

## Frequently Asked Questions

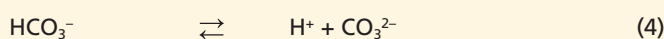
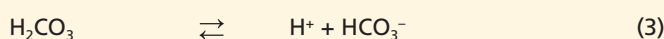
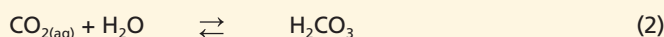
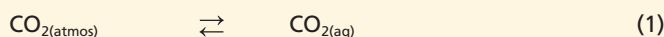
**FAQ 3.3 | How Does Anthropogenic Ocean Acidification Relate to Climate Change?**

*Both anthropogenic climate change and anthropogenic ocean acidification are caused by increasing carbon dioxide concentrations in the atmosphere. Rising levels of carbon dioxide (CO<sub>2</sub>), along with other greenhouse gases, indirectly alter the climate system by trapping heat as it is reflected back from the Earth's surface. Anthropogenic ocean acidification is a direct consequence of rising CO<sub>2</sub> concentrations as seawater currently absorbs about 30% of the anthropogenic CO<sub>2</sub> from the atmosphere.*

Ocean acidification refers to a reduction in pH over an extended period, typically decades or longer, caused primarily by the uptake of CO<sub>2</sub> from the atmosphere. pH is a dimensionless measure of acidity. Ocean acidification describes the direction of pH change rather than the end point; that is, ocean pH is decreasing but is not expected to become acidic (pH < 7). Ocean acidification can also be caused by other chemical additions or subtractions from the oceans that are natural (e.g., increased volcanic activity, methane hydrate releases, long-term changes in net respiration) or human-induced (e.g., release of nitrogen and sulphur compounds into the atmosphere). Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity.

Since about 1750, the release of CO<sub>2</sub> from industrial and agricultural activities has resulted in global average atmospheric CO<sub>2</sub> concentrations that have increased from 278 to 390.5 ppm in 2011. The atmospheric concentration of CO<sub>2</sub> is now higher than experienced on the Earth for at least the last 800,000 years and is expected to continue to rise because of our dependence on fossil fuels for energy. To date, the oceans have absorbed approximately 155 ± 30 PgC from the atmosphere, which corresponds to roughly one-fourth of the total amount of CO<sub>2</sub> emitted (555 ± 85 PgC) by human activities since preindustrial times. This natural process of absorption has significantly reduced the greenhouse gas levels in the atmosphere and minimized some of the impacts of global warming. However, the ocean's uptake of CO<sub>2</sub> is having a significant impact on the chemistry of seawater. The average pH of ocean surface waters has already fallen by about 0.1 units, from about 8.2 to 8.1 since the beginning of the Industrial Revolution. Estimates of projected future atmospheric and oceanic CO<sub>2</sub> concentrations indicate that, by the end of this century, the average surface ocean pH could be 0.2 to 0.4 lower than it is today. The pH scale is logarithmic, so a change of 1 unit corresponds to a 10-fold change in hydrogen ion concentration.

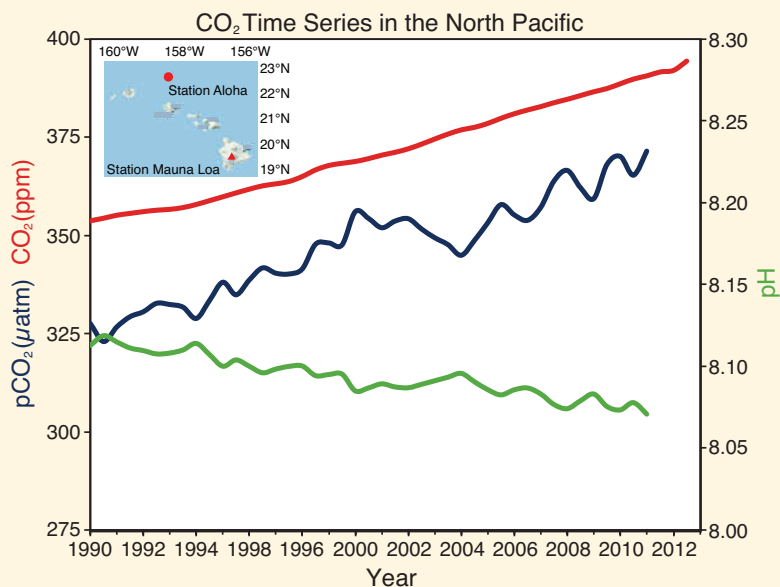
When atmospheric CO<sub>2</sub> exchanges across the air–sea interface it reacts with seawater through a series of four chemical reactions that increase the concentrations of the carbon species: dissolved carbon dioxide (CO<sub>2(aq)</sub>), carbonic acid (H<sub>2</sub>CO<sub>3</sub>) and bicarbonate (HCO<sub>3</sub><sup>-</sup>):



Hydrogen ions (H<sup>+</sup>) are produced by these reactions. This increase in the ocean's hydrogen ion concentration corresponds to a reduction in pH, or an increase in acidity. Under normal seawater conditions, more than 99.99% of the hydrogen ions that are produced will combine with carbonate ion (CO<sub>3</sub><sup>2-</sup>) to produce additional HCO<sub>3</sub><sup>-</sup>. Thus, the addition of anthropogenic CO<sub>2</sub> into the oceans lowers the pH and consumes carbonate ion. These reactions are fully reversible and the basic thermodynamics of these reactions in seawater are well known, such that at a pH of approximately 8.1 approximately 90% the carbon is in the form of bicarbonate ion, 9% in the form of carbonate ion, and only about 1% of the carbon is in the form of dissolved CO<sub>2</sub>. Results from laboratory, field, and modeling studies, as well as evidence from the geological record, clearly indicate that marine ecosystems are highly susceptible to the increases in oceanic CO<sub>2</sub> and the corresponding decreases in pH and carbonate ion.

Climate change and anthropogenic ocean acidification do not act independently. Although the CO<sub>2</sub> that is taken up by the ocean does not contribute to greenhouse warming, ocean warming reduces the solubility of carbon dioxide in seawater; and thus reduces the amount of CO<sub>2</sub> the oceans can absorb from the atmosphere. For example, under doubled preindustrial CO<sub>2</sub> concentrations and a 2°C temperature increase, seawater absorbs about 10% less CO<sub>2</sub> (10% less total carbon, C<sub>T</sub>) than it would with no temperature increase (compare columns 4 and 6 in Table 1), but the pH remains almost unchanged. Thus, a warmer ocean has less capacity to remove CO<sub>2</sub> from the atmosphere, yet still experiences ocean acidification. The reason for this is that bicarbonate is converted to carbonate in a warmer ocean, releasing a hydrogen ion thus stabilizing the pH. *(continued on next page)*

FAQ 3.3 (continued)



**FAQ 3.3, Figure 1** | A smoothed time series of atmospheric CO<sub>2</sub> mole fraction (in ppm) at the atmospheric Mauna Loa Observatory (top red line), surface ocean partial pressure of CO<sub>2</sub> (pCO<sub>2</sub>; middle blue line) and surface ocean pH (bottom green line) at Station ALOHA in the subtropical North Pacific north of Hawaii for the period from 1990–2011 (after Doney et al., 2009; data from Dore et al., 2009). The results indicate that the surface ocean pCO<sub>2</sub> trend is generally consistent with the atmospheric increase but is more variable due to large-scale interannual variability of oceanic processes.

**FAQ 3.3, Table 1** | Oceanic pH and carbon system parameter changes in surface water for a CO<sub>2</sub> doubling from the preindustrial atmosphere without and with a 2°C warming<sup>a</sup>.

Parameter	Pre-industrial (280 ppmv) 20°C	2 × Pre-industrial (560 ppmv) 20°C	(% change relative to pre-industrial)	2 × Pre-industrial (560 ppmv) 22°C	(% change relative to pre-industrial)
pH	8.1714	7.9202	–	7.9207	–
H <sup>+</sup> (mol kg <sup>-1</sup> )	6.739e <sup>-9</sup>	1.202e <sup>-8</sup>	(78.4)	1.200e <sup>-8</sup>	(78.1)
CO <sub>2(aq)</sub> (µmol kg <sup>-1</sup> )	9.10	18.10	(98.9)	17.2	(89.0)
HCO <sub>3</sub> <sup>-</sup> (µmol kg <sup>-1</sup> )	1723.4	1932.8	(12.15)	1910.4	(10.9)
CO <sub>3</sub> <sup>2-</sup> (µmol kg <sup>-1</sup> )	228.3	143.6	(-37.1)	152.9	(-33.0)
C <sub>T</sub> (µmol kg <sup>-1</sup> )	1960.8	2094.5	(6.82)	2080.5	(6.10)

Notes:

<sup>a</sup> CO<sub>2(aq)</sub> = dissolved CO<sub>2</sub>, H<sub>2</sub>CO<sub>3</sub> = carbonic acid, HCO<sub>3</sub><sup>-</sup> = bicarbonate, CO<sub>3</sub><sup>2-</sup> = carbonate, C<sub>T</sub> = total carbon = CO<sub>2(aq)</sub> + HCO<sub>3</sub><sup>-</sup> + CO<sub>3</sub><sup>2-</sup>.

Coastal regions have also experienced long-term dissolved oxygen changes. Bograd et al. (2008) reported a substantial reduction of the thermocline oxygen content in the southern part of the California Current from 1984 to 2002, resulting in a shoaling of the hypoxic boundary (marked by oxygen concentrations of about 60 µmol kg<sup>-1</sup>). Off the British Columbia coast, oxygen concentrations in the near bottom waters decreased an average of 1.1 µmol kg<sup>-1</sup> yr<sup>-1</sup> over a 30-year period (Chan et al., 2008). These changes along the west coast of North America appear to have been largely caused by the open ocean dissolved oxygen decrease and local processes associated with decreased vertical dissolved oxygen transport following near-surface warming and increased stratification. Gilbert et al. (2010) found evidence that for the time period 1976–2000 oxygen concentrations between 0 and 300 m depth were declining about 10 times faster in the coastal ocean

than in the open ocean, and an increase in the number of hypoxic zones was observed since the 1960s (Diaz and Rosenberg, 2008).

### 3.8.4 Nutrients

Nutrient concentrations in the surface ocean surface are influenced by human impacts on coastal runoff and on atmospheric deposition, and by changing nutrient supply from the ocean's interior into the mixed layer (for instance due to increased stratification). Changing nutrient distributions might influence the magnitude and variability of the ocean's biological carbon pump.

Globally, the manufacture of nitrogen fertilizers has continued to increase (Galloway et al., 2008) accompanied by increasing eutrophi-