Australian Government
Department of Climate Change

HOT TOPICS

# Understanding current climate change over the long term


## Summary

The Earth's temperature has fluctuated naturally over hundreds of millions of years. These past changes can help us understand the relationship between temperature, greenhouse gases and other climate drivers today.

Some of the clearest changes in temperature and atmospheric composition are recorded in ice cores over nearly one million years. The Earth has experienced cycles of ice ages separated by warm periods called interglacial periods approximately every 100,000 years. These are primarily driven by regular 'wobbles' in the Earth's orbit, which affects the amount of solar radiation reaching the Earth. From the onset of interglacial periods, the warming takes about 5000 years to complete. Significant warming begins in the Antarctic and several hundred years later the warming causes the carbon dioxide ($CO_2$) increase, mainly through ocean processes. The Northern Hemisphere deglaciation follows the $CO_2$ increase. Therefore, increases in $CO_2$ contribute an amplification (positive feedback) throughout most of the warming. The ice sheets also cause a feedback. The observed temperature changes and rates of change during the interglacial periods cannot be simulated without the observed changes in $CO_2$ or ice extent.

The past 11,000 years (the Holocene) is marked by much smaller global temperature changes, typically up to 1–1.5°C. Greenhouse gas concentrations were also relatively stable until the large and rapid increases that began about 200 years ago as a result of anthropogenic emissions. The concentration of $CO_2$ is now higher than for at least the past 800,000 years.

Variations in solar irradiance, natural and anthropogenic aerosols and land cover have also influenced climate. Since the Industrial Revolution around 1800, human activities have increased greenhouse gas concentrations. Simulations incorporating all known climate drivers show that most of the observed global warming since the mid-20$^{th}$ century is very likely due to anthropogenic increases in greenhouse gases.


The Earth's climate is determined by the balance of incoming and outgoing radiation. Variations in this balance have changed the climate over millions of years. The balance is affected by: (1) changing the incoming solar radiation (e.g., by changes in the Earth's orbit or in the Sun itself), (2) changing the fraction of solar radiation that is reflected (this fraction is called the albedo – it can be altered, for example, by changes in cloud cover, small particles called aerosols or land cover), and (3) altering the long-wave energy (heat) radiated back to space (e.g., by changes in greenhouse gas concentrations) (IPCC, 2007, FAQ 6.1). For each change in climate, the specific causes must be established individually.

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## The past 500 million years

During most of the past 500 million years, the Earth was warmer than today and probably completely free of ice sheets. While estimates of greenhouse gas concentrations prior to the last million years are rather uncertain, analysis of geological samples suggests that the warm ice-free periods coincide with high atmospheric $CO_2$ levels. On million-year time scales, $CO_2$ levels change due to tectonic activity (volcanic eruptions and movement of continents), which affects the rates of $CO_2$ exchange of ocean and atmosphere with the solid Earth (IPCC, 2007, FAQ 6.1).

$CO_2$ levels of more than 4000 parts per million (ppm) occurred during the Ordovician-Silurian (450 million years ago). There is also evidence of a glacial event occurring during this period. This has been used by some to attempt to disprove the link between temperature and $CO_2$. Royer *et al.*, (2006) considered the $CO_2$ forced climate thresholds over the Phanerozoic eon (the last 545 million years). It was found that there is insufficient proxy data to determine that a high $CO_2$ event coincided with the Ordovician-Silurian glacial event. The only proxy $CO_2$ data near this glacial event could be up to 5 million years younger than the event. Further, the Earth was a very different place during this period including differences in solar luminosity, albedo, distribution of continents and vegetation, orbital parameters and other greenhouse gases.

Atmospheric $CO_2$ concentration and temperature can change rapidly, as demonstrated by a series of events during the early Cenozoic (last 65 million years) known as hyperthermals (Zachos *et al.*, 2008). These were relatively brief intervals (less than a few tens of thousands of years) of extreme global warmth and massive carbon addition, but with widely differing scales of forcing and response. During the most prominent and best-studied hyperthermal, the Paleocene-Eocene thermal maximum (PETM) 55 million years ago, the global temperature increased by more than 5°C in less than 10,000 years (Zachos *et al.*, 2008).

The sources of massive carbon injections during early Cenozoic hyperthermals remain uncertain (Zachos *et al.*, 2008). Carbon might have come from deeply buried rocks, perhaps liberated as methane and $CO_2$ during intrusive volcanism. Alternatively, it could have come from Earth's surface as a positive feedback to initial warming. Below the sea floor methane gas is frozen in the pores of sediment known as hydrates or clathrates. A rise in deep-sea temperature might have triggered the decomposition of clathrates on continental margins, releasing substantial amounts of methane and fuelling additional warming. Another such source is the oxidation of organic matter in terrestrial environments. These warming events show characteristics that are indicative of short-term positive feedbacks, which accelerated and magnified the effects of initial carbon injection before weathering and other negative feedbacks restored the global carbon cycle to a steady state.

The positive feedbacks of greatest concern for understanding overall global warming may be those that could release hundreds to thousands of gigatonnes of carbon after initial warming (Zachos *et al.*, 2008). The large masses of organic carbon stored in soils or sediments of shallow aquatic systems represent a potential carbon input, should regions that were humid become drier. Rapid drying or fire could release carbon from these reservoirs at rates faster than carbon uptake by similar environments elsewhere.

## The past 3 million years

The geological record shows that ice ages have come and gone over the past three million years (IPCC, 2007, FAQ 6.1). Ice core measurements of the past 800,000 years reveal how the atmosphere's composition has changed in unison with these climate changes (for example $CO_2$; figure 2). The glacial (cold) and interglacial (warm) cycles are triggered by the variations in the Earth's orbit around the Sun, called Milankovitch cycles (figure 1). These alter the amount of solar radiation reaching different parts of the Earth, leading to changes in the atmospheric circulation and in the distribution of ice over tens of thousands of years. Many studies suggest that the amount of summer sunshine on northern continents is crucial: if it drops below a critical value, snow from the past winter does not melt away in summer and an ice sheet starts to grow as more and more snow accumulates (IPCC, 2007, FAQ 6.1). The next large reduction in northern summer insolation, similar to those that started past ice ages, is due to begin in 30,000 years (IPCC, 2007, FAQ 6.1).

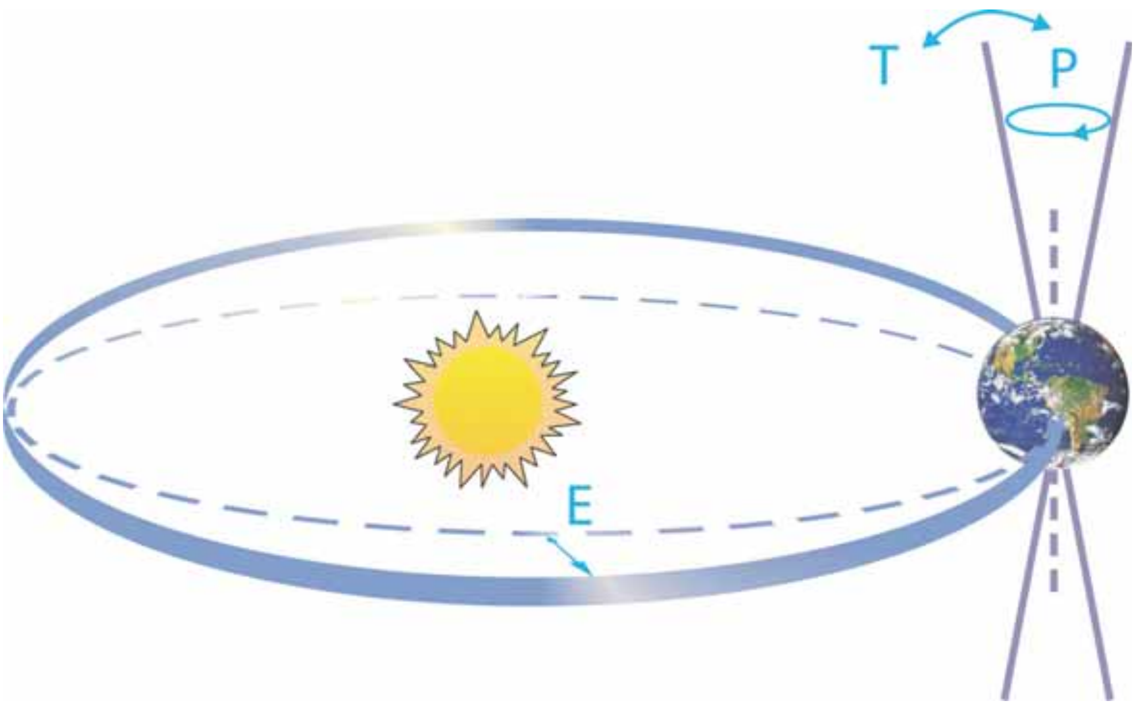


Figure 1: The Milankovitch cycles are composed of the 96,000 year eccentricity (E) cycle (which accounts for the spacing of the past six interglacials), the 40,000–41,000 year obliquity (or tilt T) cycle (which accounts for glacial cycles more than 600,000 years ago) and the 19,000–23,000 year precession (P) cycle (which accounts for temperature swings in the past 150,000 years) (Bryant, 1997; IPCC, 2007, FAQ 6.1).

The variations in solar radiation alone are not large enough to have caused the observed temperature changes, their rate of change or their global extent, particularly during the 100,000 year interglacials. Changes in greenhouse gases, particularly $CO_2$ (figure 2) have played significant amplifying roles (Petit *et al.*, 1999; Shackleton, 2000; Weaver *et al.*, 1998). During glacial periods, the $CO_2$ concentration is low (around 180 parts per million (ppm)), while during inter-glacial periods the concentration is high (up to 300 ppm) (Lüthi *et al.*, 2008). Processes in the atmosphere, in the ocean, in marine sediments and on land, and the dynamics of sea ice and ice sheets must be considered (IPCC, 2007, Box 6.2). On glacial-interglacial time scales, atmospheric $CO_2$ levels are mainly governed by the interplay between ocean circulation, marine biological activity, ocean-sediment interactions, seawater carbonate chemistry and air-sea exchange. A number of hypotheses for the low glacial $CO_2$ concentrations have emerged over the past 20 years (Webb *et al.*, 1997; Broecker and Henderson, 1998; Archer *et al.*, 2000; Sigman and Boyle, 2000; Caillon *et al.*, 2003; Kohfeld *et al.*, 2005; Jouzel *et al.*, 2007; Ahn and Brook, 2008).

For example, Caillon *et al.*, (2003) suggest that when emerging from an ice age, significant warming begins in the Antarctic. It then takes about 800 years for the Antarctic warming to transform into a $CO_2$ increase through ocean processes. The Northern Hemisphere deglaciation follows the $CO_2$ increase. The warming takes about 5000 years to complete. Therefore, increases in $CO_2$ contribute to the latter 4200 years of warming, amplifying the initial warming, i.e. a positive feedback. Ice sheets also cause feedbacks as their surface albedo (reflectivity) is larger than the water or land masses they cover. Methane and nitrous oxide concentrations also change closely in time with the glacial-interglacial periods, contributing further to the positive feedback.

Much attention has been on the rapid methane increases at the end of ice ages, in concert with warming events (possibly destabilising clathrates). Though the methane change is too small to have been the primary cause of the warming, it caused a small positive feedback. Recent evidence from radiocarbon measurements confirm that wetland emissions, not clathrates, were the main cause of the methane increase during the last rapid warming about 12000 years ago (Petrenko *et al.*, 2009).

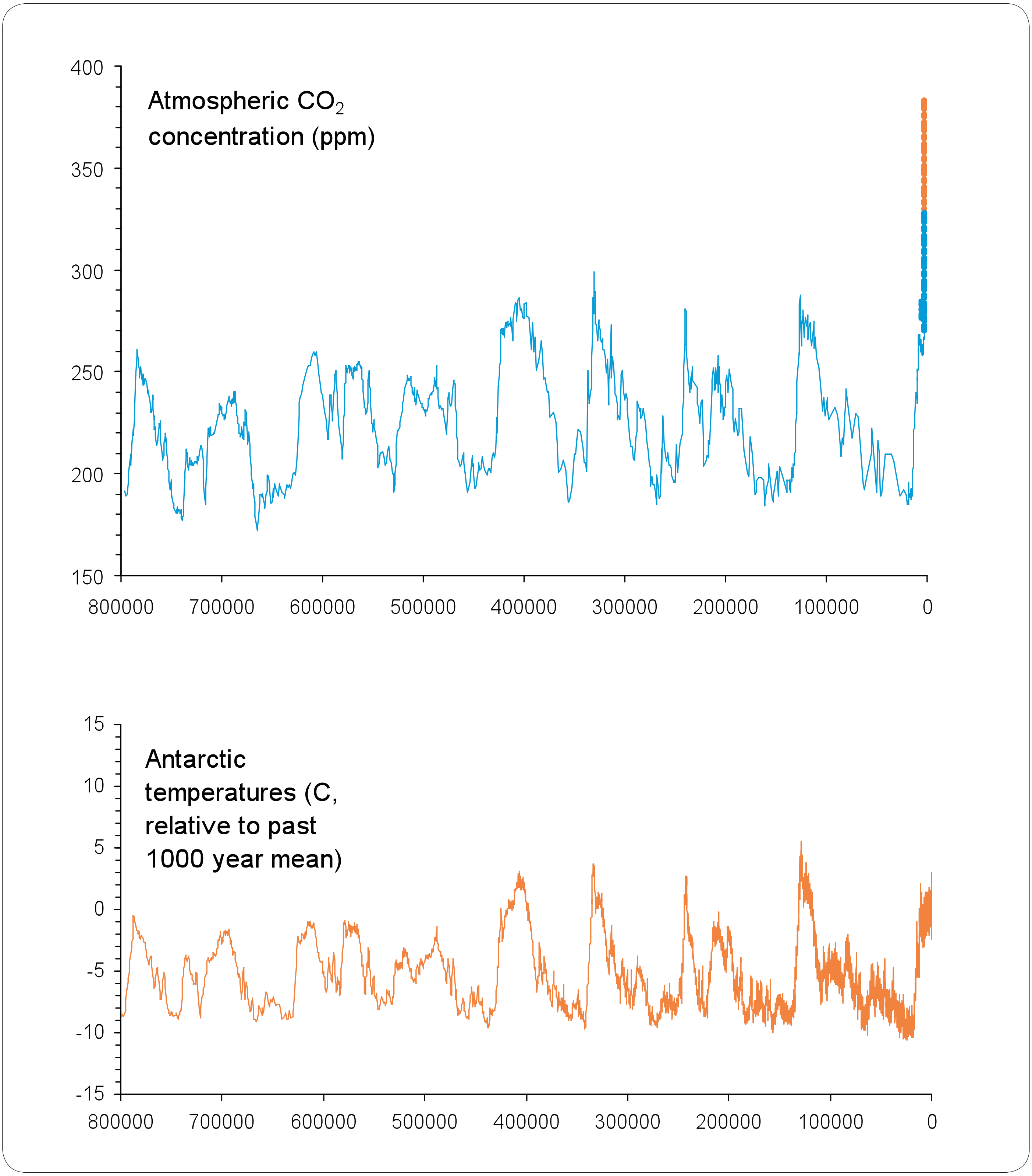


Figure 2: Top: Atmospheric $CO_2$ concentration from ice cores in blue (EPICA Dome C: Luthi *et al*, 2008; Vostok: Petit *et al.*, 1999; Law Dome: Etheridge *et al.*, 1996; MacFarling Meure *et al.*, 2006) and Cape Grim Station, Tasmania in orange (Steele *et al.*, 2007). Bottom: Antarctic temperature variations derived from ice core isotopic proxies (Jouzel *et al.*, 2007). Timescale is years before present (2009) (Source: David Etheridge, CSIRO).

## The past 11,000 years

The past 11,000 years is known as the Holocene Warm Period. It is the current inter-glacial and the time during which modern civilization has emerged. The climate of the Holocene has been relatively stable, with global temperature variations less than 1–1.5°C.

Over the past 2000 years, temperature fluctuations of 1.0–1.5°C have occurred (Bryant, 1997; Moberg *et al*., 2005) as quantified by proxy data from tree rings, ice cores, lake sediments, coral rings, bore holes, etc. which go back more than a thousand years with decreasing spatial coverage for earlier periods. All published reconstructions indicate that Northern Hemisphere (NH) temperatures were warm during medieval times (950–1100 AD), cool in the 17$^{th}$, 18$^{th}$ and 19$^{th}$ centuries, then warmed rapidly (National Research Council, 2006). Average NH temperatures during the second half of the 20$^{th}$ century were very likely higher than during any other 50-year period in the last 500 years and likely the highest in at least the past 1,300 years (National Research Council, 2006; IPCC, 2007, Mann *et al*., 2008, 2009). The linear warming trend over the past 50 years (0.13°C per decade) is much more rapid than the 4°C to 7°C warming between ice ages and warm interglacial periods, which takes about 5000 years, i.e. about 0.01°C per decade.

The changes in climate and $CO_2$ during the Little Ice Age (1500 to 1750 AD) are strongly correlated, with temperature leading $CO_2$ by about 50 years (Scheffer *et al*., 2006). These records indicate a tight relation between $CO_2$ and climate, with a gradient of 40 ppm/°C of global warming. However, given the discrepancies between different temperature reconstructions, and the uncertainties associated with interpreting Northern Hemisphere climate proxies in terms of global mean temperature, Cox and Jones (2008) estimate a gradient of 20 to 60 ppm/°C of global warming.

A remarkable feature of the Holocene is the large and rapid increase in the global concentrations of $CO_2$, methane ($CH_4$) and nitrous oxide ($N_2O$) beginning about 200 years ago (MacFarling Meure *et al*., 2006), to levels not observed for the past 800,000 years or more (see figure 2). The average rate of increase in atmospheric $CO_2$ was at least five times larger over the period from 1960 to 1999 than over any other 40-year period during the two millennia before the industrial era (MacFarling Meure *et al*., 2006). The average rate of increase in atmospheric methane was at least six times larger, and that for nitrous oxide at least two times larger (MacFarling Meure *et al*., 2006). Isotopic analysis of the $CO_2$ and a decline in atmospheric oxygen concentration confirms that the majority of the increase comes from burning fossil fuels (IPCC, 2007, Ch 2).

Simulations by a range of global climate models taking into account all known climate forcings (solar variations, volcanic and anthropogenic aerosols, land cover and greenhouse gases) closely reproduce the observed temperature changes of the past millennium. Simulations without greenhouse gases and aerosols fail to account for the warming over the past century. Most of the warming since the mid-20$^{th}$ century is very likely due to anthropogenic increases in greenhouse gases (IPCC, 2007).[1]

There is no evidence for large clathrate releases to the atmosphere in the Holocene or industrial period (post 1750). Because clathrates are metastable, warming or physical disturbances might destabilise them. Only a relatively small amount of the massive clathrate store would need to be released to cause a large increase in atmospheric concentrations (of $CH_4$ and eventually $CO_2$ as it is oxidised) and subsequent climate warming. Thus clathrate release is proposed as a small likelihood-large outcome risk for the future. But both evidence and modelling suggests that the clathrate store is likely to be stable for a while yet.

## References

Ahn, J. and Brook, E.J. (2008). Atmospheric $CO_2$ and climate on millennial time scales during the last glacial period. *Science*, **322**, 83–85 pp.

Archer, D.A., A. Winguth, D. Lea, and N. Mahowald. (2000). What caused the glacial/interglacial atmospheric $pCO_2$ cycles? *Rev. Geophys.*, **12**, 159–189 pp.

Broecker, W.S. and Henderson, G.M. (1998). The sequence of events surrounding Termination II and their implications for the cause of glacial-interglacial $CO_2$ changes. *Paleoceanography*, **13**, 352–364 pp.

Bryant, E. (1997). *Climate processes and change.* Cambridge University Press, 209 pp.

Caillon, N. Severinghaus, J.P. Jouzel, J., Barnola, J-M., Kang, J. and Lipenkov, V.Y. (2003). Timing of atmospheric $CO_2$ and Antarctic temperature changes across Termination III, *Science* **229**, 1728–1731 pp. DOI: 10.1126/science.1078758

[1] For more information see Hot Topic 'Can the warming of the 20$^{th}$ century be explained by natural variability?' available online at www.climatechange.gov.au

Cox, P. and Jones, C. (2008). Illuminating the modern dance of climate and $CO_2$, *Science*, **321**, 1642–1644 pp.

IPCC (2007). *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. www.ipcc.ch.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., 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., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J.P., Stenni, B., Stocker, T.F., Tison, J.L., Werner, M. and Wolff, E.W. (2007). Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science*, **317**, 793–796 pp.

Kohfeld, K.E., C. LeQuéré, S.P. Harrison. and R.F. Anderson. (2005). Role of marine biology in glacial-interglacial $CO_2$ cycles. *Science*, **308**, 74–78 pp.

Lüthi, D. Le Floch, M. Bereiter, B. Blunier, T. Barnola, J.M. Siegenthaler, U. Raynaud, D. Jouzel, J. Fischer, H. Kawamura, K. and Stocker, T. (2008). High-resolution carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, **453**, doi:10.1038/nature06949.

MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith A. and Elkins J. W. (2006). Law Dome $CO_2$, $CH_4$ and $N_2O$ ice core records extended to 2000 years BP, *Geophysical Research Letters*, **33(14)**, 10.1029/2006GL026152.

Mann, M.E., Bradley, R.S. and Hughes, M.K. (2009). Reply to McIntyre and McKitrick: Proxy-based temperature reconstructions are robust. *PNAS*, www.pnas.org/content/106/6/E11.extract.

Mann, M.E., Zhang, Z., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S. and Ni, F. (2008). Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *PNAS*, **105 (36)**, 13252–13257 pp. www.pnas.org_cgi_doi_10.1073_pnas.0805721105.

Moberg, A., D.M. Sonechkin, K. Holmgren, N.M. Datsenko, and W. Karlen (2005). Highly variable Northern hemisphere temperatures reconstructed from low- and high- resolution proxy data. *Nature*, **433**, 613–617 pp.

National Research Council, Committee on surface temperature reconstructions for the last 2000 years. (2006). Chair: G.R. North. *Surface temperature reconstructions for the last 2000 years*. The National Academies Press, Washington, D.C.

Petit, J. R., and Coauthors, (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, **399**, 429–436 pp.

Petrenko, V.V., Smith, A.M., Brook, E.J., Lowe, D., Riedel, K., Brailsford, G., Hua, Q., Schaefer, H,, Reeh, N., Weiss, R.F., Etheridge, D. and Severinghaus, J.P. (2009). $^{14}CH_4$ measurements in Greenland ice: Investigating last glacial termination $CH_4$ sources. *Science*, **324**, 506–508 pp DOI: 10.1126/science.1168909.

Royer, D. (2006). $CO_2$-forced climate thresholds during the Phanerozoic, *Geochimica et Cosmochimica Acta*, **70**, 5665–5675 pp (available on line at www.sciencedirect.com).

Scheffer, M. Brovkin, V. and Cox, P. (2006). Positive feedback between global warming and $CO_2$ concentration inferred from past climate change, *Geophysical Research Letters*, **33**, L10702

Shackleton, N. J., (2000) The 100,000-year ice-age cycle identif ed and found to lag temperature, carbon dioxide, and orbital eccentricity. *Science*, **289**, 1897–1902 pp.

Sigman, D.M. and E.A. Boyle, (2000). Glacial/interglacial variations in atmospheric carbon dioxide, *Nature*, **407**, 859–869 pp.

Weaver, A.J., M. Eby, A.F. Fanning, and E.C. Wiebe. (1998). Simulated inf uence of carbon dioxide, orbital forcing and ice sheets on the climate of the last glacial maximum. *Nature*, **394**, 847–853 pp.

Webb, R.S., Rind, D.H. Lehman, S.J. Healy, R.J. and Sigman D. (1997). Inf uence of ocean heat transport on the climate of the Last Glacial Maximum, *Nature*, **385**, 695–699 pp.

Zachos, J. Dickens, G. and Zeebe, R. (2008). An early Cenozoic perspective on greenhouse warming and carbon cycle dynamics, *Nature*, **451**, 279–283 pp.

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