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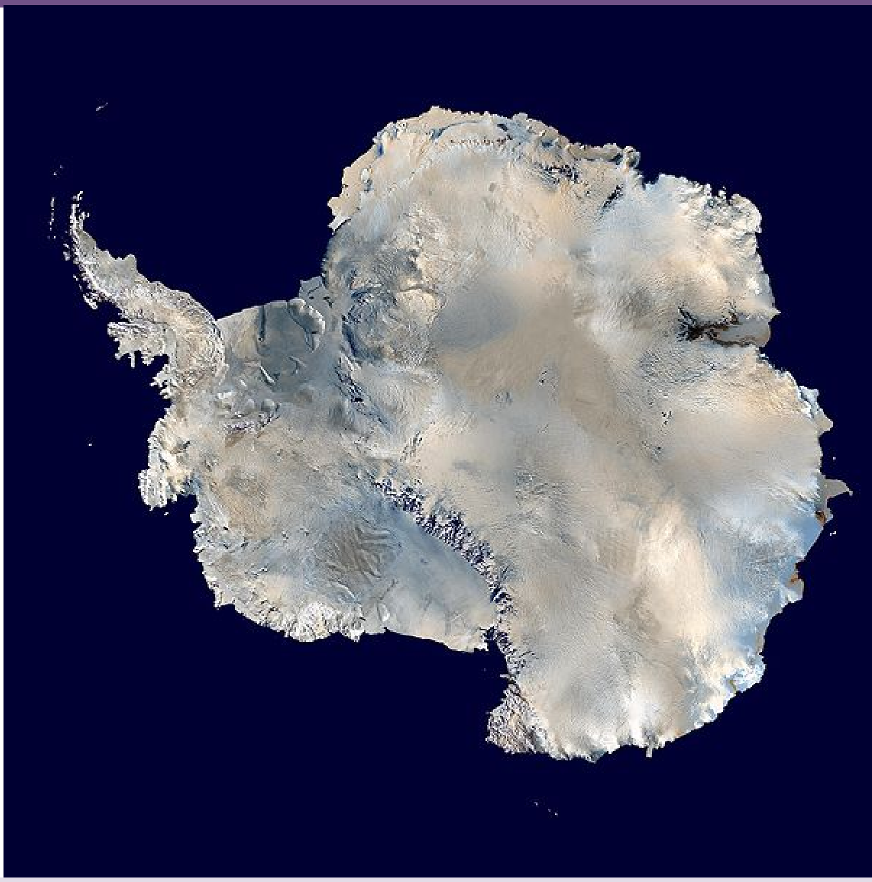

Climate change: evidence from the geological record

A statement from the Geological Society of London

November 2010

Climate change

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Climate change is a defining issue for our time. The geological record contains abundant evidence of the ways in which Earth's climate has changed in the past. That evidence is highly relevant to understanding how it may change in the future.

The Council of the Society is issuing this statement as part of the Society's work *"to promote all forms of education, awareness and understanding of the Earth and their practical applications for the benefit of the public globally"*. The statement is intended for non-specialists and Fellows of the Society. It is based on analysis of geological evidence, and not on analysis of recent temperature or satellite data, or climate model projections. It contains references to support key statements, indicated by superscript numbers, and a reading list for those who wish to explore the subject further.

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

The Earth's temperature and weather patterns change naturally over time scales ranging from decades, to hundreds of thousands, to millions of years[1]. The climate is the statistical average of the weather taken over a long period, typically 30 years. It is never static, but subject to constant disturbances, sometimes minor in nature and effect, but at other times much larger. In some cases these changes are gradual and in others abrupt.

Evidence for climate change is preserved in a wide range of geological settings, including marine and lake sediments, ice sheets, fossil corals, stalagmites and fossil tree rings. Advances in field observation, laboratory techniques and numerical modelling allow geoscientists to show, with increasing confidence, how and why climate has changed in the past. For example, cores drilled through the ice sheets yield a record of polar temperatures and atmospheric composition ranging back to 120,000 years in Greenland and 800,000 years in Antarctica. Oceanic sediments preserve a record reaching back tens of millions of years, and older sedimentary rocks extend the record to hundreds of millions of years.

This vital baseline of knowledge about the past provides the context for estimating likely changes in the future.

What are the grounds for concern?

The last century has seen a rapidly growing global population and much more intensive use of resources, leading to greatly increased emissions of gases, such as carbon dioxide and methane, from the burning of fossil fuels (oil, gas and coal), and from agriculture, cement production and deforestation. Evidence from the geological record is consistent with the physics that shows that adding large amounts of carbon dioxide to the atmosphere warms the world and may lead to: higher sea levels and flooding of low-lying coasts; greatly changed patterns of rainfall[2]; increased acidity of the oceans [3,4,5,6]; and decreased oxygen levels in seawater[7,8,9].

There is now widespread concern that the Earth's climate will warm further, not only because of the lingering effects of the added carbon already in the system, but also because of further additions as human population continues to grow. Life on Earth has survived large climate changes in the past, but extinctions and major redistribution of species have been associated with many of them. When the human population was small and nomadic, a rise in sea level of a few metres would have had very little effect on *Homo sapiens*. With the current and growing global population, much of which is concentrated in coastal cities, such a rise in sea level would have a drastic effect on our complex society, especially if the climate were to change as suddenly as it has at times in the past. Equally, it seems likely that as warming continues some areas may experience less precipitation leading to drought. With both rising seas and increasing drought, pressure for human migration could result on a large scale.

When and how did today's climate become established?

The Earth's climate has been gradually cooling for most of the last 50 million years. At the beginning of that cooling (in the early Eocene), the global average temperature was about 6-7 °C warmer than now[10,11]. About 34 million years ago, at the end of the Eocene, ice caps coalesced to form a continental ice sheet on Antarctica[12,13]. In the northern hemisphere, as global cooling continued, local ice caps and mountain glaciers gave way to large ice sheets around 2.6 million years ago[14].

Over the past 2.6 million years (the Pleistocene and Holocene), the Earth's climate has been on average cooler than today, and often much colder. That period is known as the 'Ice Age', a series of glacial episodes separated by short warm 'interglacial' periods that lasted between 10,000-30,000 years[15,16]. We are currently living through one of these interglacial periods. The present warm period (known as the Holocene) became established only 11,500 years ago, since when our climate has been relatively stable. Although we currently lack the large Northern Hemisphere ice sheets of the Pleistocene, there are of course still large ice sheets on Greenland and Antarctica[1].

What drives climate change?

The Sun warms the Earth, heating the tropics most and the poles least. Seasons come and go as the Earth orbits the Sun on its tilted axis. Many factors interacting on a variety of time scales drive climate change, by altering the amount of the Sun's heat retained at the Earth's surface and the distribution of that heat around the planet. Over millions of years the continents move, ocean basins open and close, and mountains rise and fall. All of these changes affect the circulation of the oceans and of the atmosphere. Major volcanic eruptions eject gas and dust high into the atmosphere, causing temporary cooling. Changes in the abundance in the atmosphere of gases such as water vapour, carbon dioxide and methane affect climate through the Greenhouse Effect – described below.

As well as the long-term cooling trend, evidence from ice and sediment cores reveal cycles of climate change tens of thousands to hundreds of thousands of years long. These can be related to small but predictable changes in the Earth's orbit and in the tilt of the Earth's axis. Those predictable changes set the pace for the glacial-interglacial cycles of the ice age of the past 2.6 million years[17]. In addition, the heat emitted by the Sun varies with time. Most notably, the 11-year sunspot cycle causes the Earth to warm very slightly when there are more sunspots and cool very slightly when there are few. Complex patterns of atmospheric and oceanic circulation cause the El Niño events and related climatic oscillations on the scale of a few years[1,18].

What is the Greenhouse Effect?

The Greenhouse Effect arises because certain gases (the so-called greenhouse gases) in the atmosphere absorb the long wavelength infrared radiation emitted by the Earth's surface and re-radiate it, so warming the atmosphere. This natural effect keeps our atmosphere some 30°C warmer than it would be without those gases. Increasing the concentration of such gases will increase the effect (i.e. warm the atmosphere more)[19].

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

Global sea level is very sensitive to changes in global temperatures. Ice sheets grow when the Earth cools and melt when it warms. Warming also heats the ocean, causing the water to expand and the sea level to rise. When ice sheets were at a maximum during the Pleistocene, world sea level fell to at least 120 m below where it stands today. Relatively small increases in global temperature in the past have led to sea level rises of several metres. During parts of the previous interglacial period, when polar temperatures reached 3-5°C above today's[20], global sea levels were higher than today's by around 4-9m[21]. Global patterns of rainfall during glacial times were very different from today.

Has sudden climate change occurred before?

Yes. About 55 million years ago, at the end of the Paleocene, there was a sudden warming event in which temperatures rose by about 6ºC globally and by 10-20ºC at the poles[22]. Carbon isotopic data show that this warming event (called by some the Paleocene-Eocene Thermal Maximum, or PETM) was accompanied by a major release of 1500-2000 billion tonnes or more of carbon into the ocean and atmosphere. This injection of carbon may have come mainly from the breakdown of methane hydrates beneath the deep sea floor[10], perhaps triggered by volcanic activity superimposed on an underlying gradual global warming trend that peaked some 50 million years ago in the early Eocene. CO_2 levels were already high at the time, but the additional CO_2 injected into the atmosphere and ocean made the ocean even warmer, less well oxygenated and more acidic, and was accompanied by the extinction of many species on the deep sea floor. Similar sudden warming events are known from the more distant past, for example at around 120 and 183 million years ago[23,24]. In all of these events it took the Earth's climate around 100,000 years or more to recover, showing that a CO_2 release of such magnitude may affect the Earth's climate for that length of time[25].

Are there more recent examples of rapid climate change?

Abrupt shifts in climate can occur over much shorter timescales. Greenland ice cores record that during the last glacial stage (100,000 – 11,500 years ago) the temperature there alternately warmed and cooled several times by more than 10ºC [26,27]. This was accompanied by major climate change around the northern hemisphere, felt particularly strongly in the North Atlantic region. Each warm and cold episode took just a few decades to develop and lasted for a few hundred years. The climate system in those glacial times was clearly unstable and liable to switch rapidly with little warning between two contrasting states. These changes were almost certainly caused by changes in the way the oceans transported heat between the hemispheres.

How did levels of CO_2 in the atmosphere change during the ice age?

The atmosphere of the past 800,000 years can be sampled from air bubbles trapped in Antarctic ice cores. The concentrations of CO_2 and other gases in these bubbles follow closely the pattern of rising and falling temperature between glacial and interglacial periods. For example CO_2 levels varied from an average of 180 ppm (parts per million) in glacial maxima to around 280 ppm during interglacials. During warmings from glacial to interglacial, temperature and CO_2 rose together for several thousand years, although the best estimate from the end of the last glacial is that the temperature probably started to rise a few centuries before the CO_2 showed any reaction. Palaeoclimatologists think that initial warming driven by changes in the Earth's orbit and axial tilt eventually caused CO_2 to be released from the warming ocean and thus, via positive feedback, to reinforce the temperature rise already in train[28]. Additional positive feedback reinforcing the temperature rise would have come from increased water vapour evaporated from the warmer ocean, water being another greenhouse gas, along with a decrease in sea ice, and eventually in the size of the northern hemisphere ice sheets, resulting in less reflection of solar energy back into space.

How has carbon dioxide (CO_2) in the atmosphere changed over the longer term?

Estimating past levels of CO_2 in the atmosphere for periods older than those sampled by ice cores is difficult and is the subject of continuing research. Most estimates agree that there was a significant decrease of CO_2 in the atmosphere from more than 1000 ppm at 50 million years ago (during the Eocene) to the range recorded in the ice cores of the past 800,000 years[22]. This decrease in CO_2 was probably one of the main causes of the cooling that led to the formation of the great ice sheets on Antarctica[29]. Changes in ocean circulation around Antarctica may also have also played a role in the timing and extent of formation of those ice sheets[30,31,32].

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

Atmospheric CO_2 is currently at a level of 390 ppm. It has increased by one third in the last 200 years[33]. One half of that increase has happened in the last 30 years. This level and rate of increase are unprecedented when compared with the range of CO_2 in air bubbles locked in the ice cores (170-300 ppm). There is some evidence that the rate of increase in CO_2 in the atmosphere during the abrupt global warming 183 million years ago (Early Jurassic), and perhaps also 55 million years ago (the PETM), was broadly similar to today's rate[34].

When was CO_2 last at today's level, and what was the world like then?

The most recent estimates[35] suggest that at times between 5.2 and 2.6 million years ago (during the Pliocene), the carbon dioxide concentrations in the atmosphere reached between 330 and 400 ppm. During those periods, global temperatures were 2-3°C higher than now, and sea levels were higher than now by 10 – 25 metres, implying that global ice volume was much less than today[36]. There were large fluctuations in ice cover on Greenland and West Antarctica during the Pliocene, and during the warm intervals those areas were probably largely free of ice[37,38,39]. Some ice may also have been lost from parts of East Antarctica during the warm intervals[40]. Coniferous forests replaced tundra in the high latitudes of the Northern Hemisphere[41], and the Arctic Ocean may have been seasonally free of sea-ice[42].

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

No. During the glacial periods in the Pleistocene the drop in temperature was much greater in polar regions than in the tropics. There is good evidence that the difference between polar and tropical temperatures in the warmer climate of the Eocene to Pliocene was smaller than it is today. The ice core record also shows differences between Greenland and Antarctica in the size and details of the temperature history in the two places, reflecting slow oceanic heat transport between the two poles[16].

In conclusion - what does the geological record tell us about the potential effect of continued emissions of CO_2?

Over at least the last 200 million years the fossil and sedimentary record shows that the Earth has undergone many fluctuations in climate, from warmer than the present climate to much colder, on many different timescales. Several warming events can be associated with increases in the 'greenhouse gas' CO_2. There is evidence for sudden major injections of carbon to the atmosphere occurring at 55, 120 and 183 million years ago, perhaps from the sudden breakdown of methane hydrates beneath the seabed. At those times the associated warming would have increased the evaporation of water vapour from the ocean, making CO_2 the trigger rather than the sole agent for change. During the Ice Age of the past two and a half million years or so, periodic warming of the Earth through changes in its position in relation to the sun also heated the oceans, releasing both CO_2 and water vapour, which amplified the ongoing warming into warm interglacial periods. That process was magnified by the melting of sea ice and land ice, darkening the Earth's surface and reducing the reflection of the sun's energy back into space.

While these past climatic changes can be related to geological events, it is not possible to relate the Earth's warming since 1970 to anything recognisable as having a geological cause (such as volcanic activity, continental displacement, or changes in the energy received from the sun)[43]. This recent warming is accompanied by an increase in CO_2 and a decrease in Arctic sea ice, both of which – based on physical theory and geological analogues - would be expected to warm the climate[44]. Various lines of evidence, reviewed by the Intergovernmental Panel on Climate Change, clearly show that a large part of the modern increase in CO_2 is the result of burning fossil fuels, with some contribution from cement manufacture and some from deforestation[44].

In total, human activities have emitted over 500 billion tonnes of carbon (hence over 1850 billion tons of CO_2) to the atmosphere since around 1750, some 65% of that being from the burning of fossil fuels[18,45,46,47,48]. Some of the carbon input to the atmosphere comes from volcanoes[49,50], but carbon from that source is equivalent to only about 1% of what human activities add annually and is not contributing to a net increase.

In the coming centuries, continued emissions of carbon from burning oil, gas and coal at close to or higher than today's levels, and from related human activities, could increase the total to close to the amounts added during the 55 million year warming event – some 1500 to 2000 billion tonnes.

Further contributions from 'natural' sources (wetlands, tundra, methane hydrates, etc.) may come as the Earth warms[22]. The geological evidence from the 55 million year event and from earlier warming episodes suggests that such an addition is likely to raise average global temperatures by at least 5-6°C, and possibly more, and that recovery of the Earth's climate in the absence of any mitigation measures could take 100,000 years or more. Numerical models of the climate system support such an interpretation[44]. In the light of the evidence presented here it is reasonable to conclude that emitting further large amounts of CO_2 into the atmosphere over time is likely to be unwise, uncomfortable though that fact may be.

Acknowledgements

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Background Reading

For those wishing to read further, the following provide an accessible overview of the topic:

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A collection of articles on various aspects of Rapid Climate Change is available from the proceedings of the National Academy of Sciences web site at: http://www.pnas.org/cgi/collection/rapid_climate

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