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An addendum to the Statement on Climate Change: Evidence from the Geological Record

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Climate change

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The Geological Society published a Statement on 'Climate Change: Evidence from the Geological Record' in November 2010. In light of further research that has been published since then, the Geological Society reconvened the expert working group that drafted the 2010 Climate Change Statement to consider whether it was still fit for purpose, and if necessary to amend or add to it.

The working group and Council have concluded that the 2010 Climate Change Statement continues to be valid, and does not need to be amended. Instead, the working group has produced an addendum setting out new research findings relevant to the questions raised in the original statement.

A non-technical summary of the key points from the addendum is set out below, aimed principally at non-specialists and Fellows of the Society with a general interest. This is followed by the full technical version of the addendum, for those who wish to read in more detail about advances in the relevant research. The full technical version includes references to the published papers on which it draws. It is intended to be read alongside the original 2010 Climate Change Statement, and follows the same Q&A format.

Summary

Since our original 2010 statement, new climate data from the geological record have arisen which strengthen the statement's original conclusion that CO₂ is a major modifier of the climate system, and that human activities are responsible for recent warming.

Palaeoclimate records are now being used widely to test the validity of computer climate models used to predict climate change. Palaeoclimate models can simulate the large-scale gradients of past change, but tend not to accurately reproduce fine-scale spatial patterns. They also have a tendency to underestimate the magnitude of past changes. Nevertheless they are proving to be increasingly useful tools to aid thinking about the nature and extent of past change, by providing a global picture where palaeoclimate data are geographically limited.

Geologists have recently contributed to improved estimates of climate sensitivity (defined as the increase in global mean temperature resulting from a doubling in atmospheric CO₂ levels). Studies of the Last Glacial Maximum (about 20,000 years ago) suggest that the climate sensitivity, based on rapidly acting factors like snow melt, ice melt and the behaviour of clouds and water vapour, lies in the range 1.5°C to 6.4°C. Recent research has given rise to the concept of 'Earth System sensitivity', which also takes account of slow acting factors like the decay of large ice sheets and the operation of the full carbon cycle, to estimate the full sensitivity of the Earth System to a doubling of CO₂. It is estimated that this could be double the climate sensitivity.

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When viewed in the context of geological time, today's conditions are atypical. We are living through an interglacial period, whose mean temperature is representative of only 10% of the last 800,000 years. The other 90% of that time, temperatures were lower, ice sheets larger and sea levels lower. This highlights how unusual current temperatures, and estimated future warming, are.

Before the current warming trend began, temperatures in the Holocene (the last 11,000 years) were declining. This was due largely to insolation – the solar radiation received by the Earth's surface – and dictated by the Earth's orbit and the tilt of the Earth's axis. Insolation declined throughout the Holocene. This cooling took Earth's climate into a Neoglacial period, culminating in the 'Little Ice Age' (1450 – 1850).

Astronomical calculations indicate that this period of low insolation and associated cool conditions should continue for about another 1,000 years. Nevertheless, after 1900 the overall decline in temperature sharply reversed. According to one recent study, it is likely that the area-weighted global average temperature for the 30 year period from 1970 to 2000 was higher than at any time in nearly 1,400 years. Tree ring data confirm that recent warming is unprecedented in central Europe over the past 2,500 years, and in eastern Europe over the past 1,000 years. Palaeoclimate records from the Arctic show that the warmest 50-year interval of the past 2,000 years occurred between 1950 and 2000 AD.

Atmospheric CO₂ is currently just below 400 parts per million (ppm) on average. It last reached similar levels during the Pliocene (5.3-2.6 million years ago). At that time, temperatures rose to levels 2-3°C warmer than today, and sea level rose by up to 20m in places. Sea level takes a few hundred years to reach equilibrium in response to changes in atmospheric CO₂ and temperature, which may explain why sea level has not yet risen to the same levels seen in the Pliocene.

Atmospheric CO₂ is increasing at around 2 ppm per year (1995-2010 average). If this rate continues, it may reach 600 ppm by the end of this century – a value that appears not to have been typical for at least 24 million years.

Our 2010 statement suggested that the rise in Antarctic temperature at the end of the Last Glacial Maximum (approximately 20,000 years ago) began a few centuries before CO₂ showed any reaction. New data now indicate that CO₂ rose at the same time as Antarctic temperature, and ahead of the global rise in temperature. This strengthens the argument that rises in CO₂ levels triggered by regional factors were instrumental in triggering global temperature increases, with positive climate feedbacks magnifying this effect.

There is now greater confidence that a relatively modest rise in atmospheric CO₂ levels and temperatures results in significant (though not globally uniform) sea level rise. Increased CO₂ in the atmosphere also increases CO₂ levels in the oceans, making sea water slightly more acidic and less oxygenated. In past warming events, such as at the Paleocene-Eocene Thermal Maximum (PETM) 55 million years ago, this caused marine crises and extinctions. The Earth System usually takes around 100,000 years to recover from such events.

Given the above, based on a growing abundance of palaeoclimate data, there is now greater confidence than in 2010 that the only plausible explanation for the rate and extent of temperature increase since 1900 is the exponential rise in CO₂ and other greenhouse gases in the atmosphere since the Industrial Revolution. This rate of increase of CO₂ is unprecedented, even in comparison with the massive injection of carbon into the atmosphere 55 million years ago that led to the major PETM warming event, and is likely to lead to a similar rise in both temperature and sea level.

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What is climate change, and how do geologists know about it?

No additions

What are the grounds for concern?

To put rising temperature into perspective, the full range of global mean temperature from a maximum ice-age state to the present interglacial state was about 4°C¹. Regional and seasonal variations of much greater magnitude are masked in the global mean value. These changes led to large changes in landscape, sea level, habitats and ecosystems across the globe. In this context, a projected rise of 2°C or more due to anthropogenic CO₂ emissions may also be expected to have serious consequences.

Calculating what to expect in the future from a doubling of CO₂ in the atmosphere requires an understanding of the climate sensitivity (defined as the increase in global mean temperature resulting from a doubling in CO₂). Many model-based estimates suggest that the short-term climate sensitivity lies in the range 1.5°C to 4.5°C (e.g. ²). They are based on fast changes like those involving snow melt, ice melt, and the behaviour of clouds and water vapour. Evidence from studies of past climate change now suggests that in addition we must consider a second and longer term sensitivity parameter - the Earth System sensitivity³, which includes slower changes like those involving the decay of the ice sheets and the longer-term carbon cycle, which take thousands of years to respond to a change. The Earth System sensitivity is important because it reflects the full consequences of atmospheric CO₂ increase and its influence on long term changes in climate and sea level. Studies of the Last Glacial Maximum (approximately 20,000 years ago) suggest that the climate sensitivity is unlikely to be less than 1.4°C or above 6.4 °C^{3,4}, while studies of the mid-Pliocene (3-4 million years ago), where mean sea surface temperatures were likely 1.7°C warmer than present and CO₂ concentrations were in the range 330-420 ppm, suggest that the Earth System sensitivity could be twice the short-term climate sensitivity⁵.

The palaeoclimate record is also essential for testing the validity of computer climate models used to predict climate change. Studies of past climate contributed in two important ways to the development and testing of these models. Firstly, they showed that a wider range of natural variability needed to be represented in the latest climate models^{6,7,8}. Secondly, palaeoclimate data used to test the ability of the models to simulate climate change show that while the models can simulate the large-scale gradients of change, they cannot accurately reproduce detailed spatial patterns⁹. When there is disagreement between models and data, in general the climate models underestimate past changes¹⁰.

When and how did today's climate become established?

In addition to what is said in the original GSL climate change statement, we note that viewed in the context of geological time today's conditions are atypical. The mean temperature of the Holocene characterizes only 10% of the palaeoclimate record for the past 800,000 years, which serves to illustrate both the unusual nature of interglacials, and the anomaly represented by estimates of future greenhouse gas induced warming. Mostly during the past million years the world has been colder, ice sheets more expanded and sea levels lower than at present.

What drives climate change?

As spelled out in the initial climate change statement, the main controls are changes in the Earth's orbit and axial tilt, modified by volcanic emissions, changes in the output of the sun (e.g. via sunspots), and changes in the amounts of greenhouse gases in the atmosphere (chiefly carbon dioxide and methane) and their effects on water vapour (itself a greenhouse gas but limited in range by the hydrological cycle).

The summer insolation, determined by the Earth's orbit and axial tilt, reached a peak most recently in the northern hemisphere about 11,000 years ago at the beginning of the Holocene interglacial. Since then, the insolation of the northern hemisphere has been in steady decline. While southern hemisphere insolation follows an opposite path, the amount of warmth of the southern hemisphere summer depends less on absolute insolation than upon the duration of the southern summer, which correlates with northern hemisphere insolation, thus aligning the climates of the two hemispheres.

Palaeoclimate studies confirm that the global average temperature declined along with the insolation, from a 'Holocene Thermal Maximum' during which the major northern hemisphere ice sheets melted, into a 'Neoglacial' period starting about 6,000 years ago and punctuated by periodic glacial re-advances¹¹. Recent compilations of global records^{11,12} show a net global cooling of about 0.7°C over the Holocene¹², followed by warming into the modern era¹³. The cooling caused the North Atlantic Current bringing heat to the north to diminish, contributing to cooling in Europe^{14,15,16}.

Some parts of Antarctica experienced rapid ice retreat in the early Holocene, followed by relative stability^{17,18}. In Greenland, after an early Holocene melt-back, some parts of the ice sheet margin re-advanced in the late Holocene, followed by marked ice retreat after the Little Ice Age (1450-1850)¹⁹. Mountain glaciers advanced globally during the Holocene Neoglacial as insolation decreased. They reached a maximum during the Little Ice Age, since when their retreat has been more extensive than at any other period in the past 2,000 years^{20,21,22}.

Global ice retreat parallels other signs of rapid warming seen globally in palaeoclimate records after 1900. This rapid warming is a significant departure from the long term cooling trend, though temperatures have not yet risen to those of the Holocene Thermal Maximum²³. According to one recent study, the area-weighted global average temperature for the last 30-year period (1971-2000) is likely higher than at any time in nearly 1,400 years²³.

This is consistent with palaeoclimate records from the Arctic, which show that the warmest 50-year interval of the past 2,000 years occurred between 1950 and 2000 AD²⁴. Tree-ring data confirm that recent warming is unprecedented in central Europe over at least the past 2,500 years²⁵ and in eastern Europe over at least the past 1,000 years²⁶.

What is the Greenhouse Effect?

There is little to add to what was said in the original climate change statement, but it seems appropriate to emphasize the extensive history of development of the subject. The potential role of CO₂ as a greenhouse gas was first established by physicist John Tyndall in 1859/60. Its role in possibly governing the changes from glacial to interglacial was investigated by Nobel Prize-winning chemist Svante Arrhenius in 1896, whose ideas stimulated geologist Thomas Chamberlin to develop a working hypothesis for the role of CO₂ in climate change through time in 1897-1899. The history of the subsequent development of ideas on CO₂ as a greenhouse gas have been extensively reviewed in recent years by Pierrehumbert²⁷, Archer²⁸, and Hawkins²⁹, for example. These pioneer studies and subsequent bodies of work have demonstrated, beyond reasonable doubt, the thermal insulating properties of atmospheric CO₂, which can be measured experimentally. The physics is clear: an increase in CO₂ content in the atmosphere will (eventually) lead to increased surface temperatures.

What effect do natural cycles of climate change have on the planet?

The melting of the great ice sheets after the Last Glacial Maximum caused the occasional discharge of masses of freshwater into the ocean, creating 'meltwater pulse' or flood events during which sea level rose by many metres in a few hundred years. The largest of these was a rise of between 14 and 18m that occurred between 14,650 and 14,310 years ago³⁰.

This represents a rate of sea-level rise of 41–53mm/yr, which is 15–19 times the rate in the late 20th century (average 2.8mm/yr; ranging between 2.5 and 3.4mm/yr)². Current estimates of sea level rise attributable to melting ice sheets are estimated to lie between 0.4 to 0.8mm per year², although a rate of 1.3 ± 0.4 mm per year has been suggested³¹. The rate has accelerated over the past 18 years³¹.

Sea ice extent and volume in the Arctic have been reducing strongly over recent decades, opening up areas previously accessible only with powerful icebreakers. Proxies of various kinds show that sea-ice has been present in parts of the Arctic for several million years³². One reconstruction suggests that the recent reduction in ice extent may be unprecedented over the last 1,450 years³³.

Superimposed on the Holocene cooling trend are slight global warmings and coolings of up to a few tenths of a degree C lasting a few centuries and reflecting slight changes in the sun's output. The changes in solar output can be detected via isotopes of carbon and beryllium produced in the upper atmosphere when solar activity is weak, and extracted from tree rings and polar ice cores³⁴. These fluctuations do not coincide precisely with palaeoclimatic events like the Medieval Climate Anomaly (although solar output was high during part of that time) or the Little Ice Age (during which there were some periods of minimal solar output). A lengthy burst of volcanic activity may have played a part in initiating the Little Ice Age²⁴. These two events were strongest in western Europe, and lack a coherent global signal²³. The Little Ice Age represents the peak of the Holocene Neoglacial, attributable to declining insolation. According to astronomical calculations of Earth's orbital and axial properties this period of low insolation and associated cool conditions should continue for about another 1,000 years^{35,36}, subject to small changes in volcanic and solar activity and emissions of CO₂.

Has sudden climate change occurred before?

The GSL statement drew attention to the CO₂-induced warming at the Paleocene-Eocene boundary and alluded to the effects of raised CO₂ on oceanic acidification and oxygenation. Marine crises and extinctions have occurred half a dozen times during geologically brief intervals of rapid CO₂ increase and concomitant global warming over the last 500 million years (e.g.^{37,38}). Adding CO₂ to the atmosphere causes it to increase also in the ocean, making seawater slightly more acid and so stressing marine organisms that are adapted to rather narrow limits of acidity (pH)³⁹. As the oceans warm they lose oxygen, which further stresses marine animals. Both seawater acidification and deoxygenation have occurred in the past with deleterious effects on a wide range of marine animals^{37,40,41,42,43}. The onset of these past events occurred in less than 10,000 years and probably much faster, but most likely not as fast as the rate at which we are currently introducing CO₂ to the atmosphere and oceans. The Earth system is robust and came back into equilibrium following these past events, but only over very long times (100,000 years) relative to the human life span.

Are there more recent examples of rapid climate change?

No addition

How did levels of CO₂ in the atmosphere change during the ice age?

While the older data reported in the initial GSL statement on climate change suggested that the rise in Antarctic temperature at the end of the last glacial maximum probably began a few centuries before the CO₂ showed any reaction, new data indicate that CO₂ most likely rose at the same time as temperature in East Antarctica^{44,45,46} and ahead of the global rise in temperature¹. This is new and stronger evidence that CO₂ is an agent capable of turning a local and small climate change in insolation into a global event.

Palaeoclimatologists now think that changes in the Earth's orbit combined with changes in ocean heat transport drove an initial rise in Antarctic temperature and a simultaneous release of CO₂ from the Southern Ocean. The rising CO₂ strengthened the temperature rise and turned it into a global response reinforced by increasing water vapour (another greenhouse gas); decreasing sea ice and land ice coverage then reduced albedo (reflection of heat from the Earth's surface) providing further positive feedback to the change¹.

How has carbon dioxide (CO₂) in the atmosphere changed over the longer term?

No addition

How has carbon dioxide in the atmosphere changed in recent times?

Atmospheric CO₂ is currently just below 400 ppm on average and is increasing at about 2 ppm/year (1995-2010 average), although the rate of increase is itself increasing. If atmospheric CO₂ continues to rise at around its present rate, then it may well reach 600 ppm by the end of this century. A daily value of 400 ppm was reached in May 2013.

When was CO₂ last at today's level, and what was the world like then?

Recent studies of past levels of atmospheric CO₂ and global temperatures from the Pliocene and Miocene indicate that CO₂ reached between 330 and 420 ppm^{5,47,48}. CO₂ was the largest contributor to mid-Pliocene warmth^{5,49}, when global mean temperatures were 2 - 3°C warmer than they are today with even larger responses in the high latitudes and the Arctic⁵⁰. Significantly higher CO₂ levels, similar to those that may well be reached by the end of this century, appear to have been typical only at or before 24 million years ago.

Based on Pliocene data, it is clear from a range of studies that sea level at equilibrium was higher than today but probably less than +20m, taking uncertainties into account. Assuming that atmospheric CO₂ levels close to those of today persist, one recent study suggests that the equilibrium sea level is likely to be achieved over a period of 500 to 2,500 years⁵¹. With yet higher CO₂ levels, as is very likely to be the case, higher sea levels will be attained more rapidly. However the global distribution of sea level rise will not be uniform. Glacial isostatic adjustment (the rising of land formerly depressed by ice), along with the effect of mass redistribution on the Earth's gravity field⁵², will cause sea levels to be higher in some areas than in others⁵³. The higher sea levels of the Pliocene must have included a contribution from partial melting of the East Antarctic ice sheet, evidence for which has recently been obtained from deep-ocean drilling off the Antarctic coast⁵⁴.

These Pliocene changes are broadly consistent with computer climate models for that period⁵⁵, but are much larger than we have experienced since 1900 despite the similarity in CO₂ levels. That is most probably because the high concentrations of CO₂ in the Pliocene were maintained for many millennia, allowing ice sheets and oceans to come to equilibrium, whereas our present climate is not in equilibrium with the current rapid rise in CO₂.

When global temperature changed, did the same change in temperature happen everywhere?

The pattern of climate change during the early to mid-Holocene across the northern hemisphere was not uniform, mainly due to the temporary local persistence of the North American and Scandinavian ice sheets, which served to keep their local environments cooler than they would otherwise have been, and which finally disappeared around 6,000-7,000 years ago¹¹.

During the late Holocene, the distribution of warm and cool events like the Medieval Climate Anomaly and Little Ice Age was not uniform across the globe²³. Regional variability tended to predominate. For instance during the past 2,000 years the eastern side of the Antarctic Peninsula progressively cooled, while the western side warmed. Over the past 100 years both sides have warmed^{56,57}.

In conclusion - what does the geological record tell us about the potential effect of continued emissions of CO₂?

Data published since production of the GSL statement toward the end of 2010, and especially the finding that CO₂ and temperature increased simultaneously in ice cores from East Antarctica, make it even more obvious than it was in 2010 that CO₂ is a major modifier of the climate system. It is also more obvious now that during the Holocene there was a general decline in global temperature driven by the ongoing decline in insolation attributable to changes in the Earth's orbital and axial properties, but that this temperature decline sharply reversed since about 1900 without any corresponding change in insolation. The scientific community can find no plausible explanation for the rate and extent of this reversal in the second half of the 20th century, other than the increasing rise in CO₂ and other greenhouse gases that began slowly with the Industrial Revolution (see Figure 1). These conclusions are supported by a fast increasing abundance of palaeoclimate records, and by numerical climate models applied to past times, though it is clear that the models tend to underestimate the extremes reflected in the empirical records.

It is equally clear that the rates of increase of CO₂ since 1970 are unprecedented, even in comparison with the massive injections of carbon to the atmosphere at the Palaeocene-Eocene boundary, which led to a major thermal event 55 million years ago. Recent data have also firmed up estimates of sea level rise associated with quite small increases in CO₂ and temperature, for example from the Pliocene. These adjustments are not uniform across the globe, because the relaxation of the Earth's deformed surface, which rises when glacial ice is removed, causes relative (local) sea level to rise higher in some areas than in others. These various geologically based considerations lend strength to the argument that continued emissions of CO₂ will drive further rises in both temperature and sea level. Given that the Earth system takes a long time to reach equilibrium in the face of change, the present warming and sea-level rise are likely to continue long beyond 2100 until equilibrium is reached.

In this addendum we draw more attention than before to a side-effect of CO₂ emissions – namely the rise in acidification and associated deoxygenation of the ocean, which significantly affected marine biodiversity in past oceans and has already begun to have that effect in the present ocean. Continued CO₂ emissions will raise the dissolved CO₂ concentration of the ocean, further lowering its pH and affecting the ability of many oceanic organisms to function normally – especially those building skeletons from calcium carbonate, a process that will become progressively more difficult with time. Worryingly, this will affect in particular the production of plankton at the base of the food chain on which higher organisms depend.

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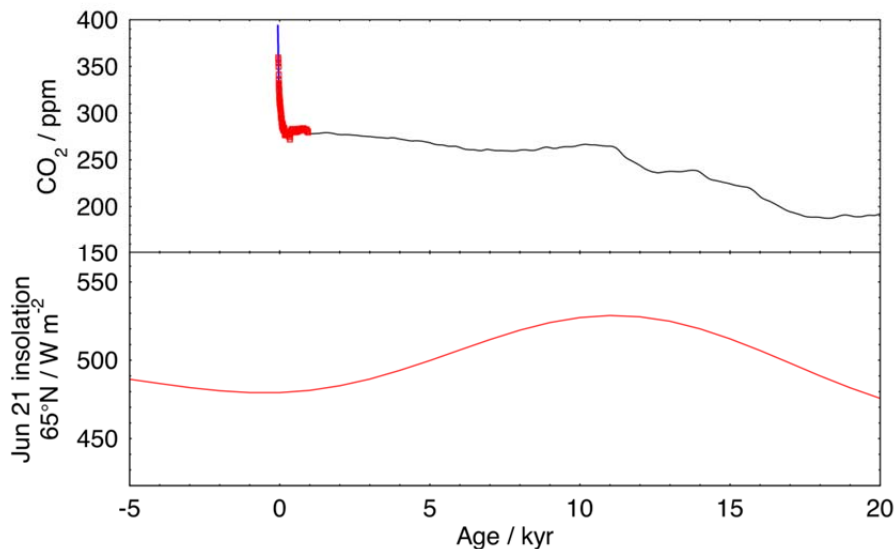


Figure 1. Solar insolation at 65°N at the summer solstice, and the variation in CO₂ as determined from analyses of bubbles of air in ice cores and from modern measurements of air at Mauna Loa (Hawaii). The plot runs from 20,000 years ago (about the time of the last glacial maximum) to 5,000 years in the future. The insolation is calculated from astronomical data⁵⁸ using the Analyseries software. The summer insolation at 65°N (given in Watts per square metre) is particularly important for the formation and loss of northern hemisphere ice sheets, but a decline in summer insolation over the last 10 kyr across the northern hemisphere seems to have driven an overall reduction in temperatures throughout the Holocene. The CO₂ data consist of: annual averages measured in the air at the remote site of Mauna Loa since 1959 (blue, courtesy of NOAA/ESRL (ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt)); firn air and ice core data from Law Dome, Antarctica (red) for the last 1000 years^{59,60}; and a composite spline (black) of ice core data from various cores covering the last 20,000 years⁶¹. The key greenhouse gas, CO₂, increased slowly out of the last glacial, and then remained relatively steady until the abrupt upturn caused by the industrial revolution. Present warming is attributed to this sudden upswing, which is not matched by changes in insolation or solar strength.

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New General Reading

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2 Cowie, J., 2013, *Climate Change – Biological and Human Aspects*. 2nd Ed., Cambridge University Press, 558pp.

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