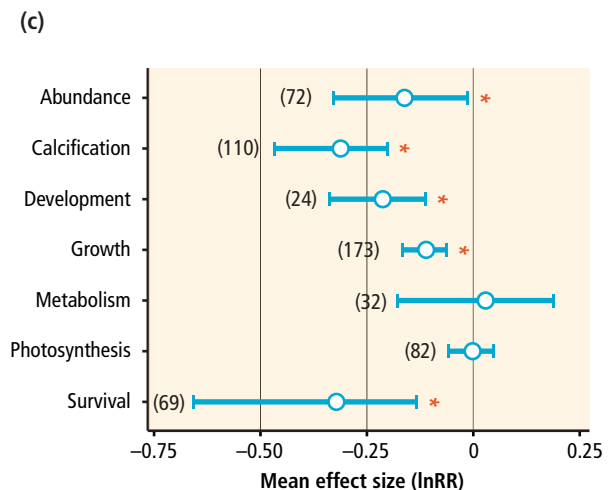
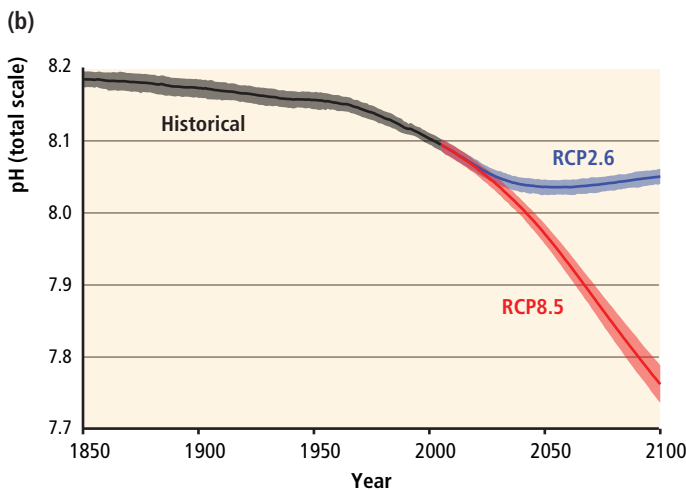
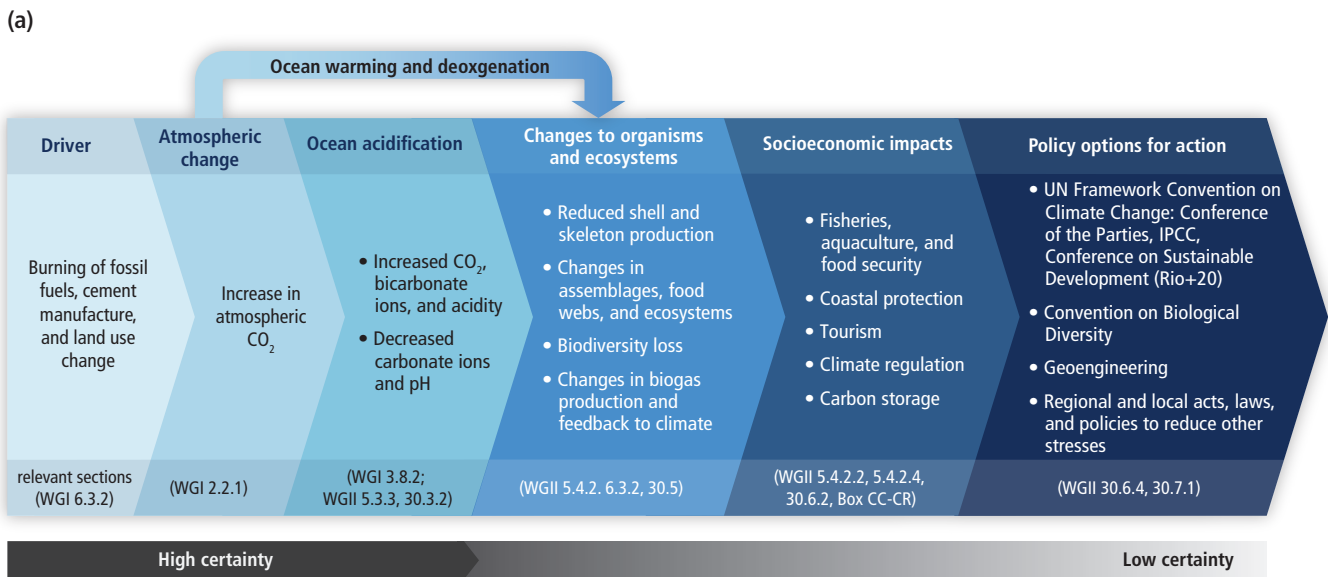
Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several meta-analyses (Sections 6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; Sections 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Figure OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories, and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; Sections 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; Sections 5.4.2.3, 6.3.2.2, 6.3.2.3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not

all, sea floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves, and gastropods, reducing the competitiveness with non-calcifiers (Sections 5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4). Some corals and temperate fishes experience disturbances to behavior, navigation, and their ability to tell conspecifics from predators (Section 6.3.2.4). However, there is no evidence for these effects to persist on evolutionary time scales in the few groups analyzed (Section 6.3.2).

Some phytoplankton and molluscs displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; Section 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; Section 6.1.2).

Projections of ocean acidification effects at the ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator–prey relationships and competitive interactions (Sections



**Figure OA-1** | (a) Overview of the chemical, biological, and socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). (b) Multi-model simulated time series of global mean ocean surface pH (on the total scale) from Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model simulations from 1850 to 2100. Projections are shown for emission scenarios Representative Concentration Pathway (RCP)2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (gray shading) is the modeled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO<sub>2</sub> concentrations (WGI AR5 Figures SPM.7 and TS.20). (c) Effect of near-future acidification (seawater pH reduction of  $\leq 0.5$  units) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (lnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. The \* denotes a statistically significant effect.

6.3.2.5, 6.3.5, 6.3.6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO<sub>2</sub> vents indicate decreased species diversity, biomass, and trophic complexity of communities (Box CC-CR; Sections 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (Section 5.4.2.2).

Owing to an incomplete understanding of species-specific responses and trophic interactions, the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic, or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

### Risks, Socioeconomic Impacts, and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (Section 6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, Section 5.4.2.4) and the goods and services that they provide such as fisheries, tourism, and coastal protection (*limited evidence, high agreement*; Box CC-CR; Sections 6.4.1.1, 19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed because of the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (Section 19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially exploited shelled molluscs (Section 6.4.1.1) would result in a reduction of USA production of 3 to 13% according to the Special Report on Emission Scenarios (SRES) A1FI emission scenario (*low confidence*). The global cost of production loss of molluscs could be more than US\$100 billion by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic, and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Section 6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2012, to be US\$870 and 528 billion, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; Section 6.4.1). Although this number is small compared to global gross domestic product (GDP), it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (Sections 25.7.5, 29.3.1.2).

### Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e., reduce anthropogenic emissions of CO<sub>2</sub>) and/or adaptation by reducing the consequences of past and future ocean acidification (Section 6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO<sub>2</sub> is the most effective and the least risky method to limit ocean acidification and its impacts (Section 6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (Section 6.4.2.2). Geoengineering techniques to remove CO<sub>2</sub> from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO<sub>2</sub> storage capacity (Section 6.4.2.2). In addition, some ocean-based approaches, such as iron fertilization, would only relocate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Sections 6.4.2.2, 30.3.2.3, 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO<sub>2</sub>, such as nutrient pollution (Section 6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (Section 5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (Section 6.4.2.1).

## References

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