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Climate Change: The Physical Picture

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1.1 Introduction

The oceans are the life-blood of the climate. The sun is its energy, the atmosphere provides a warming skin, but the ocean currents are the arteries that carry the sun's heat around the world. That heat powers the weather, the wind, the cyclones and the rain. Change those and you change the climate. In all there are five primary climate drivers: the sun's irradiance, the earth's albedo (how much of the sun's energy it reflects), aerosols in the stratosphere acting as a sunshade, the atmosphere's greenhouse gases and ocean currents. Change in any one of these can force a change in the others and any change causes a change in global temperature. Temperature change leads to climate change.

Very obviously the temperature at any place on Earth is changing all the time; day to night, winter to summer. These changes are part of local weather and are all averaged out to give the local climate, the local average temperature, rainfall and winds. Equally obviously, the temperature changes with latitude and it is the difference in temperature between the tropics and the poles that generates the weather patterns. But global climate change is entirely different. It is the Earth's response to a change in global heat content.

Earth's temperature, which is the manifestation of its heat, comes from the sun. When the sun is directly overhead there is about 1.36 kw of solar energy per square meter and this falls off geometrically toward the poles so that overall the Earth gets about 340 w/sq m. The tropics take in a greater proportion of the sun's energy than do the regions north and south of the tropics, with the result that the tropical oceans are warm (up to 30°C) and the Arctic and Southern Oceans are cool (freezing at -2°C). It is the oceans that do the most work in moving Earth's heat around. In order to examine the progress of 20th and 21st century climate change, we need to understand how those five climate drivers work.

1.2 Climate

1.2.1 The Sun

The Earth's climate drivers are not constant and the sun is no exception. Over a year the sun's irradiance changes little, but there is about a 2 Wm^{-2} variation over the 11-year sunspot cycle (Figure 1.1). This is just enough to be detectable in global temperatures, but this cycle is too fast

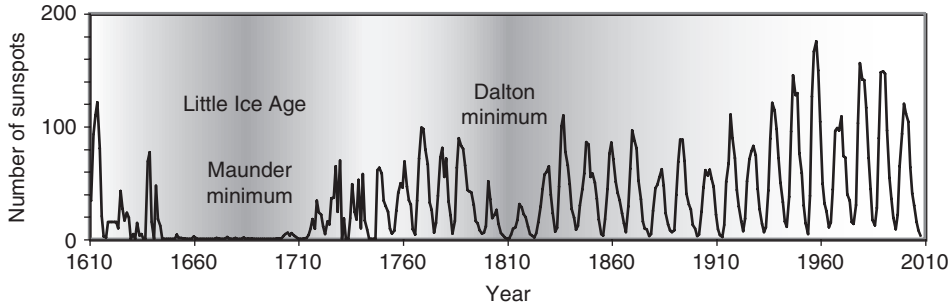


Figure 1.1 Sunspot cycles from 1610. Data from Hoyt & Schatten (1998).

to have any long term impact on climate. When there are more sunspots (the easily seen features) there are also more bright patches on the sun (faculae) which increase the sun’s irradiance. There may be a longer cycle, or it may be that the sun goes through as yet unexplained changes in the development of sunspots, but there is clear evidence that at times the number of sunspots has dwindled, to none (during the Maunder Minimum from 1645 to 1715), and not quite so much between 1790 and 1830 (the Dalton Minimum). These sunspot minima coupled with increased volcanic aerosols (PAGES 2k Consortium, 2013) led to what has become known as the Little Ice Age, when European temperatures fell by about half a degree Celsius.

After the sun’s heat reaches the Earth several things happen. Of the average 340 Wm^{-2} of incoming solar radiation, 23% is absorbed by the atmosphere on the way in. At the short wavelength end of the solar spectrum ultra-violet radiation is absorbed by oxygen at heights above 100 km (Figure 1.2). Lower down oxygen, ozone and water all absorb radiation toward the red end of the visible spectrum. (IPCC, 2013: AR5-WG1 p. 181). The sun’s radiation intensity peaks at about 500 nm wavelength, a part of the electromagnetic spectrum to which the atmosphere is largely transparent.

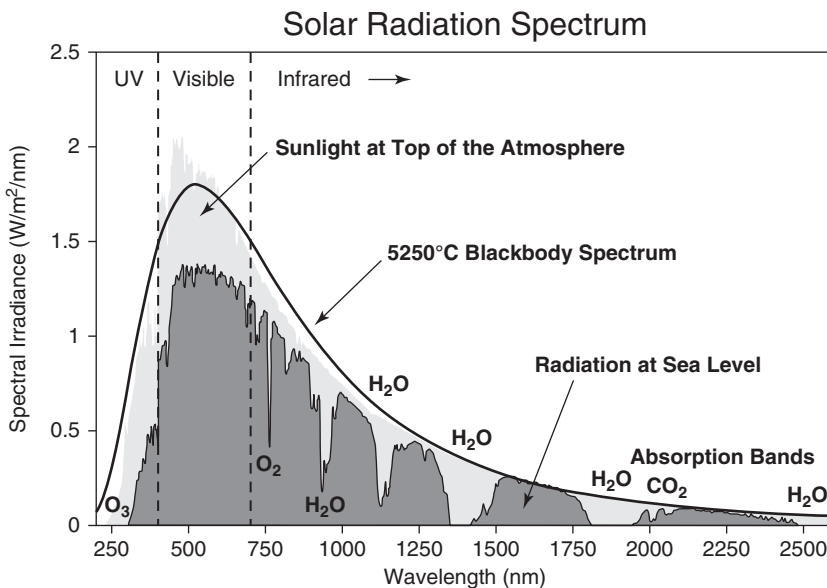


Figure 1.2 Solar radiation spectrum. From Wikipedia.

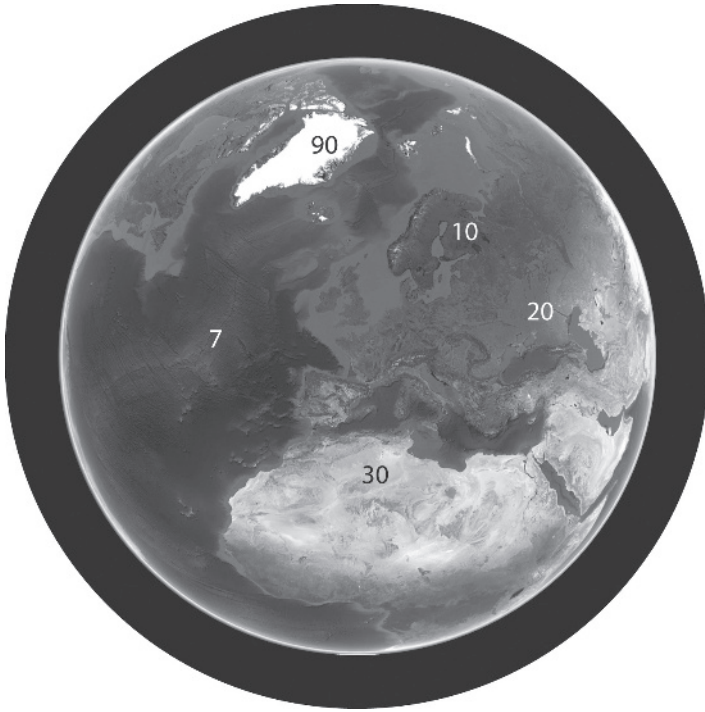


Figure 1.3 Variation in Earth's albedo (Earth image: Google Earth).

1.2.2 Albedo

Earth's albedo is about 0.3; that is, Earth reflects 30% of the incident sunlight (Figure 1.3). Three-quarters of the Earth's albedo is contributed by the atmosphere and clouds reflecting sunlight, with some minor fluctuation. There is also annual variation, most markedly as the northern land masses gain and lose highly reflective snow, with smaller changes as plants go through their annual greening cycle. Melting the Arctic sea ice has an immediate thermal effect as the local albedo changes from 0.9 to 0.07. With 24-hours of midsummer sunshine, the Arctic Ocean can be absorbing more heat per square meter than are the tropical oceans. At present the area of the Arctic Ocean changes by 10 million km^2 between winter and summer (from 15 to 5 km^2), a small area of heat absorption compared to the ever present 200 million km^2 of the tropical oceans, but still enough to be contributing to Arctic warming at twice the rate of Earth as a whole. This increase is termed the Polar Amplification Factor.

Of the 340 Wm^{-2} striking the upper atmosphere only 55% or 185 Wm^{-2} reach the surface and of these 24 Wm^{-2} are reflected back into space, leaving 161 Wm^{-2} to warm the surface. Note though that the atmosphere has already been warmed by the 23% (79 Wm^{-2}) absorbed by the incoming radiation. In summary, 240 Wm^{-2} warm the Earth (Figure 1.4).

1.2.3 Aerosols

Particles in the upper atmosphere are known as aerosols. Sulfate is one; either in the form of tiny droplets of sulfuric acid or as particles of ammonium or other sulfates, a consequence of burning sulfur-containing fuels and from volcanoes with the release of SO_2 . Sulfur dioxide is immediately further oxidized and hydrated to sulfuric acid ($2\text{SO}_2 + \text{O}_2 + 2\text{H}_2\text{O} = 2\text{H}_2\text{SO}_4$) forming droplets having high reflectivity and so acting to cool the planet.

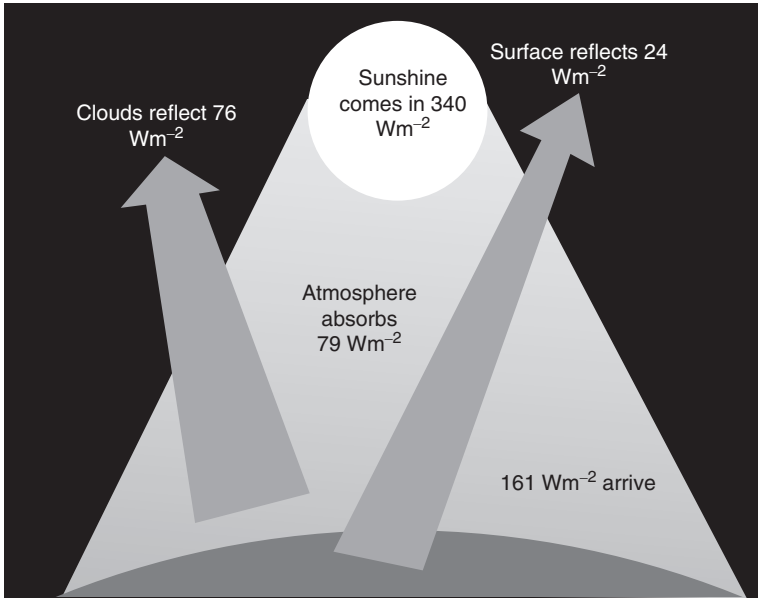


Figure 1.4 Global mean energy budget under present-day climate conditions. Numbers state magnitudes of the individual energy fluxes. Adapted from IPCC (2013: AR5 WG1 p. 181).

Volcanic aerosols may cool the earth for some years after a violent eruption (Figure 1.5). Mt Pinatubo reduced the incoming solar radiation by about 15% shortly after its eruption (Mishchenko *et al.*, 2007).

Larger particles still are volcanic dust and ash as well as soot from burning. The bigger the particle the shorter the time it stays in the air before falling or being rained out. Fine volcanic dust and sulfate certainly remain in the stratosphere for several years, as red sunsets for a year after the explosion of Krakatoa in 1883 and the experience from El Chichon and Mt Pinatubo testify.

Soot, also known as black carbon, gets into the air from almost anything that burns, especially forest fires and wood-burning cooking fires, but coal, oil, diesel, petrol all contribute. The overall impact of soot is one of the less well-known parts of the climate story. Being black, soot absorbs radiation so its effect in the atmosphere is to warm it; it does not reflect much sunlight in the way sulfate aerosol does. When it falls out of the air it can darken the Earth's surface especially if it falls on snow.

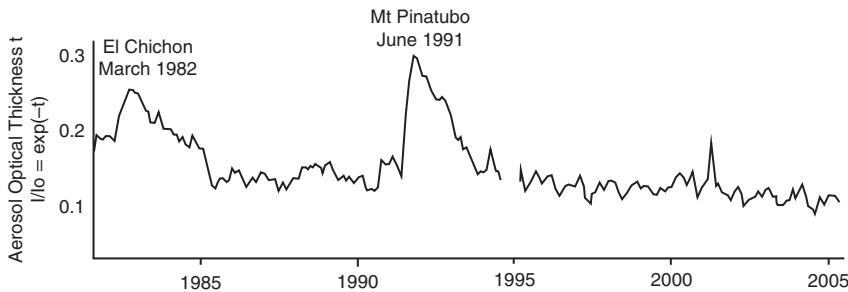


Figure 1.5 Spikes in atmospheric aerosols following major volcanic eruptions (after Mishchenko *et al.*, 2007).

1.2.4 Greenhouse Gases

The sun warms the Earth and the Earth becomes a radiator in its own right, sending heat back into space. There should be a balance between the heat coming in and the heat going out; if there were not the planet would warm or cool depending on the direction of the imbalance. Earth radiates heat into the atmosphere, and 90% of it does not emerge directly, being absorbed and re-emitted by gases collectively known as greenhouse gases. The remaining 10% does escape directly to space. Eventually, when the Earth's climate system is in equilibrium, the atmosphere and clouds radiate exactly as much heat energy as the sun provides. The sun's input is measured at $240 \pm 2 \text{ Wm}^{-2}$ and Earth's output is estimated at $239 \pm 3 \text{ Wm}^{-2}$. According to studies of ocean heat (Hansen *et al.*, 2012) there is presently global heat storage amounting to 0.6 Wm^2 . That is, the Earth is warming.

The Earth's radiation spectrum is of much longer wavelength than that of the sun. It peaks at around $10 \mu\text{m}$ and atmospheric gases have significant absorption bands across that spectrum (Figure 1.6). Water absorbs quite broadly across the whole spectrum, ozone absorbs at $10 \mu\text{m}$ and CO_2 in a wide band at around $15 \mu\text{m}$ (Table 1.1).

Greenhouse gases concentrations vary locally, mainly through changes in water vapor content, but also methane levels can be locally high, such as where the gas is escaping from coal deposits (NASA Science News 9 October 2014) or over the Arctic where methane levels have reached 50% more than the global average.

1.2.5 Ocean Currents

The ocean covers two thirds of the planet, and because water absorbs almost all of the sun's heat that strikes it, the oceans store about 90% of the Earth's surface heat. They transmit the heat around the globe via a system of currents known as the Great Ocean Conveyor Belt. Cold

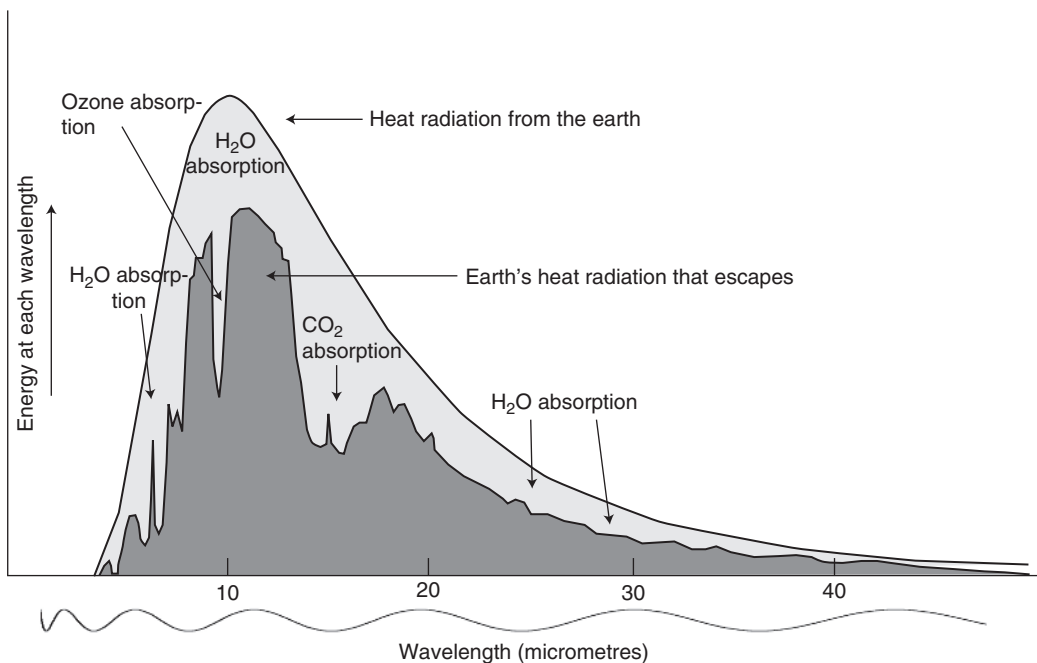


Figure 1.6 Earthshine spectrum and the absorbing greenhouse gases. (After Kiehl & Trenberth, 1997).

Table 1.1 The several greenhouse gases make different contributions to the Greenhouse Effect and have different residence times.

Gas	Concentration average (and range)	Percentage of Greenhouse Effect (approx.)	Residence time (approx.)
Water vapor	0–4%, temperature dependent	60	~10 days
CO ₂	400 ppm	25%	~100 years
CH ₄	1.8 ppm	7%	12 years
Ozone (troposphere)	~0.04 ppm (.01–0.1)	6%	Variable, ~3 weeks
N ₂ O	0.325 ppm	2	120 years

water from the poles sinks and flows toward the equator while tropical warm water flows east to west before bouncing off America and warming northwest Europe as the Gulf Stream (Figure 1.7). An important aspect of this is the surface current across the Pacific Ocean which can vary in temperature depending on the character of the winds driving it. Known as the Southern Oscillation, warm water extending across the Pacific leads to the weather pattern known as *El Niño* which brings warm dry conditions to eastern Australia and cool wet weather to North America. When the Pacific surface water is cool, *La Niña* prevails, reversing those weather patterns. These are variations of a relatively short duration, one or two years and exemplify one way in which the oceans control the climate in the short term.

In the longer term, the oceans strongly affect local climate. Coastal regions have smaller diurnal and annual temperature ranges than inland regions, because local ocean temperatures change little and act as a thermal buffer.

Evaporation moves heat from the ocean to the atmosphere, the latent heat of evaporation being released when the water vapor condenses as rain or snow (78 Wm^{-2}). Conduction between the sea surface and the air above also transfer heat as does direct radiation from the warm ocean (24 Wm^{-2}). Most of the latter is returned as back radiation from the greenhouse gases, mainly by water vapor (66 Wm^{-2}) (Gordon, 2007).

1.3 Knowledge Gaps

Applying climate science to the understanding of climate change demands that we know the factors that determine the climate. Many of these factors are known, admittedly with varying degrees of confidence and assurance, but there are uncertainties which limit our ability to fully explain the current climate's variations, and so put severe limits on the ability to predict.

The global temperature effect of clouds is one of the main areas where climate science is still struggling to quantify their contribution to Earth's thermal balance. For example tropical cumulus clouds reflect a lot of the sun's heat whereas higher and thinner cirrus clouds act as a greenhouse gas, absorbing Earth's radiant heat. Lindzen *et al.* (2001) argued that if the global temperature rises for whatever reason, the increased evaporation produced by the warming will lead to a reduction in the amount of tropical cirrus and so allow more of the Earth's heat to radiate out which will then cool the Earth, thereby limiting any temperature rise. Using the same criteria, Lin *et al.* (2001) came to the opposite conclusion.

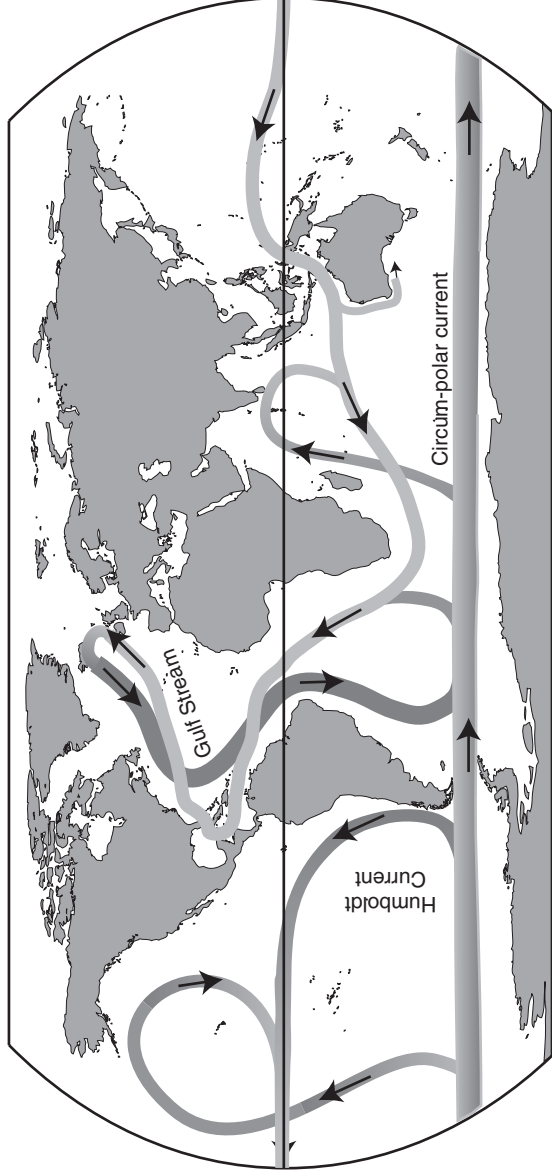


Figure 1.7 The Great Ocean Conveyor Belt. Concept sourced from *World Ocean Review* (2010), Maribus, Hamburg.

1.4 Climate Change

1.4.1 Forcing

At the start of this chapter we looked at the four drivers of Earth's climate. If any one of those drivers were to change, say for example the sun were to become 2% dimmer, then that would force the climate into a new state; specifically, the Earth would cool. A 2% change from the present would amount to a decrease in incoming solar energy of 27.4 Wm^{-2} which would force the global temperature to cool. Climate scientists would call such a change a *Radiative Forcing* of -27.4 Wm^{-2} .

Alternatively the Earth's albedo might be reduced by 1% as a result of some natural process – perhaps from volcanism in Alaska covering the snow and ice with black volcanic ash. The surface currently reflects 24 Wm^{-2} ; decreasing this figure by 1% would constitute a forcing of $+0.24 \text{ Wm}^{-2}$.

Radiative Forcing is a simple measure for quantifying and ranking the many different influences on climate change in terms of energy balance. Thus it refers to the extent to which any agent of change, be it from the sun, in the atmosphere, in the ocean or on the ground, will force a change in the previous balance that dictated the climate. To be specific, it is the rate of energy change caused by that agency per unit area of the globe as measured at the top of the atmosphere.

The IPCC in its 2013 Assessment Report 5 introduced a new term: *Effective Radiative Forcing*, distinguishing this from the term Radiative Forcing. Radiative Forcing as used in earlier IPCC Assessment Reports did not include the effect of the lower atmosphere's rapid adjustments to temperature change, such as cloud response. Effective Radiative Forcing does include such rapid adjustments, but the difference is quite slight. Forcings happen naturally and continuously, from day to night, as the clouds come and go, or as plant cover changes with the seasons thereby changing the amount of the sun's heat that is reflected, or by the natural cycle of CO_2 variation between seasons.

However in the context of anthropogenic climate change, Forcing is specifically connected to changes in any climate driver resulting from human activity. The Intergovernmental Panel on Climate Change evaluates Forcings of the well-mixed greenhouse gases CO_2 , CH_4 , N_2O and halocarbons in terms of their impact since 1750 (IPCC, 2013: AR5-WKG1 p. 676). It is necessary to pick a starting time, because forcing is defined in terms of *change* from a previous situation, so some prior condition must be specified. Taking 1750 as the initial time, when CO_2 stood at 278 ppm, the change in forcing (symbolized ΔF) from then to the 2015 CO_2 level of 400 ppm is:

$$\Delta F = 5.35 \ln(400 / 278) = 1.95 \text{ Wm}^{-2}$$

(Equation from Myhre *et al.*, 1998.)

Because of the variety of atmospheric aerosols and the chemical reactions between them, their combined radiative forcing becomes somewhat complex. The dominant agents are sulfate, estimated to have a forcing of -0.40 Wm^{-2} , and black carbon, estimated to have had exactly the opposite effect, viz, $+0.4 \text{ Wm}^{-2}$. The forcing from other aerosols combined is estimated at -0.35 Wm^{-2} (IPCC, 2013: AR5-WG1 p. 683).

Changes in Earth's albedo is another of the areas where it is difficult to reach robust conclusions. Estimates in radiative forcing from albedo changes resulting from land use changes since 1780 are of the order of -0.1 Wm^{-2} (IPCC, 2013: AR5-WG1 p. 688). In summary, for the well mixed greenhouse gases (1780 to 2011 – see IPCC, 2013: AR5-WG1 p. 679 for details), radiative forcings are: Methane $+0.48 \text{ Wm}^{-2}$; Halocarbons $+0.36 \text{ Wm}^{-2}$; N_2O $+0.17 \text{ Wm}^{-2}$. And for other agents: Ozone $+0.35 \text{ Wm}^{-2}$; Aerosols -0.35 Wm^{-2} ; Albedo -0.1 Wm^{-2} .

In its estimates of anthropogenic climate forcing, the IPCC assumes ocean and sea-ice conditions are unchanged. Clearly the extent of summer Arctic sea-ice has changed over the past 30 years and this will have caused some reduction in Earth's albedo and so become a positive radiative forcing. Hudson (2011) estimated the extent of this forcing since 1979 at about $+0.1 \text{ Wm}^{-2}$. According to the IPCC summary, total anthropogenic forcing 1750–2011 lies in the range 1.1 to 3.3 Wm^{-2} with a most probable value of 2.3 Wm^{-2} (IPCC, 2013: AR5-WG1 p. 696).

1.4.2 Water Vapor

The amount of water vapor added directly to the atmosphere by human activity is negligible compared to the amount that is present naturally. Water vapor is therefore not included in the concept of Forcing leading to climate change but is rather seen as a feedback as a result of the other forcings (IPCC, 2013: AR5-WG1 p. 665).

The amount of water vapor in the air is determined by air temperature. If the air temperature rises, so does the water vapor content, for this reason it is a feedback. Importantly, water vapor can precipitate as rain or snow, whereas the other greenhouse gases remain gaseous over all Earth's temperature range. The IPCC emphasizes the difference between water vapor and the other greenhouse gases in these words:

Currently, water vapor has the largest greenhouse effect in the Earth's atmosphere. However, other greenhouse gases, primarily CO_2 , are necessary to sustain the presence of water vapor in the atmosphere. Indeed, if these other gases were removed from the atmosphere, its temperature would drop sufficiently to induce a decrease of water vapor, leading to a runaway drop of the greenhouse effect that would plunge the Earth into a frozen state... Therefore, although CO_2 is the main anthropogenic control knob on climate, water vapor is a strong and fast feedback that amplifies any initial forcing by a typical factor between two and three. Water vapor is not a significant initial forcing, but is nevertheless a fundamental agent of climate change.

(IPCC, 2013: AR5-WG1 p. 667)

1.4.3 Clouds

As explained in the section where knowledge gaps were discussed, clouds can both cool and warm the Earth, depending on the proportion of the sun's heat they reflect and of the Earth's radiation they absorb. A further complication is that aerosols act as nuclei on which water vapor can condense. Thus increasing anthropogenic aerosols can lead to increased cloud. Overall, the IPCC considers that the effective radiative forcing due to anthropogenic aerosols interaction with clouds is $\sim -0.45 \text{ Wm}^{-2}$ (IPCC, 2013: AR5-WG1 p. 667).

1.5 Evidence for Change Since 1880

The evidence for global warming and for the consequential change in Earth's climate is incontrovertible. That the science is robust has not stopped a very few climate scientists and a slightly greater number of non-scientists from claiming that all the evidence is false and that nothing unusual is happening to the climate. Such claims have been rebutted over and over again, and though the denials keep reappearing, this section will concentrate on the science only.

1.5.1 Global Surface Temperature

The primary evidence for change is the inexorable rise in global surface temperature since 1880. There are of the order of 30,000 meteorological stations world-wide with reliable records,

and when these are brought to a common basis they show that temperatures have risen, with some irregularities, by 1°C in the past 100 years (Figure 1.8).

1.5.2 Extreme Events

A single degree rise is essentially imperceptible to us; it is the consequence this has for extreme temperatures that has impact. How “extreme” is defined in this context may be open to argument, but the IPCC defines extreme as an event lying outside the 10th or 90th centile of that event’s frequency distribution. An example is the change in summer temperatures in the central Australian town of Alice Springs. From 1910 to 1930, only 10% of summer maxima exceeded 39.2°C, one could say that then, temperatures above 39.2°C were extreme. From 1990 to 2010, 25% of summer maxima exceed 39.2°C, showing a distinct increase in the number of extreme hot days.

Hansen *et al.* (2012) have analyzed extreme temperature anomalies globally, and show that relative to the base period 1950–1980, which they argue is the best available to represent the Holocene climate to which plant and animal life is adapted, extreme temperatures of that base period are now far more frequent (Figure 1.9).

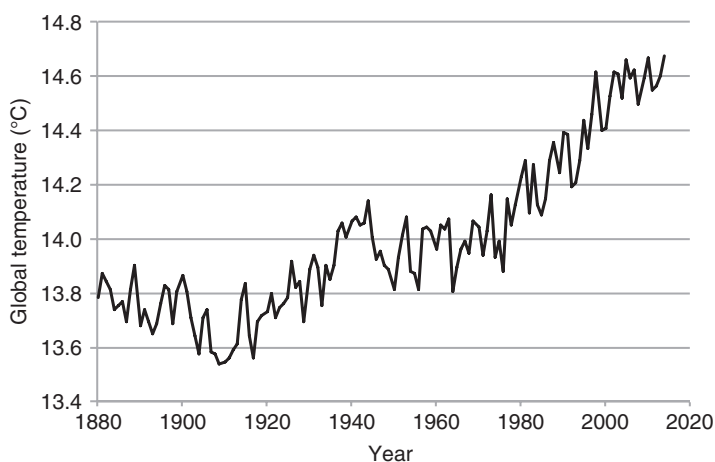


Figure 1.8 Global land-ocean temperature annual average (Source: NASA at http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/GLBTSST/).

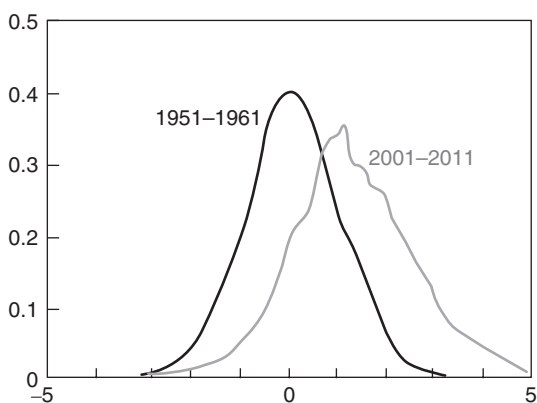


Figure 1.9 Frequency of occurrence (y-axis) of local temperature anomalies divided by local standard deviation (x-axis) obtained by binning all local results for 11-year periods into 0.05 frequency intervals. Area under each curve is unity. Standard deviations are for the indicated base periods (after Hansen *et al.*, 2012, *qv* for detail).

Although there is considerable variation across the globe, there is good evidence that there has been an increase in the number of heavy precipitation events in North America and Europe, and for South America there is evidence that heavy rain events are increasing in frequency and intensity (IPCC, 2013: AR5-WG1 p. 213; Donat *et al.*, 2013).

Confidence in attributing other extreme climate events to global warming is somewhat less assured. Super storm Sandy which hit New York in 2012, Atlantic tropical cyclones Katrina and Wilma in 2005, the drought across Australia from 1995 to 2009, and in America from 2000 to 2014 have all been considered to have been exacerbated by global warming, but statistical trends are not obvious (IPCC, 2013: AR5-WG1 p. 218).

1.5.3 Melting Ice

Ice on Earth is found in four environments: as polar sea ice; as ice caps over the polar land masses of Antarctica, Greenland and northern Canada; in mountain glaciers and as permafrost across Siberia. But over the past 40 years, the amount of ice in all of these places except the Southern Ocean has been declining. Loss of Arctic Summer sea-ice has been the most dramatic and most frequently cited. Since the beginning of satellite measurements in 1980 the area of September ice cover has steadily declined from almost 8 million km² in 1980 to about half that area in 2014 (Figure 1.10). Over the same period Antarctic summer sea-ice has been increasing at a rate of about 1.5% per decade (IPCC, 2013: AR5-WG1 p. 333).

Arctic sea-ice has also thinned over this period from an average thickness of 3.6 m in 1980 to 2.4 m 20 years later. In the Antarctic the data are lacking, mainly because submarines rarely go there, and it is measurements by US navy submarines that have provided most of the north polar ice thickness estimates.

Melting of polar sea-ice adds no water to the ocean, but melting the continental ice caps does. The IPCC reports the extent of ice-cap melting in terms of how much the added meltwater raises sea-level. From 1992 to 2012, melting of the Greenland ice sheet raised sea-level by 8 mm. Over the same period the Antarctic ice-sheet contributed a further 6 mm to sea level rise (IPCC, 2013: AR5-WG1 p. 351). Shepherd *et al.* (2012) estimate that the Greenland and Antarctic ice sheets combined are losing mass at the rate of almost 350 Gt a year, and doing so at an increasing rate.

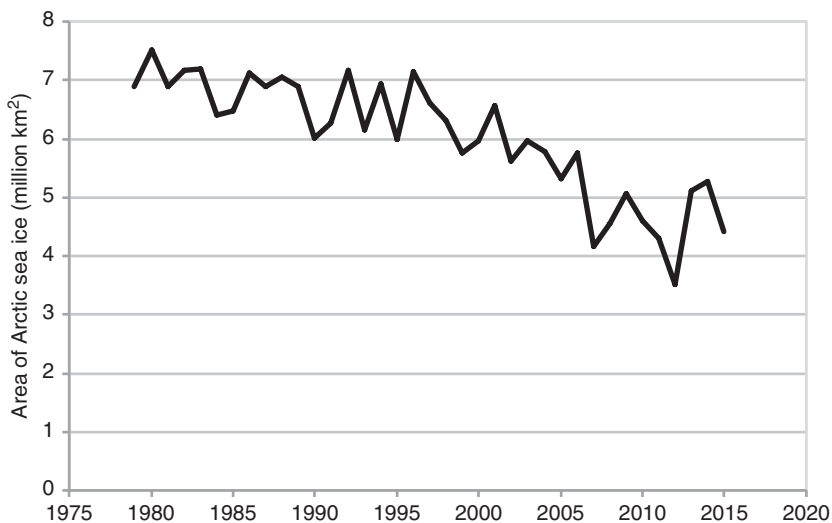


Figure 1.10 September Arctic sea ice extent (data: National Snow & Ice Data Center).

Alpine, or valley glaciers are also losing ice. There are more than 150,000 alpine glaciers on Earth, and almost all are shrinking, and as they melt they are contributing to sea level rise. According to Gardner *et al.* (2013), from 2003 to 2009 the biggest glacier loss was from Alaska with an average of 50 Gt a year, followed by Greenland (38) and north Canada (33). Over that period, 259 Gt of ice melt a year from all alpine glaciers has led to sea level rise of 0.7 mm a year. The IPCC concludes that were all alpine glaciers to vanish, sea level would rise by almost half a meter (IPCC, 2013: AR5-WG1 p. 335).

North of the Arctic Circle, across Siberia, Alaska and northern Canada, ground that is frozen solid to depths up to 1 km throughout the year is known as permafrost. Measurements made at 10 places around the Arctic, two in Russia, two in Canada, five in Alaska and one in Norway, all show an overall gradual rise in annual average temperature of the permafrost. Really cold permafrost, such as that measured at Alert in Canada is warming at over 2°C per decade (Romanovsky *et al.*, 2010). Permafrost whose temperature is just below zero warms more slowly because the sun's energy is used up in melting, rather than raising the temperature. The temperature of permafrost cannot rise above zero until all the ice has melted.

The rate of warming of the permafrost is in agreement with climate scientists' expectation for the way the temperature should rise with increasing amounts of greenhouse gases. Based on evidence from the geologic past, the Arctic regions are predicted to warm faster than the global average, and these observations seem to agree with that prediction. An indirect indication of Arctic warming is evident in an analysis of the flow of six major rivers draining the Eurasian Arctic land mass into the Arctic Ocean. Since 1960 the total flow from these rivers has been increasing at a rate of about 2 cubic kilometers of water each year.

1.6 Changes to the Ocean

As by far the dominant part of Earth's surface, the oceans have been most powerfully affected by the rising greenhouse gas content of the atmosphere. Ocean changes include increasing heat content and rising temperature, increased amount of dissolved CO₂, falling pH, salinity change and sea level change.

1.6.1 Ocean Heat Content

With its immense area and low albedo, it is the ocean that absorbs and stores most of the energy from the sun, accounting since 1955 for 93% of Earth's warming (Levitus *et al.*, 2012). The sea surface temperature has risen by ~0.7°C since 1900 (IPCC, 2013: AR5-WG1 p. 192), and since 1971 upper ocean temperatures (above 75 m) have risen at the rate of 0.11°C per decade (Levitus *et al.*, 2012; IPCC, 2013: AR5-WG1 p. 262).

The rising ocean heat content is critical in the context of climate change and global warming. Since 1950 the top 2,000 m of the oceans have taken up heat at the rate of 4×10^{21} Jyr⁻¹ (Figure 1.11). Numbers like this may be difficult to see in true perspective. John Cook at the University of Brisbane in the website *Skeptical Science* explains this heat increase as equivalent to four Hiroshima-sized atom bombs exploding every second. Levitus *et al.* (2012) express the concept in another way; they point out that if all the excess heat in the ocean's upper 2,000 m were to be transferred rapidly to the atmosphere the temperature would rise by 36°C.

The way that the heat in the ocean is transferred to the atmosphere depends on the behaviour of the ocean currents (see for example Rahmstorf, 2002). Excess tropical heat is taken to mid latitudes by the meridional (N/S) overturning circulations (MOC). The Atlantic MOC moves warm water northward at depths down to 1,200 m with denser cold water returning

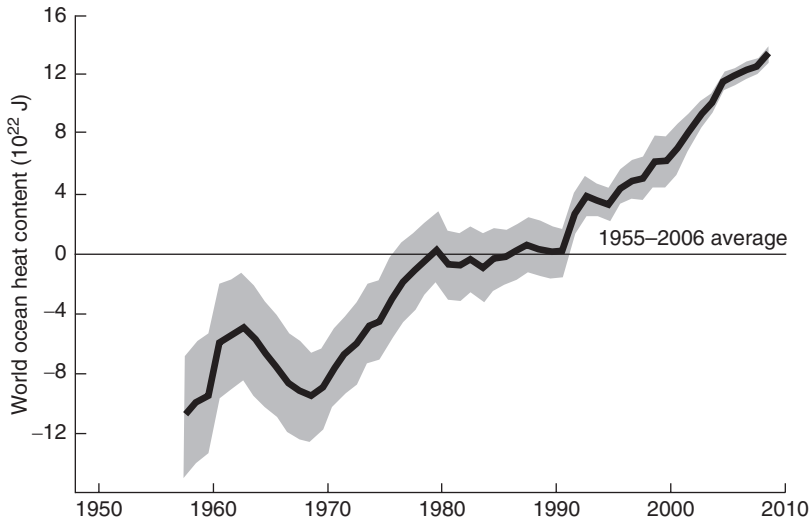


Figure 1.11 5-year averaged time series of ocean heat content 0–2,000 m. Shaded band is ± 2 SD. (After Levitus *et al.*, 2012).

southward below the warm water to 5,000 m. The north Atlantic part of this current is known as the Gulf Stream. In the Pacific there are a number of complex currents, with an equatorial east–west, or zonal current the most influential. This arises from the east–west trade winds and drives warm surface water across the Pacific into the Indian Ocean. Changes in air pressure between South America and Indonesia drive the climate variation known as the Southern Oscillation (Walker, 1923; Bjerknes, 1969; Julian & Chervin, 1978). An outline of the oceans’ global currents is shown in Figure 1.7 and see also Kuhlbrodt *et al.* (2007).

Over the past 50 years there have been changes detected in the ocean currents, most clearly in the Pacific, but data are insufficient to draw firm conclusions about any impact rising global temperatures might have had. (IPCC, 2013: AR5-WG1 p. 285 and preceding).

1.6.2 Ocean Chemistry: CO₂, pH and Salinity

The ocean and the atmosphere are in constant exchange. Water evaporates from ocean to air, and returns as rain or snow. Carbon dioxide is absorbed by sea water, taken up by organisms, and released to the atmosphere. Currently about 30% of anthropogenic CO₂ is taken up by the oceans (IPCC, 2013: AR5-WG1 p. 292). An immediate consequence of this is to acidify the ocean according to the equation $\text{CO}_2 + \text{H}_2\text{O} = \text{HCO}_3^- + \text{H}^+$. Several studies have shown an increase in ocean carbon dioxide and pH over the past 50 years (Dore *et al.*, 2009; Bates *et al.*, 2012, 2014; IPCC, 2013: AR5-WG1 p. 293) (Figure 1.12). The total decrease in pH since the start of the industrial era is estimated at 0.1 pH units (IPCC, 2013: AR5-WG1 p. 294), amounting to an increase in the hydrogen ion concentration of seawater of about 25%.

The oceans’ salinity is somewhat stratified. In the tropics where evaporation is high, surface water is more salty. Where rainfall is high the surface waters are less salty. Salinity is measured by electrical conductivity and referenced to a standard KCl solution. The so-called Practical Salinity Scale (PSS78) accepted by oceanographers in 1978 and used to measure seawater salinity, yields, by definition, numbers close to the weight of dissolved salts per kilogram. Average seawater contains 35 g/kg dissolved salts and the PSS78 value is about the same.

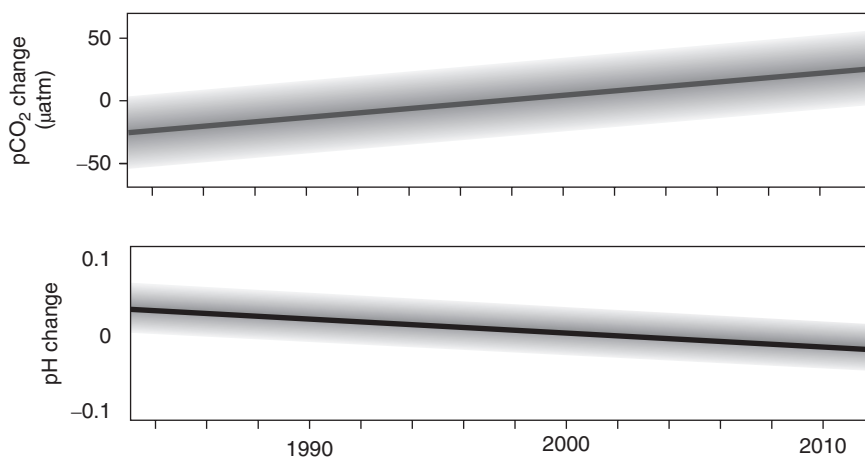


Figure 1.12 Change in ocean partial pressure of CO₂ and pH in the sub-tropical North Atlantic Ocean near Bermuda (1985–2012). Black line indicates trend, grey band covers the range of observations (simplified after Bates *et al.*, 2012).

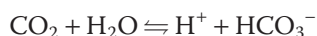
Since 1950 increased evaporation in the sub-tropical oceans has caused an increase in salinity and in doing so put more moisture into the atmosphere. This has then fallen as fresh water in the oceans far from the tropics making those areas less saline. The Southern Ocean and the northern Pacific Ocean are less saline than the waters along 20° North and South latitudes by up to 4 PSS78 (Antonov *et al.*, 2010; Helm *et al.*, 2010). The IPCC 5th AR concludes that it is virtually certain that salinity contrast between high and low salinity regions has increased over the last 60 years. The change in PSS78 across the world's oceans since 1950 amounts to an increase of about 0.4 PSS78 in the north and south Atlantic and a decrease of the same amount over the western Pacific. These changes are attributed to changes in evaporation and precipitation as the upper ocean has warmed (IPCC, 2013: AR5-WG1 p. 265).

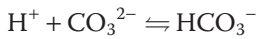
Levels of ocean oxygen are highest at the surface, declining with depth as consumption rises and surface exchange reduces, reaching a minimum typically at a few hundred meters depth. Below that consumption falls allowing oxygen levels to increase somewhat. As the ocean temperature rises, dissolved oxygen levels fall simply because warmer water contains less dissolved gas. According to a summary by Keeling *et al.* (2010), over the past 50 years, although observations are patchy, declines in ocean oxygenation are of the order of 5% (see also IPCC, 2013: AR5-WG1 p. 294).

1.6.3 Aragonite and Calcite

Calcium carbonate has two polymorphs: calcite and aragonite. Limestone, marble and the shells of many marine creatures are made of the more stable calcite. Some marine creatures, mainly corals and plankton, construct their shells from the less stable aragonite. Both these forms of CaCO₃ are soluble in seawater to an extent depending on the ambient chemical conditions.

Seawater in equilibrium with the atmosphere contains undissolved CO₂, bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions in solution. The negative ions are balanced largely by Ca²⁺. The hydrogen ions released when more carbon dioxide dissolves in seawater then react with carbonate ions to produce more bicarbonate:





That is, adding carbon dioxide to sea water decreases the dissolved carbonate ion content. Carbon dioxide dissolved in sea water reacts with calcium carbonate shells according to the equation:



Which direction this reaction goes depends on the carbonate ion concentration at the particular temperature and pressure. For both calcite and aragonite, solubility increases with depth and temperature, and there is a depth, called the aragonite saturation horizon, below which aragonite dissolves. But as the carbonate ion concentration falls, so the solubility of the carbonate minerals rises and the depth of the aragonite saturation horizon rises with it. Thus deep water today is like shallow water will be in 30 years if CO_2 levels continue to rise (see Feely *et al.*, 2004, 2009; IPCC, 2013: AR5-WG1 p. 293).

Pteropods are important group of organisms in Antarctic waters with an aragonite shell. Below the aragonite saturation horizon pteropods cannot make their shells. At present it is between 1,000 and 2,000 m depth in the Sub-Antarctic (47°S) Southern Ocean. By 2030, when CO_2 reaches 450 ppm, the line will be at the surface for waters south of the polar front, and soon after for Sub-Antarctic waters. Figure 1.13 compares two shells, one sampled at 1,000 m, the other at 2,000 m (Roberts *et al.*, 2011). This organism is on its way out, and with it will go all those larger creatures that depend on it for food.

These are just a few specific examples of the research that warns us of the impact increasing atmospheric CO_2 is having on the world's oceans. In their review of ocean acidification Doney *et al.* (2009) wrote: "*The potential for marine organisms to adapt to increasing CO_2 and the broader implications for ocean ecosystems are not well known; an emerging body of evidence suggests that the impact of rising CO_2 on marine biota will be more varied than previously*

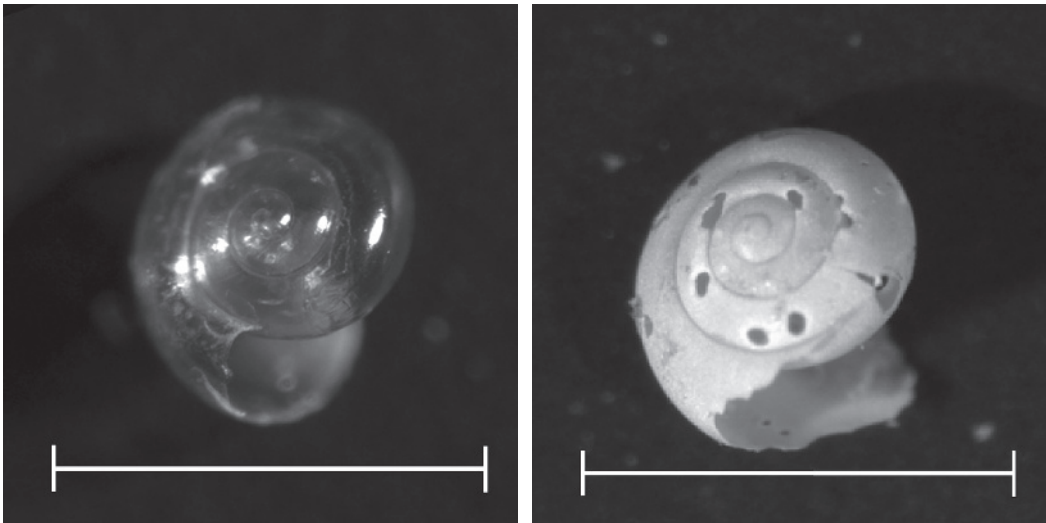


Figure 1.13 Pteropod shells taken at 1,000 m depth (left) and 2,000 m (right) from the Southern Ocean. The dissolution of the aragonite shell taken from deeper water is very obvious. Scale bar is 1 mm. Photos Donna Roberts. Reprinted from Eggleton (2011) *A Short Introduction to Climate Change*, CUP, with permission.

thought, with both ecological winners and losers". However they concluded that, "Acidification will directly impact a wide range of marine organisms that build shells from calcium carbonate, from planktonic coccolithophores and pteropods and other molluscs, to echinoderms, corals, and coralline algae" and further, that "Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods" (see also *Oceanography* v. 22 # 4).

1.6.4 Sea Level

Warming the ocean makes it expand, hence global warming inevitably leads to sea level rise (IPCC, 2013: AR5-WG1 p. 291). Since 1900 sea level has risen by at least 15 cm and it is now rising at about 3 mm a year (Figure 1.14) (Church & White, 2011). At present, 30% of the rise is attributed to an expanding ocean, the rest comes mainly from the melting ice sheets of Antarctica, Greenland, and Canada as well as from melting mountain glaciers, with about 10% the result of ground water release (IPCC, 2013: AR5-WG1).

1.7 Climates of the Past

Throughout geologic time Earth's climate has changed (Figure 1.15). The evidence points to two things: the changes were driven by carbon dioxide and the changes impacted marine life. The first climate change for which there is clear evidence happened around 800 million years ago. While the cause is not known with any certainty, one hypothesis is that the gradual subtraction of CO₂ from the atmosphere, either from rock weathering or by burgeoning marine organisms, sent the climate into what has been termed Snowball Earth. Over a period of possibly 200 million years the Earth was frozen from the poles almost to the equator. Volcanic carbon dioxide emissions probably reversed the cooling.

Another significant global cooling started about 370 million years ago, caused this time by the rise of land plants and the removal of CO₂ into what eventually become the coal deposits we mine today. By the end of the Carboniferous and into the Permian period glaciation was widespread and associated with this cooling came one of Earth's major extinctions. At the time now known as the Permian–Triassic boundary 250 million years ago, about 95% of marine species became extinct as well as 70% of terrestrial vertebrates. At that time surface equatorial seawater temperatures may have reached 40°C, a lethal temperature for marine creatures (Sun

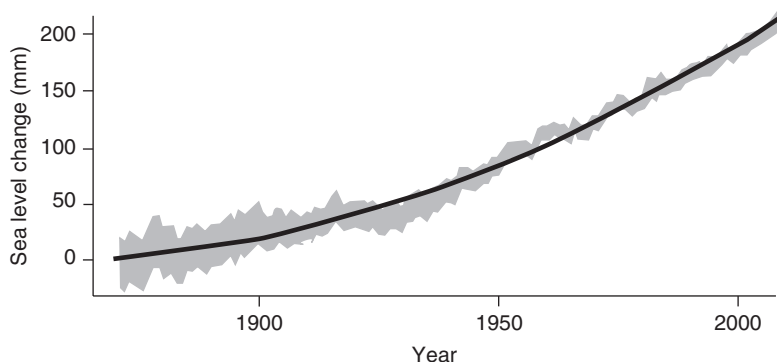


Figure 1.14 Sea level rise since 1860. After Church & White (2011).

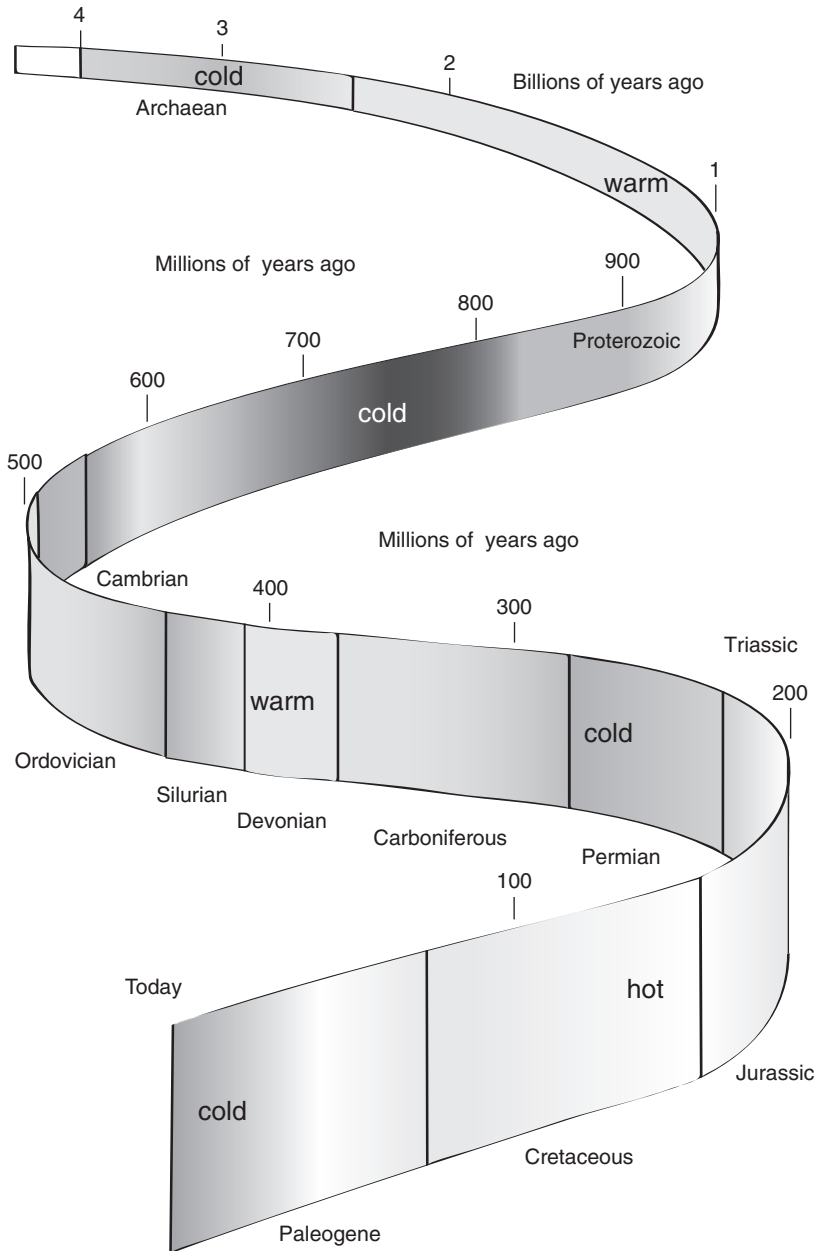


Figure 1.15 Geological time scale showing times of cooling (darker) and of warming (lighter). Snowball Earth is marked by the “cold” segment between 800 and 650 million years ago. Reprinted from Eggleton (2011) *A Short Introduction to Climate Change*, CUP, with permission.

et al., 2012). Exactly what caused this extinction is debated, runaway greenhouse following the release of CO_2 by massive vulcanism is most commonly argued (Payne & Clapham, 2012; Sun *et al.*, 2012). Impact by a comet or asteroid has also been postulated.

Over the Phanerozoic (from the beginning of the Cambrian Period) up until the end of the Permian, the changes in climate have proceeded at an extraordinarily slow pace, as slow as one

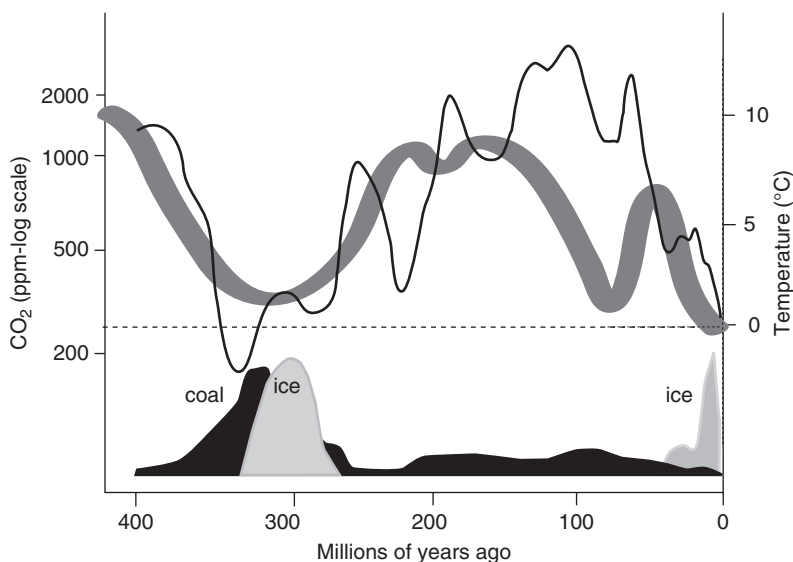


Figure 1.16 Diagram relating climate evidence and deduced CO₂ levels in the atmosphere for the past 400 million years. Variation from today's temperature is the upper black line, taken from Zachos *et al.* (2001) for the period 0–65 million years ago, and from Royer *et al.* (2004) from 65 million years ago to 400 million years. CO₂ through the ages is the broad grey band after Franks *et al.* (2014). Temperature and CO₂ have changed roughly in step, with ice ages and coal deposits providing some of the evidence.

degree temperature change in 10 million years. Over the past 400 million years there has been a general correlation between atmospheric carbon dioxide and global temperature (Figure 1.16). A sudden increase in global temperature 253 million years ago may have occurred as rapidly as 1°C in 25,000 years (Sun *et al.*, 2012). A faster climate event occurred 56 million years ago at the Paleocene–Eocene boundary, known as the Paleocene–Eocene Thermal Maximum (PETM). This event produced a global temperature rise and fall of 5°C over a time span of only 170,000 years with a concomitant spike in atmospheric CO₂ or methane or both. As at the end of the Permian, this climate change impacted on marine life with mass extinction of benthic foraminifera (IPCC, 2013: AR5-WG1 p. 399).

Since then, the global temperature slowly fell by some 10°C, at an average rate of a degree every 5 million years, in sharp contrast to the PETM changes of perhaps 1°C in a ten thousand years.

Much more recently climate change triggered by orbital factors, the Milankovitch Cycles (IPCC, 2013: AR5-WG1 p. 388), and enhanced by CO₂ and polar ice changes, led to alternating glacial and interglacial phases, beginning about one million years ago. Throughout the ice-ages global temperatures oscillated over a range of 6°C, each sequence from ice age to interglacial lasting about 120,000 years (IPCC, 2013: AR5-WG1 p. 400). Rates of temperature change at this time reached 1° in 2,000 years during the warming stages (IPCC, 2013: AR5-WG1 p. 400). About 12,000 years ago during the final stage of deglaciation, the northern Atlantic was periodically inundated by the sudden release of cold waters dammed up as continental ice sheets melted. This caused catastrophic drops in temperature in the surrounding countries from Greenland (Dansgaard *et al.*, 1989) to Spain (Rodrigues *et al.*, 2010) with rates of change estimated at 5° in 100 years (see also Eggleton, 2011 pp. 134–136).

After the end of the last glaciation, 10,000 years ago global temperatures were as much as 0.4°C warmer than the 1960–1990 instrumental average (Marcott *et al.*, 2013). There was little

Table 1.2 Summary of the physical picture of climate change.

Topic	Key point	Conclusion
Climate drivers	Sun, Earth's albedo, greenhouse gases, aerosols, ocean currents all affect the climate	Earth eventually maintains an energy balance however these may vary
Radiative forcing	Change since 1750 of 2.3 Wm^{-2}	Causing global warming
Feedback	Changing one climate driver can change others	Warming from CO_2 enhanced by rising water vapor and melting ice
Global temperature	Risen 1°C since 1900	Caused by rising CO_2
Ice	Sea and land ice all decreasing	Caused by global warming
Ocean heat	Rising at $4 \times 10^{21} \text{ Jyr}^{-1}$	Heat will be released to the atmosphere
Ocean chemistry	pH falling, pCO_2 rising, changes occurring in salinity distribution	Impacts forcefully on marine life
Sea level	Rising at 3 mm/year	Caused by expanding warmer ocean and melting ice
Geological evidence	Over the past 400 million years higher global temperatures matched higher atmospheric CO_2	History is repeating but much faster

change for the next 6,000 years, but thereafter, perhaps driven by orbital factors which predict 50,000 years of cooling ahead, global temperatures cooled by more than half a degree until only 200 or so years ago. Warming since then has not quite reached the highest post-glacial temperatures, but is predicted to surpass this level by the end of the century (Table 1.2).

The geological record allows the present warming to be put into context. A rate of 1°C in one hundred years is 20 times faster than any known change in global temperature. During and after each of the two best known major thermal events (end Permian, PETM), there was severe extinction of marine fauna. Both of these events were almost certainly triggered by rapid rise in atmospheric carbon dioxide. It is knowledge such as this that allows climate science to make relatively robust predictions about the climate of the coming centuries.

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