Ocean Acidification - Expectations

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http://ccdatacenter.org/documents/OceanAcidificationExpectations.pdf

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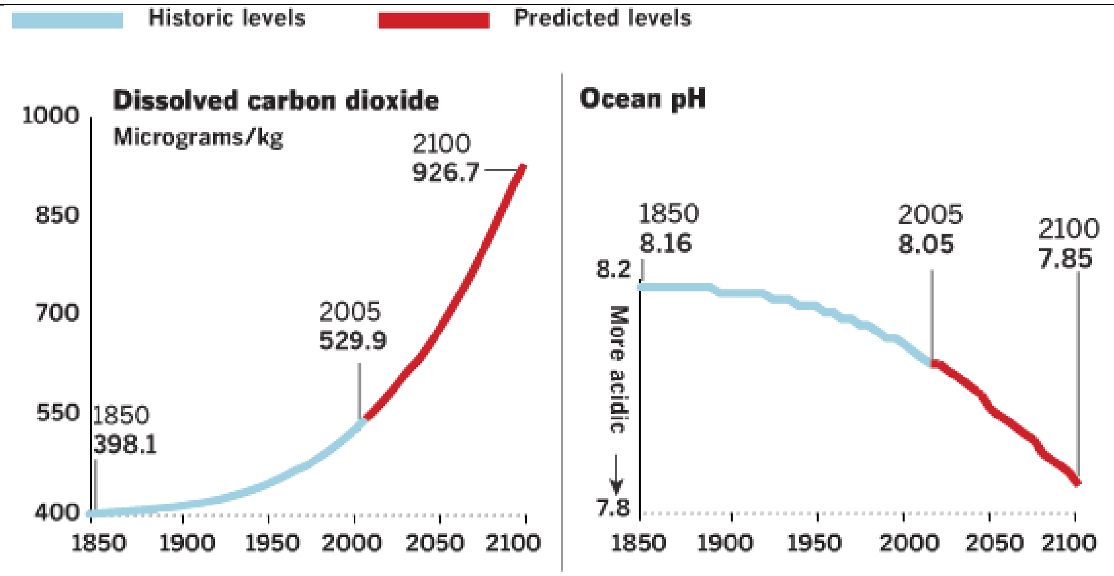
- The oceans have absorbed about 30 percent of the CO_2 emitted from all human activities (about 530 $GTCO_2$ from 1750-2005), and this has increased the oceans' acidity about 30 percent[1,2].
- Because of increased ocean acidification, new shells end up being thinner and more fragile while existing shells become pitted and weak[1].
- If CO_2 emissions continue at the current rate the ocean pH will likely drop another 0.3 to 0.4 pH units by2100, which would kill off most corals and shell fish[3].
- For the Southern Ocean, the acidification tipping point is about 450-ppm atmospheric CO_2, which will be reached in less than 20 years at the current rate of increase (2.11PPM/Year from 2005-2015, while there was a 3% increase from 2015 to 2016)[3,3A].
- By 2050, live corals could become rare in tropical and sub-tropical reefs due to the combined effects of warmer water and increased ocean acidity[4].
- Oceans could lose up to $1 trillion in annual value by 2100 due to acidification[5]
- Sea bass and other species targeted by fishing fleets could decline as a result of fish losing sense of smell in acidic ocean as they use their sense of smell to avoid predators and to find food[6]

OA1	**Effects of Changing the Carbon Cycle** About 30 percent of the carbon dioxide that people have put into the atmosphere has diffused into the ocean through the direct chemical exchange. Dissolving carbon dioxide in the ocean creates carbonic acid, which increases the acidity of the water. Or rather, a slightly alkaline ocean becomes a little less alkaline. Since 1750, the pH of the ocean's surface has dropped by 0.1, a 30 percent change in acidity. Ocean acidification affects marine organisms in two ways. First, carbonic acid reacts with carbonate ions in the water to form bicarbonate. However, those same carbonate ions are what shell-building animals like coral need to create calcium carbonate shells. With less carbonate available, the animals need to expend more energy to build their shells. As a result, the shells end up being thinner and more fragile. Second, the more acidic water is, the better it dissolves calcium carbonate. In the long run, this reaction will allow the ocean to soak up excess carbon dioxide because more acidic water will dissolve more rock, release more carbonate ions, and increase the ocean's capacity to absorb carbon dioxide. In the meantime, though, more acidic water will dissolve the carbonate shells of marine organisms, making them pitted and weak. Warmer oceans—a product of the greenhouse effect—could also decrease the abundance of phytoplankton, which grow better in cool, nutrient-rich waters. This could limit the ocean's ability to take carbon from the atmosphere through the fast carbon cycle. On the other hand, carbon dioxide is essential for plant and phytoplankton growth. An increase in carbon dioxide could increase growth by fertilizing those few species of phytoplankton and ocean plants (like sea grasses) that take carbon dioxide directly from the water. However, most species are not helped by the increased availability of carbon dioxide. https://earthobservatory.nasa.gov/Features/CarbonCycle/page5.php

OA2	 Note: 100 micrograms represents a 10,000th of one gram for each thousand grams of seawater. Based on "Ocean acidification due to atmospheric carbon dioxode, Altered Oceans: A Chemical Imbalance". See also "Ocean acidification due to increasing atmospheric carbon dioxide" (http://www.us-ocb.org/publications/Royal_Soc_OA.pdf)
OA3	If CO2 emissions continue at the current rate the ocean pH will likely drop another 0.3 to 0.4 pH units by2100, which would kill off most corals and shell fish. For the Southern Ocean, the acidification tipping point is about 450-ppm atmospheric CO2 (http://www.pnas.org/content/105/48/18860.long) , which will be reached in less than 20 years at the current rate of increase (2.11PPM/Year). Ocean Acidification will almost certainly be catastrophic (or at least very bad) based on any reasonable CO2 emissions mitigation scenario
OA3A	**Ocean acidification is having major impact on marine life** In new research, scientists say cuts in global CO2 emissions are essential to limit further damage to coral reefs and kelp forests July 28, 2018 University of Plymouth Carbon dioxide emissions are killing off coral reefs and kelp forests as heat waves and ocean acidification damage marine ecosystems, scientists have warned. But if CO2 levels continue to rise as predicted, the coming decades and lowering seawater pH levels will have an even greater and potentially catastrophic impact. https://www.sciencedaily.com/releases/2018/07/180728083507.htm
OA4	**Plants, Animals, and Ecosystems** By 2050, live corals could become rare in tropical and sub-tropical reefs due to the combined effects of warmer water and increased ocean acidity caused by more carbon dioxide in the atmosphere. The loss of coral reefs will reduce habitats for many other sea creatures, and it will disrupt the food web that connects all the living things in the ocean. https://www3.epa.gov/climatechange//kids/impacts/effects/ecosystems.html
OA5	**Oceans Could Lose $1 Trillion in Value Due to Acidification** By Jennifer Huizen, ClimateWire on October 21, 2014

	One estimate looking only at lost ecosystem protections, such as that provided by tropical reefs, cited an economic value of $1 trillion annually. https://www.scientificamerican.com/article/oceans-could-lose-1-trillion-in-value-due-to-acidification/ https://www.natureworldnews.com/articles/9469/20141008/ocean-acidification-cost-world-coral-trillion-dollars.htm
OA6	**Fish losing sense of smell in acidic ocean** Ben Webster, Environment Editor July 24 2018, 12:01am, The Times Fish are losing their sense of smell as the ocean absorbs rising levels of carbon dioxide in the atmosphere and becomes more acidic, a study found. Sea bass and other species targeted by fishing fleets could decline as a result because they use their sense of smell to avoid predators and to find food. https://www.thetimes.co.uk/edition/news/fish-losing-sense-of-smell-in-acidic-ocean-carbon-dioxide-7xznbdx63
	Current understanding and challenges for oceans in a higher-CO2 world Catriona L. Hurd, Andrew Lenton, Bronte Tilbrook & Philip W. Boyd Nature Climate Change (2018) | Published: 23 July 2018 **Abstract** Ocean acidification is a global phenomenon, but it is overlaid by pronounced regional variability modulated by local physics, chemistry and biology. Recognition of its multifaceted nature and the interplay of acidification with other ocean drivers has led to international and regional initiatives to establish observation networks and develop unifying principles for biological responses. There is growing awareness of the threat presented by ocean acidification to ecosystem services and the socio-economic consequences are becoming increasingly apparent and quantifiable. In this higher-CO2 world, future challenges involve better design and rigorous testing of adaptation, mitigation and intervention options to offset the effects of ocean acidification at scales ranging from local to regional. https://www.nature.com/articles/s41558-018-0211-0
	Ocean acidification will likely have severe impacts before 2050
	FAQs about Ocean Acidification Thus, a 2°C increase in temperature results in about a 10% decrease in carbon uptake in surface waters. marine shellfish that have evolved in seawater with a higher and less variable pH are more susceptible to changes in pH Will ocean acidification kill all ocean life? No. However, many scientists think that ocean acidification will lead to important changes in marine ecosystems. In general, ocean life recovers from extinction episodes by adaptation and evolution of new species, but this takes roughly 10 million years to achieve pre-extinction levels of biodiversity. Today's rates of CO2increase in the atmosphere are therefore approximately 100 times greater than most changes sustained over geologic time. It is within our technical and economic means to modify our energy and transportation systems and land-use practices to largely eliminate carbon dioxide emissions from our economies by mid-century. It is thought that

	the cost of doing this — perhaps 2% of the worldwide economic production — would be small, yet at present it has proven difficult for societies to decide to undertake this conversion. — Ken Caldeira, Senior Scientist, Carnegie Institution for Science, USA http://www.whoi.edu/page.do?pid=83380&tid=7342&cid=131410

	The Ocean Is Acidifying The ocean absorbs about 30 percent of the CO_2 emitted from human activities. When the ocean absorbs CO_2, it converts the gas into carbonic acid. Until the Industrial Revolution, there wasn't enough carbonic acid in the water to unbalance the ecosystem. But after more than a century of unchecked carbon emissions, the ecosystem has been measurably upended. The pH level of surface waters has dropped from 8.18 to 8.07, an unprecedented shift in the last 300 million years of the fossil record. [a change of 0.11 in pH corresponds to an increase of about 30% in the hydrogen ion concentration. - https://www.pmel.noaa.gov/co2/story/A+primer+on+pH)] it means less calcium carbonate. This mineral is a key ingredient in the shells of several marine species, and without it, fewer shellfish are surviving to adulthood. One oyster farm in Washington state reported that their oyster production declined by 42 percent in just 10 years. The tiny shellfish that feed Alaska's salmon stocks are also in danger, to say nothing of the state's lucrative crab fishery. Carbonic acid not only dissolves calcium carbonate, it also dissolves limestone, which makes it more difficult for coral to grow. Combine that with the reduction of pteropods and other zooplankton at the bottom of the food chain and the impacts to marine life are potentially catastrophic. Life above sea level will also be impacted. Investigations of carbon upwelling zones along the West Coast suggest that lower pH levels make it more difficult for certain phytoplankton to absorb nutrients, rendering them vulnerable to disease and toxins. And that's a problem, because healthy phytoplankton produce about 60 percent of the oxygen on Earth. Like the disappearance of microscopic pteropods, losing coral has a major ripple effect across the marine food chain. Though they cover less than one percent of the ocean floor, coral reefs support a quarter of all marine life. https://www.huffingtonpost.com/pierce-nahigyan/ocean-acidification-is-ba_b_8952240.html
	Ocean Acidification Assuming a "business-as-usual" IPCC CO_2emission scenario, predictive models of ocean biogeochemistry project that surface waters of the Arctic and Southern Oceans will become undersaturated with aragonite (a more soluble form of calcium carbonate) within a few decades, meaning that these waters will become highly corrosive to the shells and skeletons of aragonite-producing marine calcifiers like planktonic marine snails known as pteropods. http://www.whoi.edu/ocean-acidification/
	Ocean pH vs Atmospheric CO2 PPM

	Pre-industrial	Today	2× pre-industrial	3× pre-industrial	4× pre-industrial	5× pre-` industrial	6× pre-industrial
Atmospheric concentration of CO_2	280 ppm	380 ppm	560 ppm	840 ppm	1120 ppm	1400 ppm	1680 ppm
H_2CO_3 (mol/kg)	9	13	19	28	38	47	56
HCO_3^- (mol/kg)	1768	1867	1976	2070	2123	2160	2183
CO_3^{2-} (mol/kg)	225	185	141	103	81	67	57
Total dissolved inorganic carbon (mol/kg)	2003	2065	2136	2201	2242	2272	2296
Average pH of surface oceans	8.18	8.07	7.92	7.77	7.65	7.56	7.49
Calcite saturation	5.3	4.4	3.3	2.4	1.9	1.6	1.3
Aragonite saturation	3.4	2.8	2.1	1.6	1.2	1.0	0.9

Table 1. Changes to ocean chemistry and pH estimated using the OCMIP3 models calculated from surface ocean measurements and our understanding of ocean chemistry. Note that the concentration of bicarbonate ion (HCO3 –) and carbonic acid (H2CO3) increase with rising atmospheric concentration of CO2 while carbonate ion (CO3 2–) decreases. The average pH of the surface ocean waters decreases with increasing atmospheric CO2 concentration. (Assumptions used in model: Total alkalinity = 2324 mol/kg, temperature = 18° C. All other assumptions as per OCMIP3 (Institut Pierre Simon Laplace 2005). Aragonite and calcite saturation calculated as per Mucci & Morse (1990). Physical oceanographic modelling is based on Bryan (1969) and Cox (1984).

If CO2 emissions continue on current trends, this could result in the average pH of the surface oceans decreasing by 0.5 units below the level in pre-industrial times, by 2100. This is beyond the range of natural variability and represents a level probably not experienced for at least hundreds of thousands of years and possibly much longer (Caldeira & Wickett 2003). Critically, the rate of change is also at least 100 times higher than the maximum rate observed during this time period. These changes are so rapid that they will significantly reduce the buffering capacity of the natural processes that have moderated changes in ocean chemistry over most of geological time.

Royal Society - http://www.us-ocb.org/publications/Royal_Soc_OA.pdf

Good source for ocean acidification information: http://news-oceanacidification-icc.org/

Climate Science Special Report
Fourth National Climate Assessment (NCA4), Volume I

Chapter 13: Ocean Acidification and Other Ocean Changes
13.3: Ocean Acidification
13.3.1 General Background

In addition to causing changes in climate, increasing atmospheric levels of carbon dioxide (CO2) from the burning of fossil fuels and other human activities, including changes in land use, have a direct effect on ocean carbonate chemistry that is termed ocean acidification. , Surface ocean waters absorb part of the increasing CO2 in the atmosphere, which causes a variety of chemical changes in seawater: an increase in the partial pressure of CO2 (pCO2,sw), dissolved inorganic carbon (DIC), and the concentration of hydrogen and bicarbonate ions and a decrease in the concentration of carbonate ions (Figure 13.4). In brief, CO2 is an acid gas that combines with water to form carbonic acid, which then dissociates to hydrogen and bicarbonate ions. Increasing concentrations of seawater hydrogen ions result in a decrease of carbonate ions through their conversion to bicarbonate ions. The concentration of carbonate ions in seawater affects saturation states for calcium carbonate compounds, which many marine species use to build their shells and skeletons. Ocean acidity refers to the concentration of hydrogen ions in ocean seawater regardless of ocean pH, which is fundamentally basic (e.g., pH > 7). Ocean surface waters have become 30% more acidic over the last 150 years as they have absorbed large amounts of CO2 from the atmosphere, and anthropogenically sourced CO2 is gradually invading into oceanic deep waters. Since the preindustrial period, the oceans have absorbed approximately 29% of all CO2 emitted to the atmosphere. Oceans currently absorb about 26% of the human-caused CO2 anthropogenically emitted into the atmosphere.

13.3.2 Open Ocean Acidification
Surface waters in the open ocean experience changes in carbonate chemistry reflective of large-scale physical oceanic processes (see Ch. 2: Physical Drivers of Climate Change). These processes include both the global uptake of atmospheric CO2 and the shoaling of naturally acidified subsurface waters due to vertical mixing and upwelling. In general, the rate of ocean acidification in open ocean surface waters at a decadal time-scale

closely approximates the rate of atmospheric CO_2 increase. Large, multidecadal phenomena such as the Atlantic Multidecadal Oscillation and Pacific Decadal Oscillation can add variability to the observed rate of change.

13.3.3 Coastal Acidification

Coastal shelf and nearshore waters are influenced by the same processes as open ocean surface waters such as absorption of atmospheric CO_2 and upwelling, as well as a number of additional, local-level processes, including freshwater, nutrient, sulfur, and nitrogen inputs. , Coastal acidification generally exhibits higher-frequency variability and short-term episodic events relative to open-ocean acidification. , , , Upwelling is of particular importance in coastal waters, especially along the U.S. West Coast. Deep waters that shoal with upwelling are enriched in CO_2 due to uptake of anthropogenic atmospheric CO_2 when last in contact with the atmosphere, coupled with deep water respiration processes and lack of gas exchange with the atmosphere. , Freshwater inputs to coastal waters change seawater chemistry in ways that make it more susceptible to acidification, largely by freshening ocean waters and contributing varying amounts of dissolved inorganic carbon (DIC), total alkalinity (TA), dissolved and particulate organic carbon, and nutrients from riverine and estuarine sources. Coastal waters of the East Coast and mid-Atlantic are far more influenced by freshwater inputs than are Pacific Coast waters. Coastal waters can episodically experience riverine and glacial melt plumes that create conditions in which seawater can dissolve calcium carbonate structures. , While these processes have persisted historically, climate-induced increases in glacial melt and high-intensity precipitation events can yield larger freshwater plumes than have occurred in the past. Nutrient runoff can increase coastal acidification by creating conditions that enhance biological respiration. In brief, nutrient loading typically promotes phytoplankton blooms, which, when they die, are consumed by bacteria. Bacteria respire CO_2 and thus bacterial blooms can result in acidification events whose intensity depends on local hydrographic conditions, including water column stratification and residence time. Long-term changes in nutrient loading, precipitation, and/or ice melt may also impart long-term, secular changes in the magnitude of coastal acidification.

13.3.4 Latitudinal Variation

Ocean carbon chemistry is highly influenced by water temperature, largely because the solubility of CO_2 in seawater increases as water temperature declines. Thus, cold, high-latitude surface waters can retain more CO_2 than warm, lower-latitude surface waters. , Because carbonate minerals also more readily dissolve in colder waters, these waters can more regularly become undersaturated with respect to calcium carbonate whereby mineral dissolution is energetically favored. This chemical state, often referred to as seawater being “corrosive” to calcium carbonate, is important when considering the ecological implications of ocean acidification as many species make structures such as shells and skeletons from calcium carbonate. Seawater conditions undersaturated with respect to calcium carbonate are common at depth, but currently and historically rare at the surface and near-surface. Some high-latitude surface and near-surface waters now experience such corrosive conditions, which are rarely documented in low-latitude surface or near-surface systems. For example, corrosive conditions at a range of ocean depths have been documented in the Arctic and northeastern Pacific Oceans. , , , Storm-induced upwelling could cause undersaturation in tropical areas in the future. It is important to note that low-latitude waters are experiencing a greater absolute rate of change in calcium carbonate saturation state than higher latitudes, though these low-latitude waters are not approaching the undersaturated state except within near-shore or some benthic habitats.

13.3.5 Paleo Evidence

Evidence suggests that the current rate of ocean acidification is the fastest in the last 66 million years (the K-Pg boundary) and possibly even the last 300 million years (when the first pelagic calcifiers evolved providing proxy information and also a strong carbonate buffer, characteristic of the modern ocean). , The Paleo-Eocene Thermal Maximum (PETM; around 56 million years ago) is often referenced as the closest analogue to the present, although the overall rate of change in CO_2 conditions during that event (estimated between 0.6 and 1.1 GtC/year) was much lower than the current increase in atmospheric CO_2 of 10 GtC/year. , The relatively slower rate of atmospheric CO_2 increase at the PETM likely led to relatively small changes in carbonate ion

	concentration in seawater compared with the contemporary acidification rate, due to the ability of rock weathering to buffer the change over the longer time period. Some of the presumed acidification events in Earth's history have been linked to selective extinction events suggestive of how guilds of species may respond to the current acidification event. 13.3.6 Projected Changes Projections indicate that by the end of the century under higher scenarios, such as SRES A1FI or RCP8.5, open-ocean surface pH will decline from the current average level of 8.1 to a possible average of 7.8 (Figure 13.5). When the entire ocean volume is considered under the same scenario, the volume of waters undersaturated with respect to calcium carbonate could expand from 76% in the 1990s to 91% in 2100, resulting in a shallowing of the saturation horizons—depths below which undersaturation occurs. , Saturation horizons, which naturally vary among ocean basins, influence ocean carbon cycles and organisms with calcium carbonate structures, especially as they shoal into the zones where most biota lives. , As discussed above, for a variety of reasons, not all ocean and coastal regions will experience acidification in the same way depending on other compounding factors. For instance, recent observational data from the Arctic Basin show that the Beaufort Sea became undersaturated, for part of the year, with respect to aragonite in 2001, while other continental shelf seas in the Arctic Basin are projected to do so closer to the middle of the century (e.g., the Chukchi Sea in about 2033 and Bering Sea in about 2062). Deviation from the global average rate of acidification will be especially true in coastal and estuarine areas where the rate of acidification is influenced by other drivers than atmospheric CO2, some of which are under the control of local management decisions (for example, nutrient pollution loads).