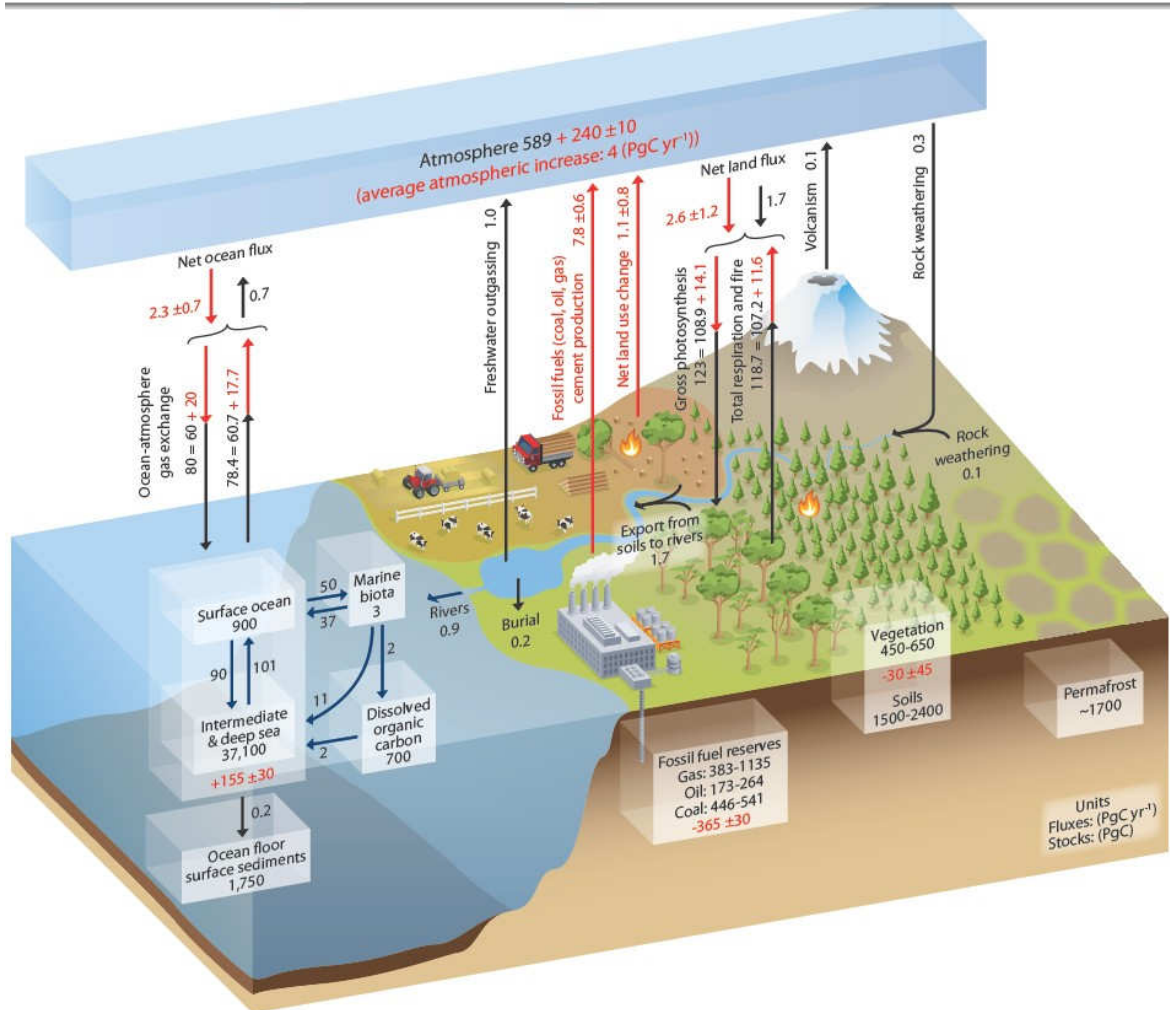


## 1) The Changing Carbon Cycle



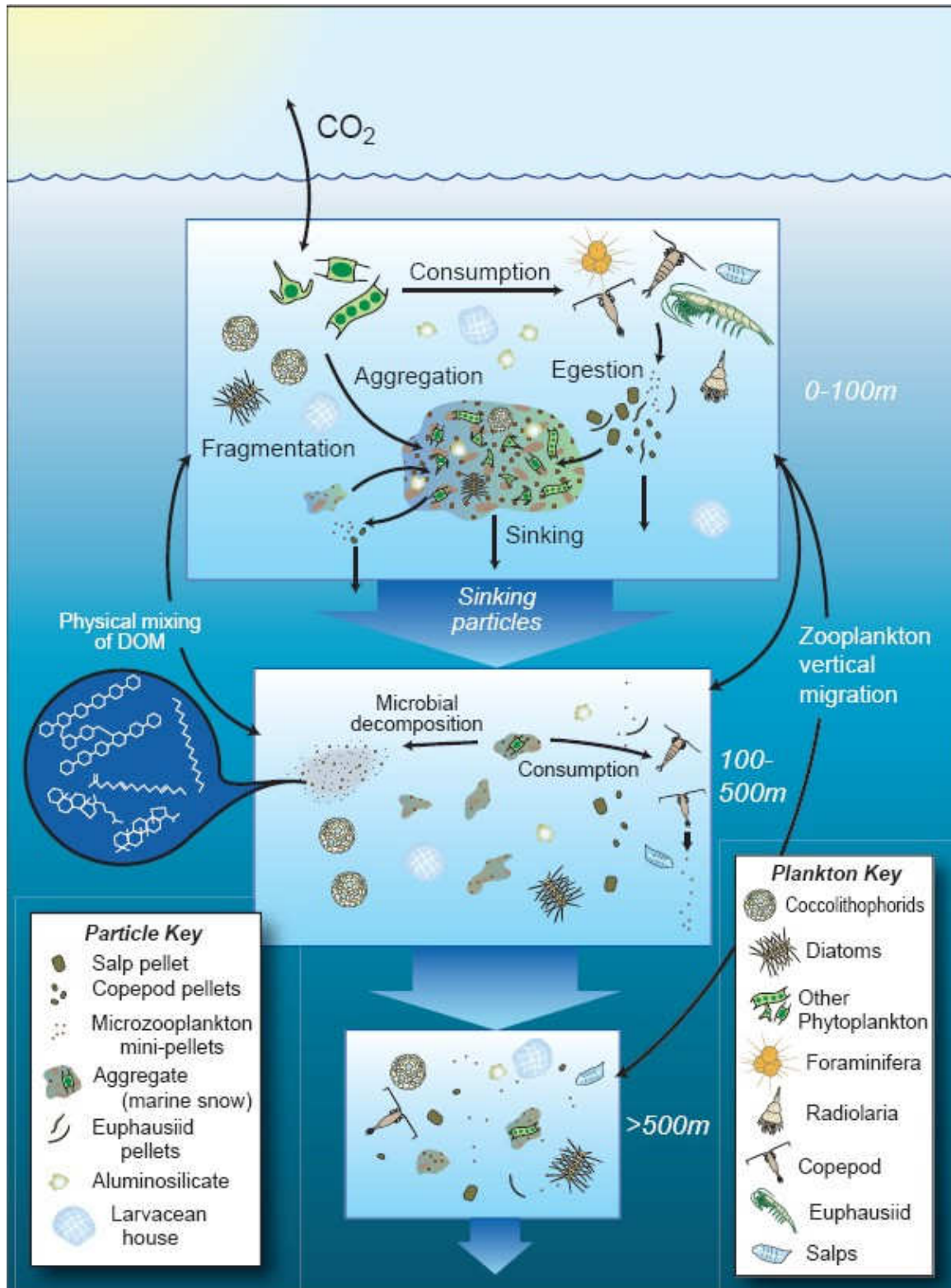
WG1 Chapter 6, figure 1 The numbers represent carbon reservoirs in Petagrams of Carbon (PgC;  $10^{15}$ gC) and the annual exchanges in PgC/year. The black numbers and arrows show the pre-Industrial reservoirs and fluxes. The red numbers and arrows show the additional fluxes caused by human activities averaged over 2000-2009, which include emissions due to the burning of fossil fuels, cement production and land use change (in total about 9 PgC/year). Some of this additional anthropogenic carbon is taken up by the land and the ocean (about 5 PgC/year) while the remainder is left in the atmosphere (4 PgC/year), explaining the rising atmospheric concentrations of  $\text{CO}_2$ . The red numbers in the reservoirs show the cumulative changes in anthropogenic carbon from 1750-2011; a positive change indicates that the reservoir has gained carbon.

Summary:

- The global carbon cycle can be viewed as a series of reservoirs of carbon in the Earth System, which are connected by exchange fluxes of carbon. An exchange flux is the amount of carbon which moves between reservoirs each year.
- Before human activities such as land use changes and industrial processes had a significant impact, the global carbon cycle was roughly balanced.
- $\text{CO}_2$  increased by over 40% from around 280 ppm in 1750 to 400 ppm in 2015.

- Higher atmospheric CO<sub>2</sub> concentrations, and associated climate impacts of present emissions, will persist for hundreds of years into the future.

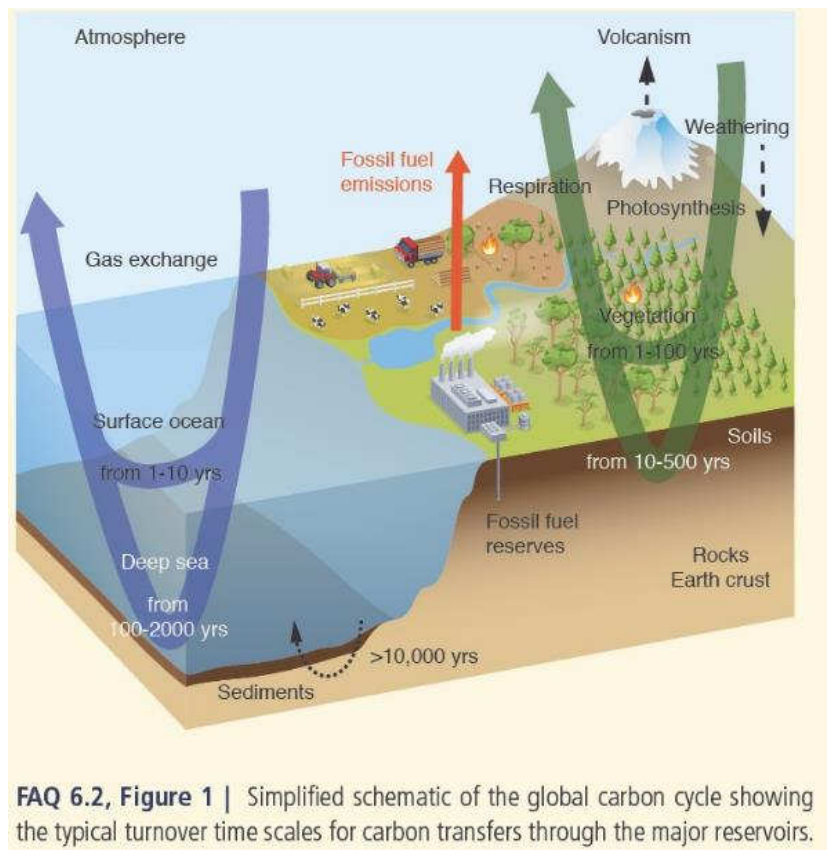
Case Study: The Ocean's Biological Pump



WG2 chapter 6 figure 4. The ocean's biological pump is one way in which carbon can be captured and deposited. Given the available science, it is difficult to know exactly how the pump may be altered by climate change and whether it would present a positive or negative feedback to climate change. Changes will affect, for example, grazing rates by larger fauna on the plankton, the depth at which various fauna live and changes to the speeds at which bacteria decompose material.

**Biological Pump:** The process of transporting carbon from the ocean's surface layers to the deep ocean by the primary production of marine phytoplankton, which converts dissolved inorganic carbon (DIC), mainly CO<sub>2</sub>, and nutrients into organic matter through photosynthesis.

Further Information:



### How fast is the carbon cycle?

There are two domains in the global carbon cycle, fast and slow. The fast domain has large exchange fluxes and relatively 'rapid' reservoir turnovers. This includes carbon on land in vegetation, soils, peat and freshwater and in the atmosphere, ocean and surface ocean sediments. Reservoir turnover times (a measure of how long the carbon stays in the reservoir) range from a few years for the atmosphere to decades to millennia for the major carbon reservoirs of the land vegetation and soil and the various domains in the ocean.

The slow domain consists of the huge carbon stores in rocks and sediments which exchange carbon with the fast domain through volcanic emissions of CO<sub>2</sub>, erosion and sediment formation on the sea floor. Reservoir turnover times of the slow domain are 10,000 years or longer.

Before the Industrial Era, the fast domain was close to a steady state. Data from ice cores show little change in the atmospheric CO<sub>2</sub> levels over millennia despite changes in land use and small emissions from humans. By contrast, since the beginning of the Industrial Era (around 1750), fossil fuel extraction and its combustion have resulted in the transfer of a significant amount of fossil carbon from the slow domain into the fast domain, causing a major change to the carbon cycle.

#### **Some reservoirs of carbon:**

In the atmosphere, CO<sub>2</sub> is the dominant carbon containing trace gas with a mass of 828 PgC (Petagrams of Carbon or  $\times 10^{15}$ gC). Additional trace gases include methane (CH<sub>4</sub>, currently about 3.7 PgC) and carbon monoxide (CO, around 0.2 PgC), with still smaller amounts of hydrocarbons, black carbon aerosols and other organic compounds.

The terrestrial biosphere reservoir contains carbon in organic compounds in vegetation (living biomass) (450 to 650 PgC) and in dead organic matter in litter and soils (1500 to 2400 PgC). There is an additional amount of old soil carbon in wetland soils (300 to 700 PgC) and in permafrost (1700 PgC).

#### **Some fluxes of carbon:**

CO<sub>2</sub> is removed from the atmosphere by plant photosynthesis (123±8 PgC/ year). Carbon fixed into plants is then cycled through plant tissues, litter and soil carbon and can be released back into the atmosphere by plant, microbial and animal respiration and other processes (e.g. forest fires) on a very wide range of time scales (seconds to millennia).

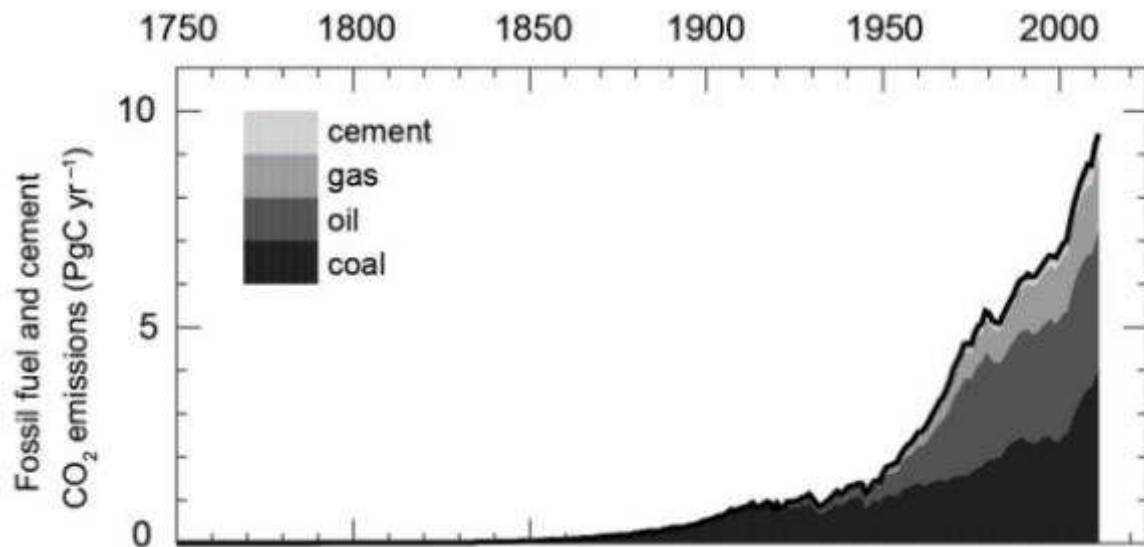
A significant amount of terrestrial carbon (1.7 PgC/year) is transported from soils to rivers. A fraction of this carbon is released as CO<sub>2</sub> by rivers and lakes to the atmosphere, a fraction is buried in freshwater organic sediments and the remaining amount (~0.9 PgC/ year) is delivered by rivers to the coastal ocean. Atmospheric CO<sub>2</sub> is exchanged with the surface ocean through gas exchange.

Carbon is transported within the ocean by three mechanisms;

- (1) the 'solubility pump' (see glossary),
- (2) the 'biological pump' (see case study),
- (3) the 'marine carbonate pump' which is caused by marine organisms forming shells in the surface ocean. These sink, are buried in the sediments and eventually form sedimentary rocks (such as limestone or chalk).



## Changes to the carbon cycle



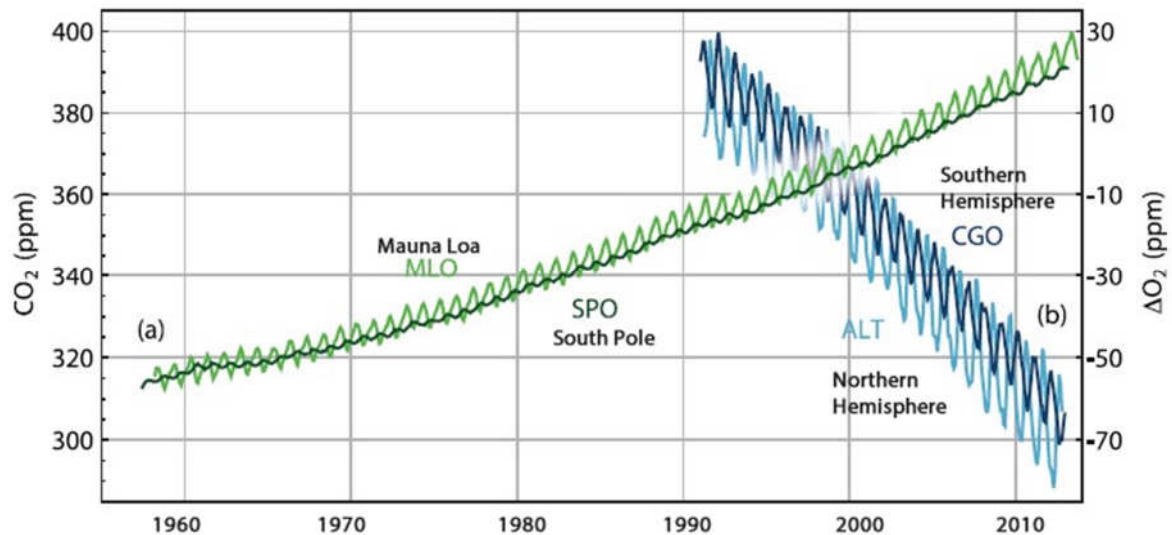
WG1 Technical Summary Figure 4. Annual global anthropogenic CO<sub>2</sub> emissions (PgC/year) from 1750 to 2011

Anthropogenic CO<sub>2</sub> emissions to the atmosphere were  $555 \pm 85$  PgC between 1750 and 2011. Of this, fossil fuel combustion and cement production contributed  $375 \pm 30$  PgC and land use change (including deforestation, afforestation (planting new forest) and reforestation) contributed  $180 \pm 80$  PgC. In 2002–2011, average fossil fuel and cement manufacturing emissions were 7.6 to 9.0 PgC/year, with an average increase of 3.2%/ year compared with 1.0%/ year during the 1990s. In 2011, fossil fuel emissions were in the range of 8.7 to 10.3 PgC.

Emissions due to land use changes (primarily tropical deforestation) between 2002 and 2011 are estimated to range between 0.1 to 1.7 PgC/year. This includes emissions from deforestation of around 3 PgC/ year compensated by an uptake of around 2 PgC/year by forest regrowth (mainly on abandoned agricultural land).

The IPCC concluded that the increase in CO<sub>2</sub> emissions from both fossil fuel burning and land use change are the dominant cause of the observed increase in atmospheric CO<sub>2</sub> concentration.

Globally, the combined natural land and ocean sinks of CO<sub>2</sub> kept up with the atmospheric rate of increase, removing 55% of the total anthropogenic emissions every year on average during 1958–2011. The ocean reservoir stored  $155 \pm 30$  PgC. Vegetation biomass and soils stored  $160 \pm 90$  PgC.



WG1 chapter 6, figure 3 Concentrations of carbon dioxide and oxygen in the atmosphere  
 Atmospheric concentration of a) carbon dioxide in parts per million by volume from Mauna Loa (MLO, light green) and the South Pole (SPO, dark green) and of b) changes in the atmospheric concentration of O<sub>2</sub> from the northern hemisphere (ALT, light blue) and the southern hemisphere (CGO, dark blue) relative to a standard value.

Carbon Dioxide concentrations in the atmosphere increased by over 40% from 278 ppm in 1750 to 400 ppm in 2015.

Most of the fossil fuel CO<sub>2</sub> emissions take place in the industrialised countries north of the equator. Consistent with this, the annual average atmospheric CO<sub>2</sub> measurement stations in the Northern Hemisphere (NH) record slightly higher CO<sub>2</sub> concentrations than stations in the Southern Hemisphere (SH). As the difference in fossil fuel combustion between the hemispheres has increased, so has the difference in concentration between measuring stations at the South Pole and Mauna Loa (Hawaii, NH).

The atmospheric CO<sub>2</sub> concentration increased by around 20 ppm during 2002–2011. This decadal rate of increase is higher than during any previous decade since direct atmospheric concentration measurements began in 1958.

Because CO<sub>2</sub> uptake by photosynthesis occurs only during the growing season, whereas CO<sub>2</sub> release by respiration occurs nearly year-round, both the Mauna Loa and South Pole concentrations show an annual cycle, with more CO<sub>2</sub> in the atmosphere in winter. However, as there is far more land mass and therefore vegetation in the Northern Hemisphere, the annual cycle is more pronounced at Mauna Loa.

Past changes in atmospheric greenhouse gas concentrations can be determined with very high confidence from polar ice cores. During the 800,000 years prior to 1750, atmospheric CO<sub>2</sub> varied from 180 ppm during glacial (cold) up to 300 ppm during interglacial (warm) periods. Present-day (2011) concentrations of atmospheric carbon dioxide far exceed this range. The current rate of CO<sub>2</sub> rise in atmospheric concentrations is unprecedented with respect to the highest resolution ice core records which cover the last 22,000 years.

## What is the relationship between the Carbon Cycle and Oxygen?

Atmospheric oxygen is tightly coupled with the global carbon cycle. The burning of fossil fuels removes oxygen from the atmosphere. As a consequence of the burning of fossil fuels, atmospheric O<sub>2</sub> levels have been observed to decrease slowly but steadily over the last 20 years. Compared to the atmospheric oxygen content of about 21% this decrease is very small and has no impact on health; however, it provides independent evidence that the rise in CO<sub>2</sub> must be due to an oxidation process, that is, fossil fuel combustion and/or organic carbon oxidation, and is not caused by volcanic emissions or a warming ocean releasing carbon dioxide (CO<sub>2</sub> is less soluble in warm water than cold).

### WG1 FAQ 6.2: What Happens to Carbon Dioxide After It Is Emitted into the Atmosphere?

Carbon dioxide (CO<sub>2</sub>), after it is emitted into the atmosphere, is firstly rapidly distributed between atmosphere, the upper ocean and vegetation. Subsequently, the carbon continues to be moved between the different reservoirs of the global carbon cycle, such as soils, the deeper ocean and rocks. Some of these exchanges occur very slowly. Depending on the amount of CO<sub>2</sub> released, between 15% and 40% will remain in the atmosphere for up to 2000 years, after which a new balance is established between the atmosphere, the land biosphere and the ocean. Geological processes will take anywhere from tens to hundreds of thousands of years—perhaps longer—to redistribute the carbon further among the geological reservoirs. Higher atmospheric CO<sub>2</sub> concentrations, and associated climate impacts of present emissions, will, therefore, persist for a very long time into the future.

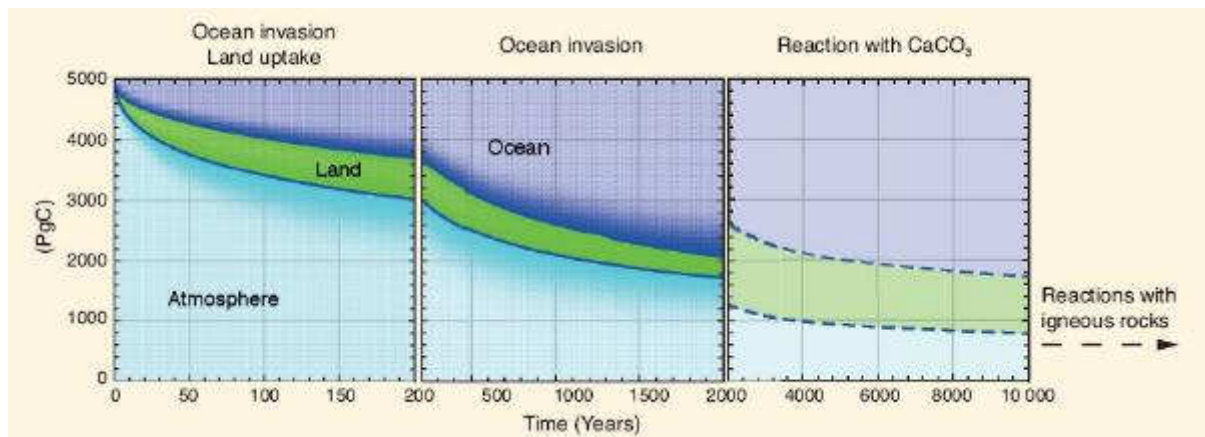
CO<sub>2</sub> is a largely non-reactive gas, which is rapidly mixed throughout the entire troposphere in less than a year. Unlike reactive chemical compounds in the atmosphere that are removed and broken down by sink processes, such as methane, carbon is instead redistributed among the different reservoirs of the global carbon cycle and ultimately recycled back to the atmosphere on a multitude of time scales. Figure 1 shows a simplified diagram of the global carbon cycle. The open arrows indicate typical timeframes for carbon atoms to be transferred through the different reservoirs.

Before the Industrial Era, the global carbon cycle was roughly balanced. This can be inferred from ice core measurements, which show a near constant atmospheric concentration of CO<sub>2</sub> over the last several thousand years prior to the Industrial Era. Anthropogenic emissions of carbon dioxide into the atmosphere, however, have disturbed that equilibrium. As global CO<sub>2</sub> concentrations rise, the exchange processes between CO<sub>2</sub> and the surface-ocean and vegetation are altered, as are subsequent exchanges within and among the carbon reservoirs on land, in the ocean and eventually, the Earth crust. In this way, the added carbon is redistributed by the global carbon cycle, until the exchanges of carbon between the different carbon reservoirs have reached a new, approximate balance.

Over the ocean, CO<sub>2</sub> molecules pass through the air-sea interface by gas exchange. In seawater, CO<sub>2</sub> interacts with water molecules to form carbonic acid, which reacts very quickly with the large reservoir of dissolved inorganic carbon—bicarbonate and carbonate ions—in the ocean. Currents and the formation of sinking dense waters transport the carbon between the surface and deeper layers of the ocean. The marine biota also redistribute carbon: marine organisms grow organic tissue and calcareous shells in surface waters, which, after their death, sink to deeper waters, where they are returned to the dissolved inorganic carbon reservoir by dissolution and microbial decomposition. A small fraction reaches the sea floor, and is incorporated into the sediments.

The extra carbon from anthropogenic emissions has the effect of increasing the atmospheric partial pressure of CO<sub>2</sub>, which in turn increases the air-to-sea exchange of CO<sub>2</sub> molecules. In the surface ocean, the carbonate chemistry quickly accommodates that extra CO<sub>2</sub>. As a result, shallow surface ocean waters reach balance with the atmosphere within 1 or 2 years. Movement of the carbon from

the surface into the middle depths and deeper waters takes longer—between decades and many centuries. On still longer time scales, acidification by the invading CO<sub>2</sub> dissolves carbonate sediments on the sea floor, which further enhances ocean uptake. However, current understanding suggests that, unless substantial ocean circulation changes occur, plankton growth remains roughly unchanged because it is limited mostly by environmental factors, such as nutrients and light, and not by the availability of inorganic carbon it does not contribute significantly to the ocean uptake of anthropogenic CO<sub>2</sub>.



Decay of a CO<sub>2</sub> excess amount of 5000 PgC emitted at time zero into the atmosphere, and its subsequent redistribution into land and ocean as a function of time, computed by coupled carbon-cycle climate models. The sizes of the colour bands indicate the carbon uptake by the respective reservoir. The first two panels show the multi-model mean from a model intercomparison project. The last panel shows the longer term redistribution including ocean dissolution of carbonaceous sediments as computed with an Earth System Model of Intermediate Complexity.

On land, vegetation absorbs CO<sub>2</sub> by photosynthesis and converts it into organic matter. A fraction of this carbon is immediately returned to the atmosphere as CO<sub>2</sub> by plant respiration. Plants use the remainder for growth. Dead plant material is incorporated into soils, eventually to be decomposed by microorganisms and then respired back into the atmosphere as CO<sub>2</sub>. In addition, carbon in vegetation and soils is also converted back into CO<sub>2</sub> by fires, insects, herbivores, as well as by harvest of plants and subsequent consumption by livestock or humans. Some organic carbon is furthermore carried into the ocean by streams and rivers.

An increase in atmospheric CO<sub>2</sub> stimulates photosynthesis, and thus carbon uptake. In addition, elevated CO<sub>2</sub> concentrations help plants in dry areas to use ground water more efficiently. This in turn increases the biomass in vegetation and soils and so fosters a carbon sink on land. The magnitude of this sink, however, also depends critically on other factors, such as water and nutrient availability. Coupled carbon-cycle climate models indicate that less carbon is taken up by the ocean and land as the climate warms constituting a positive climate feedback. Many different factors contribute to this effect: warmer seawater, for instance, has a lower CO<sub>2</sub> solubility, so altered chemical carbon reactions result in less oceanic uptake of excess atmospheric CO<sub>2</sub>. On land, higher temperatures foster longer seasonal growth periods in temperate and higher latitudes, but also faster respiration of soil carbon. The time it takes to reach a new carbon distribution balance depends on the transfer times of carbon through the different reservoirs, and takes place over a multitude of time scales. Carbon is first exchanged among the 'fast' carbon reservoirs, such as the atmosphere, surface ocean, land vegetation and soils, over time scales up to a few thousand years. Over longer time scales, very slow secondary



geological processes—dissolution of carbonate sediments and sediment burial into the Earth’s crust—become important.

FAQ 6.2, Figure 2 illustrates the decay of a large excess amount of CO<sub>2</sub> (5000 PgC, or about 10 times the cumulative CO<sub>2</sub> emitted so far since the beginning of the industrial Era) emitted into the atmosphere, and how it is redistributed among land and the ocean over time. During the first 200 years, the ocean and land take up similar amounts of carbon. On longer time scales, the ocean uptake dominates mainly because of its larger reservoir size (~38,000 PgC) as compared to land (~4000 PgC) and atmosphere (589 PgC prior to the Industrial Era). Because of ocean chemistry the size of the initial input is important: higher emissions imply that a larger fraction of CO<sub>2</sub> will remain in the atmosphere. After 2000 years, the atmosphere will still contain between 15% and 40% of those initial CO<sub>2</sub> emissions. A further reduction by carbonate sediment dissolution, and reactions with igneous rocks, such as silicate weathering and sediment burial, will take anything from tens to hundreds of thousands of years, or even longer.

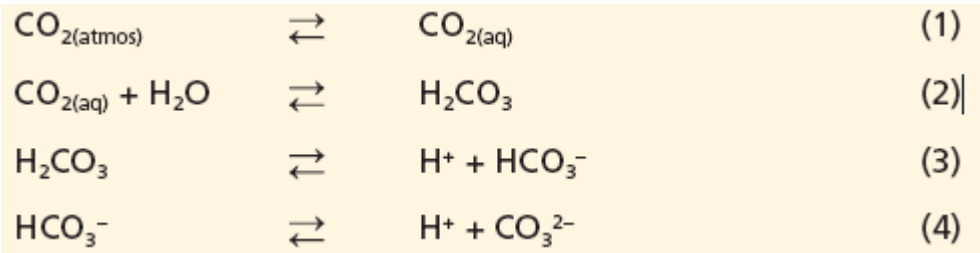
### FAQ3.3 How Does Anthropogenic Ocean Acidification Relate to Climate Change?

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 (the oceans are becoming less alkaline) but the oceans are 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.

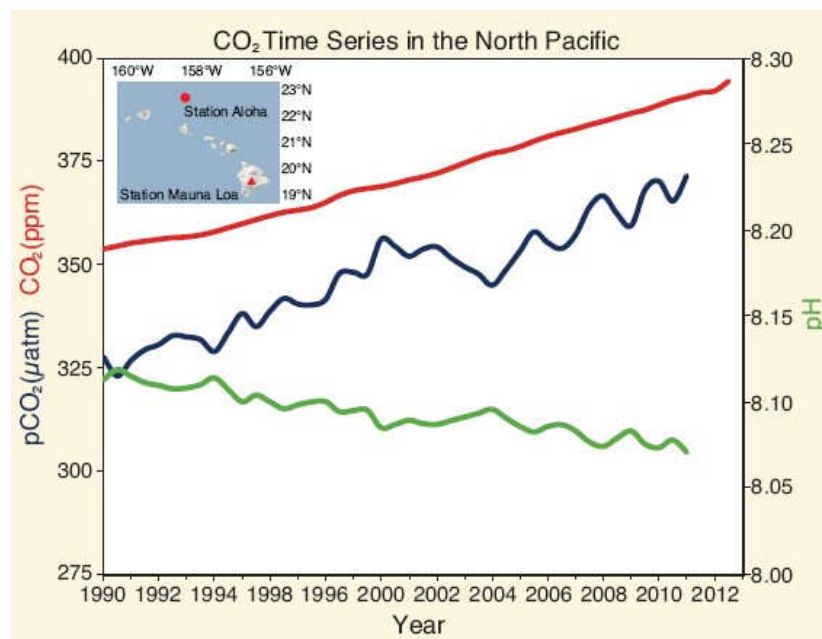
Since about 1750, the release of CO<sub>2</sub> from industrial and agricultural activities has resulted in global average atmospheric CO<sub>2</sub> concentrations that have increased from 278 to 390.5ppm in 2011. The atmospheric concentration of CO<sub>2</sub> is now higher than experienced on the 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</sub>(aq)), carbonic acid (H<sub>2</sub>CO<sub>3</sub>) and bicarbonate (HCO<sub>3</sub><sup>-</sup>)



Hydrogen ions ( $\text{H}^+$ ) 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 ( $\text{CO}_3^{2-}$ ) to produce additional  $\text{HCO}_3^-$ . Thus, the addition of anthropogenic  $\text{CO}_2$  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  $\text{CO}_2$ . Results from laboratory, field, and modelling studies, as well as evidence from the geological record, clearly indicate that marine ecosystems are highly susceptible to the increases in oceanic  $\text{CO}_2$  and the corresponding decreases in pH and carbonate ion.

Climate change and anthropogenic ocean acidification do not act independently. Although the  $\text{CO}_2$  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  $\text{CO}_2$  the oceans can absorb from the atmosphere. For example, under doubled preindustrial  $\text{CO}_2$  concentrations and a  $2^\circ\text{C}$  temperature increase, seawater absorbs about 10% less  $\text{CO}_2$  (10% less total carbon, CT) than it would with no temperature increase, but the pH remains almost unchanged. Thus, a warmer ocean has less capacity to remove  $\text{CO}_2$  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. It is virtually certain<sup>1</sup> that the upper ocean (above 700m) has warmed from 1971 to 2010, with the strongest warming of  $0.11^\circ\text{C}$  per decade found near in the upper 75 m.



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. 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.

**The full booklet, together with a significant amount of further information, a glossary and explanation of units can be downloaded from [www.metlink.org](http://www.metlink.org)**

**Further information about the carbon and water cycles, and wider support for GCSE and A level geography can be downloaded from [www.rgs.org/schools](http://www.rgs.org/schools)**

**Unless otherwise stated, all the figures, tables and Frequently Asked Questions referenced in this booklet may be downloaded from the [IPCC website](http://ipcc.ch) or [www.metlink.org](http://www.metlink.org)**

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014: *Climate Change 2014: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014: *Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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