

Climate change: evidence from the geological record



The
Geological
Society

-serving science & profession

A statement from the Geological Society of London

November 2010

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 years¹. 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 rainfall²; 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 ago¹⁴.

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 Antarctica¹.

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 years¹⁷. 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's²⁰, global sea levels were higher than today's by around 4-9m²¹. 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 6°C globally and by 10-20°C at the poles²². 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 floor¹⁰, perhaps triggered by volcanic activity superimposed on an underlying gradual global warming trend that peaked some 50 million years ago in the early Eocene. CO₂ levels were already high at the time, but the additional CO₂ 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 CO₂ release of such magnitude may affect the Earth's climate for that length of time²⁵.

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 10°C^{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 CO₂ 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 CO₂ and other gases in these bubbles follow closely the pattern of rising and falling temperature between glacial and interglacial periods. For example CO₂ 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 CO₂ 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 CO₂ showed any reaction. Palaeoclimatologists think that initial warming driven by changes in the Earth's orbit and axial tilt eventually caused CO₂ to be released from the warming ocean and thus, via positive feedback, to reinforce the temperature rise already in train²⁸. 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 (CO₂) in the atmosphere changed over the longer term?

Estimating past levels of CO₂ 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 CO₂ 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 years²². This decrease in CO₂ was probably one of the main causes of the cooling that led to the formation of the great ice sheets on Antarctica²⁹. 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 CO₂ is currently at a level of 390 ppm. It has increased by one third in the last 200 years³³. 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 CO₂ in air bubbles locked in the ice cores (170-300 ppm). There is some evidence that the rate of increase in CO₂ 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 rate³⁴.

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

The most recent estimates³⁵ 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 today³⁶. 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 intervals⁴⁰. Coniferous forests replaced tundra in the high latitudes of the Northern Hemisphere⁴¹, and the Arctic Ocean may have been seasonally free of sea-ice⁴².

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 poles¹⁶.

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

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' CO₂. 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 CO₂ 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 CO₂ 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 CO₂ and a decrease in Arctic sea ice, both of which – based on physical theory and geological analogues - would be expected to warm the climate⁴⁴. Various lines of evidence, reviewed by the Intergovernmental Panel on Climate Change, clearly show that a large part of the modern increase in CO₂ is the result of burning fossil fuels, with some contribution from cement manufacture and some from deforestation⁴⁴. In total, human activities have emitted over 500 billion tonnes of carbon (hence over 1850 billion tons of CO₂) 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 warms²². 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 interpretation⁴⁴. In the light of the evidence presented here it is reasonable to conclude that emitting further large amounts of CO₂ into the atmosphere over time is likely to be unwise, uncomfortable though that fact may be.

Acknowledgements

Members of the working group:

Dr C Summerhayes
Chairman and GSL Vice-President
*Scott Polar Research Institute,
Cambridge University*

Prof J Cann FRS
*School of Earth and Environment,
Leeds University*

Dr A Cohen
*Department of Earth and Environmental
Sciences, The Open University*

Prof J Francis
*School of Earth and Environment,
Leeds University*

Dr R Larter
British Antarctic Survey, Cambridge

Prof J Lowe
*Department of Geography, Royal
Holloway University of London*

Prof N McCave
*Department of Earth Sciences,
Cambridge University*

Dr A Haywood
*School of Earth and Environment,
Leeds University*

Prof P Pearson
*School of Earth and Ocean Sciences,
Cardiff University*

Dr E Wolff FRS
British Antarctic Survey, Cambridge

Geological Society staff:

Ms S Day
Earth Science Communicator, GSL

Mr E Nickless
Executive Secretary, GSL

Background Reading

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

Alley, R.B., 2000, *The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future*. Princeton University Press.

Bell, M. and Walker, M.J.C, 2005, *Late Quaternary Environmental Change: Physical and Human Perspectives*, (2nd edition). Pearson/Prentice Hall.

Dansgaard, W., 2005, *Frozen Annals: Greenland Ice Sheet Research*. Neils Bohr Institute, Copenhagen. The book can be downloaded for free from <http://www.iceandclimate.nbi.ku.dk/publications/FrozenAnnals.pdf>

Houghton, J., 2009, *Global Warming: The Complete Briefing*, (4th edition). Cambridge University Press.

Imbrie, J. and Imbrie, K.P, 1979, *Ice Ages: Solving the Mystery*. MacMillan, London.

IPCC, *Climate Change 2007: The Physical Science Basis*. Working Group I Contribution to the Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Lamb, H.H., 1995, *Climate, History and the Modern World*, (2nd edition). Routledge, London.

Lovell, B., 2010, *Challenged by Carbon: The Oil Industry and Climate Change*. Cambridge University Press.

Mayewski, P.A. and White, F., 2002, *The Ice Chronicles: The Quest to Understand Global Climate Change*. University of New Hampshire/University Press of New England.

Ruddiman, W.F., 2005, *Plows, Plagues and Petroleum: How Humans Took Control of Climate*. Princeton University Press.

For the more intrepid:

Alverson, K.D., Bradley, R.S. and Pedersen, T.F., (eds.) 2003, *Paleoclimate, Global Change and the Future*. The IGBP Series, Springer-Verlag, New York.

Burroughs, W.J., 2007, *Climate Change: A Multidisciplinary Approach*, (2nd edition). Cambridge University Press.

Cronin, T.M., 2009, *Paleoclimates: Understanding Climate Change Past and Present*. Columbia University Press.

Gibbard, P. and Pillans, B., (eds.), 2008, *Special Issue on the Quaternary period/system. Episodes (IUGS Journal of International Geoscience)*, vol. 31, No.2., (a collection of papers summarising the history of Earth's environmental and climatic oscillations during the last 2.7 million years).

Langway, Jr., C., 2008, The History of Early Polar Ice-Core records. U.S. Army Corps of Engineers, Research and Development Center. Available online at:
http://www.nicl-smo.sr.unh.edu/Langway_2008_Early_polar_ice_cores.pdf

Lowe, J.J. and Walker, M.J.C., 1997, Reconstructing Quaternary Environments, (2nd edition). Addison Wesley Longman Ltd.

Milne, G.A., Gehrels, W.R., Hughes, C.W. and Tamisiea, M.E., 2009, Identifying the causes of sea-level change. Nature Geoscience.

Ruddiman, W.F., 2001, Earth's Climate: Past and Future. W.H. Freeman.

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

References

- 1 Cronin, T.M., 2009, *Paleoclimates: Understanding Climate Change Past and Present*. Columbia University Press.
- 2 Alverson, K.D., Bradley, R.S. and Pedersen, T.F., (eds.), 2003, *Paleoclimate, Global Change and the Future*. The IGBP Series. Springer-Verlag, New York.
- 3 Barker, S. and Elderfield, H., 2002, Foraminiferal calcification response to Glacial-Interglacial changes in atmospheric CO₂. *Science* 297, 833 – 83.
- 4 Olafsson J. et al., 2009, Rate of Iceland Sea acidification from time series measurements. *Biogeoscience* 6, 2661-2668.
- 5 Caldeira, K. and Wickett, M.E., 2003, Anthropogenic carbon and ocean pH, *Nature* 425, 365.
- 6 Raven, J. et al., 2005, *Ocean acidification due to increasing atmospheric carbon dioxide*. Policy document. The Royal Society, London.
- 7 Whitney, F.A., Freeland, H.J. and Robert, M., 2007, Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. *Progress in Oceanography* 75 (2), 179-199.
- 8 Keeling, R.F., Kortzinger, A. and Gruber, N., 2010, Ocean Deoxygenation in a Warming World. *Annual Review of Marine Science* 2, 199-229.
- 9 Pearce, C.R., Cohen, A.S., Coe, A.L. and Burton, K.W., 2008, Molybdenum isotope evidence for global ocean anoxia coupled with perturbations to the carbon cycle during the Early Jurassic. *Geology* 3, 231-234.
- 10 Zachos, J.C., Pagani, M., Sloan, L., Thomas, E. and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 292, 686-693.
- 11 Miller, K.G., Wright, J.D. and Browning, J.V., 2005, Visions of ice sheets in a greenhouse world. *Marine Geology* 217, 215-231.
- 12 Barrett, P. J., 1996, Antarctic paleoenvironment through Cenozoic times—a review. *Terra Antarctica*, 3, 103–119.
- 13 Cooper, A.K. and O'Brien, P.E., 2004. Leg 188 synthesis: transitions in the glacial history of the Prydz Bay region, East Antarctica, from ODP drilling. In Cooper, A.K., O'Brien, P.E. and Richter, C. (eds.), *Proceedings of the Ocean Drilling Programme, Scientific Results*, 188. Available from http://www-odp.tamu.edu/publications/188_SR/VOLUME/SYNTH/SYNTH.PDF
- 14 Maslin, M.A., Li, X.S., Loutre, M.-F. and Berger, A., 1998, The contribution of orbital forcing to the progressive intensification of Northern Hemisphere glaciation. *Quaternary Science Reviews* 17, 411–426.

- 15** Lisiecki, L.E. and Raymo, M.E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic delta O-18 records. *Paleoceanography* 20 (1), PA1003.
- 16** Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Nouet, J., Barnola, J.M., Chappellaz, J., Fischer, H., Gallet, J.C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schwander, J., Spahni, R., Souchez, R., Selmo, E., Schilt, A., Steffensen, J.P., Stenni, B., Stauffer, B., Stocker, T., Tison, J.-L., Werner, M. and Wolff, E.W., 2007, Orbital and millennial Antarctic climate variability over the last 800 000 years. *Science* 317, 793-796.
- 17** Imbrie, J. and Imbrie, K.P., 1979, *Ice Ages: Solving the Mystery*. MacMillan, London.
- 18** Houghton, J., 2009, *Global Warming: The Complete Briefing*. 4th edition. Cambridge University Press.
- 19** Walker, J.C.G., Hays, P.B. and Kasting, J.F., 1981, A Negative Feedback Mechanism for the Long-Term Stabilization of Earth's Surface-Temperature. *Journal of Geophysical Research - Oceans and Atmospheres* 86, 9776-9782.
- 20** Otto-Bliesner, B.L., Marshall, S.J., Overpeck, J.T, Miller, G.H., Hu, A. and CAPE Last Interglacial Project members, 2006, Simulating Arctic Climate Warmth and Icefield Retreat in the Last Interglaciation. *Science* 311, 1751-1753.
- 21** Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C. and Oppenheimer, M., 2009, Probabilistic assessment of sea level during the last interglacial stage. *Nature* 462, 863-867.
- 22** Zachos, J.C., Dickens, G.R. and Zeebe, R.E., 2008, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature* 451, 279-283.
- 23** Kemp, D.B. et al., 2005, Astronomical pacing of methane release in the Early Jurassic period. *Nature* 437, 396-399.
- 24** Jenkyns, H.C., 2010, Geochemistry of oceanic anoxic events. *Geochemistry Geophysics Geosystems* 11(3), Q03004.
- 25** Archer, D. et al., 2009, Atmospheric Lifetime of Fossil Fuel Carbon Dioxide. *Annual Review of Earth and Planetary Sciences* 37, 117-134.
- 26** Blunier, T. and Brook, E.J., 2001, Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science* 291 (5501), 109-112.
- 27** Johnsen, S.J., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C.U., Iversen, P., Jouzel, J., Stauffer, B. and Steffensen, J.P., 1992, Irregular glacial interstadials recorded in a new Greenland ice core. *Nature* 359, 311-313.
- 28** Lüthi, D., Le Floch, M., Stocker, T.F., Bereiter, B., Blunier, T., Barnola, J.M., Siegenthaler, U., Raynaud, D. and Jouzel, J., 2008, High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature* 453, 379-382.

- 29** DeConto, R.M. and Pollard, D., 2003, Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO₂. *Nature* 421, 245–249.
- 30** Livermore, R.A., Hillenbrand, C.-D., Meredith, M. and Eagles, G., 2007, Drake Passage and Cenozoic climate: An open and shut case? *Geochemistry, Geophysics, Geosystems* 8(1), Q01005.
- 31** Huber, M., Brinkhuis, H., Stickley, C.E., Doos, K., Sluijs, A., Warnaar, J., Schellenberg, S.A. and Williams, G.L., 2004, Eocene circulation of the Southern Ocean: was Antarctica kept warm by subtropical waters? *Paleoceanography* 9(4), PA3026.
- 32** Francis, J.E., Marensi, S., Levy, R., Hambrye, M., Thorn, V.C., Mohr, B., Brinkhuis, H., Warnaar, J., Zachos, J., Bohaty, S. and DeConto, R., 2009, From Greenhouse to Icehouse – the Eocene/Oligocene in Antarctica. In Florindo, F. and Siebert, M. (eds.), *Antarctic Climate Evolution, Chapter 8, Developments in Earth and Environmental Sciences 8*, Elsevier, 209-368.
- 33** MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A. and Elkins, J., 2006, Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP. *Geophysical Research Letters* 33 (14), L14810.
- 34** Cohen, A.S., Coe, A.L. and Kemp, D.B., 2007, The Late Palaeocene Early Eocene and Toarcian (Early Jurassic) carbon isotope excursions: a comparison of their time scales, associated environmental changes, causes and consequences. *Journal of the Geological Society* 164, 1093-1108.
- 35** Seki, O., Foster, G.L., Schmidt, D.N., Mackensen, A., Kawamura, K. and Pancost, R.D., 2010, Alkenone and boron-based Pliocene pCO₂ records. *Earth and Planetary Science Letters* Volume 292, Issues 1-2, 201-211.
- 36** Dowsett, H.J. and Cronin, T.M., 1990, High eustatic sea level during the Middle Pliocene: Evidence from the southeastern U.S. Atlantic Coastal Plain. *Geology* 18, 435-438.
- 37** Naish, T. and 55 others, 2009, Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* 458, 322-328.
- 38** Lunt, D.J., Foster, G.L., Haywood, A.M and Stone, E.J., 2008, Late Pliocene Greenland glaciation controlled by a decline in atmospheric CO₂ levels. *Nature* 454 (7208), 1102-1105.
- 39** Pollard, D. and DeConto, R.M., 2009, Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* 458, 329-332.
- 40** Hill, D.J., Haywood, A.M., Hindmarsh, R.C.A. and Valdes, P.J., 2007, Characterising ice sheets during the mid Pliocene: evidence from data and models. In Williams, M., Haywood, A.M., Gregory, J. and Schmidt, D. (eds.), *Deep-time perspectives on climate change: marrying the signal from computer models and biological proxies. The Micropalaeontological Society, Special Publication, The Geological Society, London*, 517-538.

- 41** Salzmann, U., Haywood, A.M., Lunt, D.J., Valdes, P.J. and Hill, D.J., 2008, A new global biome reconstruction and data-model comparison for the Middle Pliocene. *Global Ecology and Biogeography* 17(3), 432-447.
- 42** Cronin, T.M., Whatley, R.C., Wood, A., Tsukagoshi, A., Ikeya, N., Brouwers, E.M. and Briggs, W.M., 1993, Microfaunal evidence for elevated mid-Pliocene temperatures in the Arctic Ocean. *Paleoceanography* 8, 161-173.
- 43** Bard, E. and Delaygue, G., 2008, Comment on "Are there connections between the Earth's magnetic field and climate?" by Courtillot, V., Gallet, Y., Le Mouél, J.-L., Fluteau, F. and Genevey, A. *EPSL* 253, 328, 2007. *Earth & Planetary Science Letters*, 265, No 1-2, 302-307.
- 44** Solomon, S., Qin, D., Manning, M. et al., 2007, *Climate change 2007: The physical science basis. Contribution of Working Group I to the 4th Assessment Report of the IPCC*. Cambridge University Press.
- 45** Andres, R.J., Marland, G., Boden, T. and Bischoff, S., 2000, Carbon dioxide emissions from fossil fuel consumption and cement manufacture, 1751-1991, and an estimate of their isotopic composition and latitudinal distribution. In Wigley, T.M.L. and Schimel, D.S., (eds.), *The Carbon Cycle*. Cambridge University Press, 53-62.
- 46** World Resources Institute 2010, *Climate Analysis Indicators Tool (CAIT)*: <http://cait.wri.org/>
- 47** Metz, B., Davidson, O. et al., 2007, *Climate Change 2007 – Mitigation of Climate Change. Contribution of Working Group III to the 4th Assessment of the IPCC*. Cambridge University Press.
- 48** Carbon Dioxide Information Analysis Centre of the US Department of Energy - <http://cdiac.ornl.gov/>
- 49** Williams, S.N., Schaeffer, S.J., Calvache, M.L. and Lopez, D., 1992, Global carbon dioxide emissions to the atmosphere by volcanoes. *Geochimica et Cosmochimica Acta* 56, 1765-1770.
- 50** Marty, B. and Tolstikhin, I.N., 1998, CO₂ fluxes from mid-ocean ridges, arcs and plumes. *Chemical Geology* 145, 233-248.