Pliocene climate variability: Northern Annular Mode in models and tree-ring data

D.J. Hill[a*], A.Z. Csank[b†], A.M. Dolan[c] and D.J. Lunt[d]

[a] British Geological Survey, Keyworth, Nottingham, UK
[b] Laboratory of Tree-Ring Research, University of Arizona, Tucson, USA.
[c] SGPC, School of Earth and Environment, University of Leeds, UK.
[d] BRIDGE, School of Geographical Sciences, University of Bristol, UK.
[†] Presently at: Environment and Natural Resources Institute, University of Alaska, Anchorage, USA.

* Corresponding author

Email: dahi@bgs.ac.uk
Telephone: +44 113 3431598

Abstract

The Northern Annular Mode (NAM) and its regional expression, the North Atlantic Oscillation (NAO) are the primary interannual oscillatory systems in the Northern Hemisphere. In the modern climate, NAM has been linked with a number of weather extremes, including large terrestrial temperature increases and extreme snowfalls. Its connection to climate is more controversial, although a change in its behaviour between 1970 and 2000 coincided with rapid temperature increases in the Northern Hemisphere. The North Atlantic and Nordic Seas are a key component in Pliocene climate, showing the largest increases from modern sea surface temperature. To understand these changes and the ability of climate models to reproduce them, we must consider simulations of the NAM. Here we show that existing mid-Pliocene simulations exhibit large changes to the mean state and variability in the North Atlantic and a significant dampening of the NAO. Through sensitivity experiments this change is primarily attributed to the impact of the lowering of the Rocky Mountains. As the timing of Rocky Mountains uplift is still disputed, simulations of the North Atlantic region contain significant uncertainty, particularly relating to interannual variability and its climate feedbacks. New high temporal resolution climate proxy data is required to test these model reconstructions. Here we report new annual resolution data and an analysis of climate variability from fossil tree-rings. These fossils, from sites in the Canadian Arctic, provide support for a strong North Atlantic Oscillation during the Pliocene.

Keywords: Pliocene, Northern Annular Mode, Arctic Oscillation, North Atlantic Oscillation, climate model, tree-ring

1. Introduction

Interannual climate variability is dominated by a few persistent atmospheric modes of oscillation. The dominant feature in the Northern Hemisphere is the Northern Annular Mode (NAM) or Arctic Oscillation (AO). This phenomenon is best expressed by the contrasting winter mean sea level pressure (mslp) anomalies over the high Arctic and subpolar regions (Thompson and Wallace, 1998). While the overall shape of the NAM is essentially zonally symmetric (Hurrell and Deser, 2009), regional modification by asymmetric forcings, such as topography and land-ocean temperature contrasts (Thompson et al., 2003; Hurrell and Deser, 2009) promote two main centres of action, over the North Pacific and the North Atlantic (Thompson and Wallace, 1998). In the modern climate, the NAM is most strongly expressed in the North Atlantic Oscillation (NAO), which was first documented by the relative strengths and locations of the Icelandic Low and Azores High pressure systems (Hurrell, 1995). The strength of these systems varies on all timescales in which observations have been compiled, from days to decades (Hurrell and Dickson, 2004).

The coupling between changes in climate and the NAM has yet to be clearly established (e.g. Gladstone et al., 2005). However, the NAM has a well documented impact on climate, particularly at the regional scale (e.g. Hurrell and Dickson, 2004). A general shift towards positive NAM in the 1970s is associated with terrestrial warming over northern Eurasia (Thompson et al. 2000; Rodwell, 2003) and warming in North Atlantic sea surface temperatures (Lozier et al. 2008), while some of the coldest Eurasian winters on record have been partially attributed to the negative phase of the NAM, especially 1962/1963 (Hirschi and Sinha, 2007) and 2009/2010 (Bissolli et al., 2010).

NAM variability could change when examining warm climates in either the past or the future. Increased temperatures will increase the energy in the climate system, potentially impacting weather systems and climate oscillations. The NAM could also respond to changes in the land surface, for example melting ice, mountain uplift or changes in the atmospheric interaction with the land. If the NAM changes significantly then the potential linkages to important climate feedbacks are large. As it primarily impacts the dominant pressure systems in the Northern Hemisphere, changes in the NAM would affect the dominant wind fields and storm tracks. This is particularly important in the North Atlantic region, where the Gulf Stream and North Atlantic Drift system are partially driven by these westerly winds and transport large amounts of heat northwards.

The response of the NAM in models of future climate change seems to be consistent in sign, although variable in magnitude (Rauthe et al., 2004). Some models show a significant shift towards positive NAM, while others show little trend (Miller et al., 2006). Overall, the IPCC multi-model averages show a dampened NAM, with no trend in the observed period, followed by a 1.5hPa trend towards positive values over the 21st century (Meehl et al., 2007). HadCM3, the model used in this study, produces one of the best simulations of NAM when compared to observations and exhibits a sensitivity to future climate change close to the multi-model average (Osborn, 2004). The North Atlantic Oscillation in HadCM3 shows a bias towards the central Atlantic, away from Western Europe. In common with all the other models examined by Osborn (2004), the Pacific expression is stronger than observations, although these are much more limited in the North Pacific.

Previous palaeoclimate applications show very different responses to climate change between models (Gladstone et al., 2005; Lü et al., 2010), although this has only been tested in the colder than modern climates of the Last Glacial Maximum (LGM) and for the small orbital perturbation of the mid-Holocene. As a well studied warm period of the past, the mid-Pliocene (~ 3 million years ago) provides a potentially more relevant test. It is the last period of Earth history with increased atmospheric CO_2 concentrations and global mean temperatures and relatively small changes in the Earth System. However, there are some changes in the palaeoenvironmental boundary conditions, notably orography, ice sheets and vegetation (Lunt et al., 2010), that could complicate NAM response.

Furthermore, fossil trees from around the Arctic (Matthews and Ovenden, 1990; Hill et al., 2007; Csank et al., 2011) provide a potential for unprecedented interannual records of Pliocene climate, which could record the NAM. The annual growth rings of fossil trees and their isotopic composition have been previously used in a number of studies reconstructing past NAM and NAO (Cullen et al., 2001; Cook et al., 2002; D'Arrigo et al. 2003a,b; Welker et al., 2005; Reynolds-Henne et al., 2007; Trouet et al., 2009). With fossils from throughout the Pliocene being located in some of the areas where the NAM is most keenly expressed in the climate, and also in some of the best conditions for preservation, they might be expected to contain an archive of Pliocene NAM and Arctic climate variability. As such they are an ideal candidate for testing the model simulations presented here.

2. Methods

2.1 Model Description

HadCM3, the UK Met Office's coupled atmosphere-ocean General Circulation Model (GCM), was used for each of the model simulations in this study (Gordon et al., 2000). The atmosphere model runs on a global 73 $\times$ 96 grid, giving a horizontal resolution of 2.5° in latitude and 3.75° in longitude, with 19 vertical layers in the atmosphere and a time step of 30 minutes (Pope et al., 2000). It includes a radiation scheme that represents the effects of minor trace gases (Edwards and Slingo, 1996) and a parameterized background aerosol climatology (Cusack et al., 1998). The model uses the convection scheme of Gregory et al. (1997) and the land-surface scheme of Cox et al. (1999). The ocean component is a 1.25° $\times$ 1.25º resolution, 20 level version of the Cox (1984) ocean model. There are six ocean grid boxes for each atmospheric grid box, with ocean-atmosphere coupling every model day. The mixing of tracers is performed by the Visbeck et al. (1997) parameterisation of the horizontal eddy mixing and a hybrid K-Theory scheme and Kraus-Turner mixed layer sub-model (Kraus and Turner, 1967) parameterization of near surface vertical mixing. Modifications are applied in the North Atlantic, to the overflow from the Nordic Seas, and the Mediterranean Sea, where the outflow through the Gibraltar Strait is parameterized (Gordon et al., 2000). The sea-ice model is a simple thermodynamic scheme, with parameterized ice drift and sea-ice leads (Cattle and Crossley, 1995).

2.2 Model Boundary Conditions

This study requires two different sets of model boundary conditions, a pre-industrial and a mid-Pliocene set. Pre-industrial topography (Fig. 1a) and ice-cover (Fig. 1c) are derived from the US Navy data sets (Jasperson et al., 1990) and vegetation from W&HS85 (Wilson and Henderson-Sellers, 1985) land cover scheme. Atmospheric trace gases are set to pre-industrial levels of 280 ppmv of CO_2 and 760 ppbv of methane.

Mid-Pliocene boundary conditions come from the PRISM2 palaeoenvironmental reconstruction (Dowsett et al., 1999). The PRISM (Pliocene Research, Interpretation and Synoptic Mapping) reconstruction represents the mid-Pliocene warm period (also known as the mid-Piacenzian warm period), which lies between the transition of oxygen isotope stages M2/M1 and G21/G20, corresponding to 3.29 – 2.97 Ma on the Berggren et al. (1995) geomagnetic polarity time scale (or 3.264 – 3.025 Ma on the LR04 (Lisiecki and Raymo, 2005) timescale). It includes reconstructions of sea surface temperature, sea-ice (neither of which are used in this coupled ocean-atmosphere model study), topography, ice sheets and vegetation. Atmospheric CO_2 is set to 400 ppmv, as suggested by a number of different proxies (Küschner et al., 1996; Raymo et al., 1996; Pagani et al., 2009; Seki et al., 2010), while all other parameters are kept at pre-industrial values.

While Pliocene topography is largely unchanged from today, the PRISM2 reconstruction includes a 50% reduction in the height of the Rockies, an increase of 500m in the East African rift system (Fig. 1b). PRISM2 ice sheets were based largely on sea-level records, with a 50% reduction in Greenland ice volumes and a 33%

reduction in Antarctic ice (Fig. 1d). Sea level is reconstructed at 25m above modern, based on a number of sea level records, each with significant uncertainty, but with best estimates in agreement (Dowsett and Cronin, 1990; Wardlaw and Quinn, 1991; Kennett and Hodell, 1993 cf. Dwyer and Chandler, 2009; Naish and Wilson, 2009). Vegetation is based on Pliocene data from 74 sites distributed across the globe. Each global land grid point was assigned to one of seven biome classifications, from ice, tundra, coniferous forest, deciduous forest, grassland, rainforest and desert (Fig. 1f). In regions were no Pliocene data was available modern vegetation distribution was used (Thompson and Fleming, 1996).

2.3 Experimental design

This study includes three different experiments, incorporating ten different HadCM3 simulations (Table 1). Firstly, there are two standard simulations, one for the pre-industrial climate, using the standard HadCM3 pre-industrial boundary conditions (PREIND), and one mid-Pliocene simulation (PRISM2), using the PRISM2 boundary conditions (Haywood and Valdes, 2004). Secondly, there is a series of four perturbed pre-industrial simulations, PREIND^{PLIO_VEG}, PREIND^{PLIO_IS}, PREIND^{PLIO_OROG} and PREIND^{PLIO_CO2}. Each of these simulations uses the standard pre-industrial boundary conditions, but with one boundary condition, from vegetation, ice sheets, orography and CO_2, perturbed to its mid-Pliocene state. Similarly, there is a series of four perturbed mid-Pliocene simulations, PLIO^{PREIND_VEG}, PLIO^{PREIND_IS}, PLIO^{PREIND_OROG} and PLIO^{PREIND_CO2}, each with one of the boundary conditions in a pre-industrial state (Table 1).

Each of the perturbed boundary condition simulations was initialised from an existing mid-Pliocene or pre-industrial HadCM3 experiment, which have been running alongside each other for 900 model years, over a number of different high performance computing platforms (Lunt et al., 2008). Each perturbation simulation was then run for a further 200 years using the new boundary conditions, with the final 30 years of the simulation used for climate averaging and analysis. The standard pre-industrial and mid-Pliocene simulations have both been extended by a further 200 years, to allow for a direct comparison with the perturbation simulations.

2.4 NAM analysis

The NAM is defined as the first Empirical Orthogonal Function (EOF) of Northern Hemisphere winter mean sea level pressure (mslp) above 20°N (Thompson and Wallace, 1998). AO indices, generated from Principal Component Analysis (PCA) of mean winter sea level pressure, have been widely used to provide an index of the NAM (Thompson and Wallace, 1998).

The NAO, the Atlantic expression of the NAM, was originally characterised by long atmospheric pressure records from Stykkisholmur, Iceland and Lisbon, Portugal (Hurrell, 1995). From model and reanalysis data a number of different characterisations have been produced for NAO, either from contrasting strengths and locations of the Icelandic Low and Azores High (Paeth et al., 1999) or PCA over the North Atlantic region (Hurrell et al., 2003).

In the Pliocene patterns, strength and variability could have changed from the modern, so it is important that a range of different indices are used to characterise the NAM. In this study we will be using both AO and NAO indices to characterise the variability in the Northern Hemisphere and North Atlantic and EOFs to analyse the spatial distribution of variability. We will also examine changes in the mean state variables.

2.5 Fossil tree-ring analysis

Abundant fossil forest sites of Pliocene age have been identified in Alaska (Matthews and Ovenden, 1990; Matthews et al., 2003), Siberia (Bondarenko, 2007), Greenland (Funder et al. 2001; Bennike et al., 2002), and the Canadian Arctic Archipelago (Matthews and Ovenden, 1990; Ballantyne et al., 2006; Richter et al., 2008; Ballantyne et al., 2010; Csank et al., 2011). A number of these fossil sites are being analysed for palaeoclimatic reconstruction. Here we focus on the well studied Beaver Pond locality, at the head of Strathcona Fiord on Ellesmere Island, Canada (78°N, 82°W). This site has been dated to the Pliocene and is approximately 4-5 million years old.

For ring-width measurements a Bannister Bench system was used to measure the tree-ring widths of our Pliocene samples, which has a precision of ±0.01 mm (Robinson and Evans, 1980). Isotopic studies of tree-rings present some advantages over basic ring width studies of fossil wood, being unaffected by the modern 'divergence problem' among trees at high latitudes (Porter et al., 2009) and non-climatic periodic events, such as insect outbreaks (Kress et al., 2009).

All isotopic samples were processed to α-cellulose using a modified Leavitt-Danzer method (Leavitt and Danzer, 1993). $\delta^{18}O$ analyses were conducted at the Saskatchewan Isotope Laboratory (SIL), University of Saskatchewan, using a Thermo Finnigan TC/EA coupled via a Conflo III interface to a Thermo Finnigan Delta Plus XL mass spectrometer in continuous flow mode and also at the University of Arizona using a Costech HTG EA, modified for oxygen isotope analysis of cellulose (Evans, 2008), directly coupled via a ConFlo III to a Finnigan DeltaPlus XP mass-spectrometer. Cellulose (0.30-0.35 mg) was weighed into silver capsules, pyrolyzed over glassy carbon and reported as values relative to VSMOW. Analytical error was 0.2 ‰, with duplicate samples of each ring showing a precision of 0.5 ‰. Corresponding analytical precision for repeat analyses of an internal cellulose standard was 0.3 - 0.4‰.

In order to investigate whether the fossil wood data contains any periodic or quasi-periodic frequencies that match modes of climate variability, such as the NAM, a spectral analysis has been performed. The Multi Taper Method (MTM), which provides a spectral estimation of 'noisy' time series (Thomson, 1982; Percival and Walden, 1993), has been used. MTM is nonparametric and reduces the variance of spectral estimates by using a small set of tapers rather than the prescribed frequency bands used by other methods.

3. Previous mid-Pliocene climate simulations

The mid-Pliocene has been simulated many times using a number of GCMs (e.g. Chandler et al., 1994; Sloan et al., 1996; Haywood et al., 2000; Haywood et al., 2002a; Haywood et al., 2002b; Haywood and Valdes, 2004; Haywood et al., 2008; Lunt et al., 2010). These simulations have consistently shown a number of key features of the mid-Pliocene climate. Global mean temperatures are estimated to have been 2.5 - 3.5°C warmer than pre-industrial, with a significantly reduced equator-pole temperature gradient. Concurrently global precipitation increases, whereas the overall cloud fraction decreases (Chandler et al., 1994; Haywood et al., 2000). The palaeoenvironmental information with which to evaluate atmospheric conditions in the mid-Pliocene is sparse, but the available, largely palynological, data supports the general trends of mid-Pliocene GCM simulations (Salzmann et al., 2008).

Recently, the coupled ocean-atmosphere GCM, HadCM3, has been used to simulate mid-Pliocene climate (Haywood and Valdes, 2004, Lunt et al., 2008; Lunt et al., 2010). This model simulates the state of the ocean, rather than specifying sea surface temperatures (SSTs) as an atmospheric boundary condition, allowing for the evaluation of simulations against ocean temperature reconstructions of the PRISM group (Dowsett et al., 1999; Dowsett et al., 2010; Dowsett et al., this issue). The PRISM reconstructions show warming across the world's oceans, but especially at high-latitudes of the North Atlantic. Although there is general agreement between global patterns in the PRISM data and models, HadCM3 fails to reproduce the large SST increases in the North Atlantic (Haywood and Valdes, 2004). This comparison is dealt with in much greater detail, using the new PRISM3D SST reconstruction, in Dowsett et al. (this issue).

It has often been suggested that increased northward heat transport in the North Atlantic was one of the main drivers of mid-Pliocene warmth (Rind and Chandler, 1991; Dowsett et al., 1992; Raymo et al., 1996; Williams et al., 2009). Long-standing evidence for this comes from reconstructions of large increases in North Atlantic SSTs (Dowsett et al., 1992; Robinson et al., 2009) and reductions in Arctic sea-ice cover (Cronin et al., 1993; Dowsett et al., 1999). New reconstructions of mid-Pliocene deep water temperatures suggest little change in ocean circulation (Dowsett et al. 2009), although small increases in temperature could be due to an increase in North Atlantic Deep Water formation and North Atlantic Meridional Overturning Circulation (MOC). Conversely, HadCM3 simulations show a slight decrease in North Atlantic MOC (Haywood and Valdes, 2004). This suggests that inaccuracies in the simulation of ocean circulation could be responsible for model-data SST differences in the North Atlantic, although this may reflect uncertainties in the boundary conditions rather than problems with the model physics (Robinson et al., this issue).

4. Climates of perturbed boundary condition experiments

The contributions of various components of mid-Pliocene warmth in HadCM3 simulations have already been investigated (Haywood and Valdes, 2004; Haywood et al., 2009; Bonham et al., 2009; Lunt et al., 2009). This study includes a new set of simulations, looking at the impact of individual boundary condition changes on the mid-Pliocene and pre-industrial climate. Table 1 shows the impact of the various boundary conditions on the key differences between the mid-Pliocene and pre-industrial atmospheres, while Table 2 shows the impact on the modelled oceans.

The largest driver of global warming in the mid-Pliocene is CO_2, with vegetation and orography also playing an important role. All of the boundary condition changes play a role in the decreased equator to pole temperature gradient, with CO_2 and orography particularly important. Reducing the altitude of the Rocky Mountains reduces northward heat transport into the Arctic, primarily in the oceans, but also in the atmosphere. This makes the orographic changes the largest contributor to reduced equator to pole temperature gradients in the mid-Pliocene. The role of vegetation in the reduced gradients seems to change depending on whether you start in a mid-Pliocene or pre-industrial state. In the mid-Pliocene, changing to pre-industrial vegetation seems to have little impact, whereas in the pre-industrial, changing to mid-Pliocene vegetation decreases the equator to pole temperature gradient by more than 1.5°C. CO_2, orography and vegetation play an important role in changes to global precipitation, with CO_2 producing the largest effect. CO_2 and orography also dominate the overall decreases in cloud coverage, with mid-Pliocene vegetation and ice sheet changes introducing small increases in cloud coverage.

In the key oceanic parameters CO_2 always produces the largest effect, with orographic changes also playing an important role, especially in the Northern Hemisphere sea-ice and ocean currents. The northward surface currents in the North Atlantic seem to be particularly sensitive to boundary condition changes, with individual parameters able to more than double standard 4.4% mid-Pliocene reductions or produce a mid-Pliocene increase in northward surface currents of 1-2%.

Increased North Atlantic MOC is implied by some records of ocean temperatures (Dowsett et al., 1992; Dowsett et al., 2009) and has often been suggested as a mechanism for warming the mid-Pliocene (Dowsett et al., 1992; Raymo et al., 1996; Dowsett et al., 2010). Standard HadCM3 simulations, using the PRISM2 boundary conditions, fail to reproduce this increase. However, the high sensitivity to the boundary conditions suggests that this result may not be robust to new palaeoenvironmental data and reconstructions. The simulations presented here show that Rocky Mountains orography, the vegetation reconstruction or possibly higher atmospheric greenhouse gases, could introduce increases in North Atlantic MOC.

5. NAM in standard mid-Pliocene simulations

Overall Northern Hemisphere variability changes little between standard pre-industrial and mid-Pliocene simulations, as can be seen in standardized AO indices (Fig. 2a). However, significant changes in the simulation of the Icelandic Low can be seen in our model and have been noted in previous models of the mid-Pliocene climate (Chandler et al., 1994; Haywood et al., 2000; Haywood et al., 2008). In these cases the Icelandic Low is noted to significantly increase in strength, which is reminiscent of positive phases of the NAO.

NAO indexes (Fig. 2b) show that the North Atlantic variability in the mid-Pliocene is much reduced compared to modern. This large change in North Atlantic variability can be largely attributed to a change in the mean state of the Icelandic Low, which is persistently strong in the mid-Pliocene winter (Fig. 2c). Due to the strength and persistence of this low pressure system any interannual variability in the North Atlantic is significantly dampened. EOFs show that, while Northern Hemisphere variability has remained largely constant, the main centre of NAM variability has shifted from the North Atlantic in the pre-industrial climate simulation to the North Pacific in the mid-Pliocene standard simulation (Fig. 3).

6. Causes of NAM changes

By performing a series of simulations perturbing single boundary conditions from either the pre-industrial or mid-Pliocene climate state, the cause of the significant changes in the North Atlantic region can be assessed. Fig. 4 shows the consequence of perturbing each of these parameters on the winter mslp.

Despite small changes in the Azores High, the primary differences in mslp, which ultimately manifest as changes in NAO, occur in the Icelandic Low pressure system. Causes of the modelled changes in the Icelandic Low appear to be relatively linear, with individual component changes accounting for up to 95% of the overall changes between the mid-Pliocene and pre-industrial. Vegetation seems to have very little impact, widening the differences by up to 2%. Smaller ice sheets explain at most 5% of the mslp changes. Atmospheric carbon dioxide makes a significant contribution to the changes in the Icelandic Low, accounting for up to 16% of the differences in the mid-Pliocene. However, up to 75% of the changes in North Atlantic pressure systems can be attributed to differences in the mid-Pliocene and pre-industrial orography (Fig. 4).

Changes in the Rocky Mountains, either from the simulation of past changes in altitude or differences in the way they are represented within climate models, have long been shown to introduce changes to the North Atlantic region (Bolin, 1950; Rind and Chandler, 1991; Gregory et al., 1998; Kitoh, 2002). The pattern of global atmospheric stationary waves, and therefore the persistent pressure systems, is largely driven by variations in the land surface altitude (Bolin, 1950). The atmospheric turbulence, caused as the prevailing westerlies move over the Rocky Mountains, acts as a driver of storm generation over the North American great plains and through to the Atlantic (Tucker and Crook, 1999; Haywood et al., 2008). The Rocky Mountains also act as a barrier to the normal operation of the Ferrel Cell, causing both a physical and thermal deflection of the zonally symmetric mid-latitude wind pattern and impacting northward heat transport in the Atlantic (Ringler and Cook, 1998; Brayshaw et al., 2009). Additionally, previous studies have suggested that the topography of the Rockies is the primary mechanism by which the annular structure of the NAM is modified to form the strong Atlantic expression defined as the

NAO (Thompson et al., 2003). Thus variations in topography are key for understanding changes in the processes that give rise to the NAO.

The halving of the height of the mid-Pliocene Rocky Mountains causes the mean state of the winter Icelandic Low to decrease in pressure by 8.1 mBar. Even with the rest of the simulation being in the pre-industrial state, changing the orography would cause winter mslp to fall by 7.5 mBar. This has major implications for the use of any palaeoclimate with changes in the Rocky Mountains orography as a potential analogue for future climate change. As the North Atlantic is a key region in the global climate, any factor which introduces significant biases to climate change estimates here, which won't be replicated under future scenarios, could adversely impact global estimates.

7. PRISM3D Rocky Mountains reconstruction

There are significant uncertainties in the rates and timing of Rocky Mountain uplift. The PRISM2 orographic reconstruction, which shows a 50% reduction in mid-Pliocene Rocky Mountains altitudes (Dowsett et al., 1999), was based on data suggesting significant uplift over the last 3 million years (Fleming, 1994; Huber, 1981; Winograd et al., 1985). A recent update to the orographic reconstruction used in PRISM2 is now available as part of the PRISM3D boundary condition data set (Markwick, 2007; Sohl et al., 2009; Haywood et al. 2010), available from the U.S. Geological Survey. This change is based on recent studies showing little change in the Rocky Mountains since well before the Pliocene (McMillan et al., 2006; Moucha et al., 2008).

This suggests that the mid-Pliocene simulation with pre-industrial orography may be a better representation of the true mid-Pliocene climate and that the large changes observed in previous simulations of the North Atlantic may not persist in simulations using the PRISM3D boundary conditions (Haywood et al., 2010). However, proxy records of climate variability from Pliocene fossil tree-ring records provide the opportunity to test the simulations of NAM and potentially evaluate the changes in the reconstructions of the mid-Pliocene Rocky Mountains.

8. NAM in Pliocene tree-ring records

Interannual variability is difficult to quantify from Pliocene palaeoclimate proxy records and, as a primarily atmospheric phenomenon, high resolution terrestrial records are required to test model simulations of the NAM. Although any such dataset will provide at best sparse coverage, because of the rare preservation of such features in the geological record, a few well preserved proxy records in key locations could provide sufficient data to distinguish between the large signals simulated in these models.

Recent studies of isotopic data derived from tree-rings have demonstrated good correlation with indexes of both the AO (Welker et al., 2005) and the NAO (Reynolds-Henne et al., 2007). The basis for the climate dependence of $\delta^{18}O$ in tree-rings is the temperature-dependant fractionation process during evaporation and condensation that takes place in the hydrologic cycle. The oxygen isotope ratio of tree-ring cellulose depends mainly on the isotopic composition of the water used during cellulose synthesis, albeit with a humidity signal superimposed (Edwards and Fritz, 1986; Reynolds-Henne et al., 2007). Temperature exerts the strongest influence on the isotopic value of precipitation, but moisture source and moisture recycling within clouds also play an important role (Craig and Gordon, 1965; Kohn and Welker, 2005; Vachon et al., 2010). Thus, because tree rings integrate the climatic conditions, they are excellent recorders of large scale atmospheric modes. Several studies have exploited this fact to extend climatic indices well beyond the instrumental period (MacDonald and Case, 2005; D'Arrigo et al., 2003a; Trouet et al., 2009).

MTM spectral analysis of tree-ring and isotope records from the Pliocene Ellesmere Island specimens reveals statistically significant (above the 95% confidence limit for a red-noise spectra of an AR(1) (auto-regressive) model) oscillations in the 8 year, 5.5 year and 3-4 year frequency bands (Fig. 5). These spectral features coincide with the primary periodicities of modern NAO (Hurrell et al., 2003) and a 600 year NAO proxy reconstruction, where the greatest power was at a frequency of 3.9 years (Cook et al., 2002). Although the NAM / AO, which remains strong in all the mid-Pliocene models, also operates over some of the same frequencies, the power shown in tree-ring records at 5.5 years and 8 years (as opposed to a broad peak over 8-10 year periodicities) suggests that at least some of the signal is coming from the North Atlantic. Overall, the tree-ring data from Ellesmere Island suggest the presence of a strong NAO during the Pliocene and seem to support the use of mid-Pliocene orographic reconstructions with high Rocky Mountains within climate models.

9. Discussion

9.1 Pliocene NAM

Annular modes, in both the Northern and Southern Hemispheres, are key components of global interannual variability and the primary atmospheric oscillations at high latitudes. While they are essentially a permanent feature of the climate, due to the structure of the atmosphere and rotation of the Earth, their oscillation frequencies and mean state will change according to the forcing provided by the land surface and properties of the atmosphere (Thompson et al., 2003). Previous climate models of the mid-Pliocene seem to be an example of this. While overall the oscillation is largely unaffected by the changes in atmospheric CO_2, ice sheets, orography and vegetation, significant changes occur in the NAM centres of activity. This is particularly true of the mean pressure systems in the North Atlantic and the NAO, which in modern climates is the primary expression of the NAM. In mid-Pliocene simulations using the PRISM2 boundary conditions the NAO is severely dampened and the main NAM centre of action moves to the North Pacific.

Through a series of sensitivity experiments it has been shown that these changes are largely driven by the differences between the modern Rocky Mountains and the PRISM2 reconstruction. Since there are significant uncertainties in this reconstruction (e.g. McMillan et al., 2006; Moucha et al., 2008) and the sensitivity of NAM to relatively small changes in the Rocky Mountains is unknown, large uncertainties must remain in Northern Hemisphere, and particularly North Atlantic, atmospheric variability during the mid-Pliocene. As this region is key to our understanding of mid-Pliocene warmth (Dowsett et al., 1992; Raymo et al., 1996;

Robinson, 2009) a characterisation of the state of the NAM and potential climate feedbacks would be a significant advancement and could provide important insights into the mechanisms of mid-Pliocene warming. The introduction of the PRISM3D orographic reconstruction (Sohl, 2009) in the PlioMIP experiments (Haywood et al., 2010) may remove many of these problems, although sensitivity studies are required to show this.

9.2 Consequences for palaeoclimate studies

Changes in model boundary conditions, applicable to all periods of the geological past, can have a large effect on the operation of the climate. Even changes in a single boundary condition can have a large impact on climate as a whole or any of its component phenomena. This shows that in order to accurately simulate palaeoclimates a full integration of changes in model boundary conditions is required. In the mid-Pliocene, one of the most important boundary condition changes is the reconstruction of the Rocky Mountains. There are significant uncertainties associated with the timing of Rocky Mountain uplift (Huber, 1981; McMillan et al., 2006) and different reconstructions fundamentally change the Northern Hemisphere climate variability, especially in the North Atlantic and North Pacific regions. This is only one example of how changes in the Earth System can have large effects on the climate of the past (see also Robinson et al., this issue) and such changes will become much more prevalent as older time periods in the geological record are studied.

The mid-Pliocene is increasingly being used to test both climate models (Haywood et al., 2010; Dowsett et al., this issue) and the fundamental sensitivity of the climate to changes in atmospheric CO_2 (Lunt et al., 2010; Pagani et al., 2010). Without assessing the impact of changes in the Earth System, both on the mean states and variability of the climate, a thorough understanding of the mid-Pliocene warm period cannot be obtained. This is essential, if this period of Earth history is to be used to improve of understanding of climate operation under warmer than modern temperatures and as a time period for the estimation of Earth System Sensitivity.

10. Conclusions

Previous mid-Pliocene climate model simulations include large changes to the operation of NAM and particularly its primary regional expression NAO. Sensitivity experiments show that these changes are largely due to the lowering of the Rocky Mountains in the PRISM2 palaeoenvironmental reconstruction. There is significant uncertainty in this reconstruction and the latest version of the dataset, PRISM3D, introduces modern Rocky Mountains orography. Therefore, existing mid-Pliocene climate models probably include systematic biases, particularly in North Atlantic climate variability. Initial proxy records from Pliocene fossil tree-ring analysis suggests that the expression of NAO is still strong in the Atlantic sector of the Canadian Arctic and support mid-Pliocene simulations of NAM with modern Rocky Mountains orography.

Acknowledgements

This work was undertaken as part of the Climate Change programme at British Geological Survey and the Sellwood Group for Palaeoclimatology at the School of Earth and Environment, University of Leeds. We thank Harry Dowsett and the PRISM group at the US Geological Survey for the use of PRISM2 mid-Pliocene palaeoenvironmental reconstruction. Two anonymous reviewers are acknowledged for suggesting significant improvements to the paper.

References

Ballantyne, A., Rybczynski, N., Baker, P., Harington, C.R., White, D. 2006. Pliocene Arctic temperature constraints from the growth rings and isotopic composition of fossil larch. Palaeogeography, Palaeoclimatology, Palaeoecology 242, 188-200.

Ballantyne, A.P., Greenwood, D.R., Sinnighe Damasté, J.S., Csank, A.Z., Eberle, J.J., Rybczynski, N., 2010. Significantly warmer Arctic surface temperatures during the Pliocene indicated by multiple independent proxies. Geology 38, 603-606.

Bennike, O., Abrahamsen, N., Bak, M., Israelson, C., Konradi, P., Matthiessen, J., and Witkowski, A., 2002. A multi-proxy study of Pliocene sediments from Île de France, North-East Greenland. Palaeogeography, Palaeoclimatology, Palaeoecology 186, 1-23.

Berggren, W.A., Kent, D.V., Swisher, C.C. and Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In (eds.) Berggren, W.A., Kent, D.V., Aubry, M.-P. and Hardenbol, J., Geochronology, time scales and global stratigraphic correlation. Tulsa Society for Sedimentary Geology, Special Publication 54, 129-212.

Bissolli, P., Cassou, C., Chen, L., Kiktev, D., Kryjov, V., Pattanaik, D.R., Schneider, M. and Vinit, F., 2010. Assessment of the observed extreme conditions during the 2009/2010 boreal winter. World Climate Data and Monitoring Programme (WCDMP) series, World Meteorological Organization, WMO/TD-No. 1550, pp. 12.

Bolin, B., 1950. On the influence of the Earth's orography on the general character of the westerlies. Tellus 2, 184-195.

Bondarenko, O.V., 2007. Pliocene wood of Larix from Southern Primorye (Russian far east). Paleontological Journal 41, 1054-1062.

Bonham, S.G., Haywood, A.M., Lunt, D.J., Collins, M. and Salzmann, U., 2009. El Niño-Southern Oscillation, Pliocene climate and equifinality. Philosophical Transactions of the Royal Society A 367, 127-156.

Brayshaw, D.J., Hoskins, B. and Blackburn, M., 2009. The basic ingredients of the North Atlantic Storm Track. Part I: Land-Sea contrast and orography. Journal of the Atmospheric Sciences 66, 2539-2558.

Cattle, H. and Crossley, J. 1995. Modelling Arctic climate change. Philosophical Transactions of the Royal Society London A 352, 201-213.

Chandler, M., Rind, D. and Thompson, R., 1994. Joint investigations of the middle Pliocene climate II: GISS CGM Northern Hemisphere results. Global and Planetary Change 9, 197-219.

Cook, E.R., D’Arrigo, R.D. and Mann, M.E., 2002. A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation index since A.D. 1400. Journal of Climate 15, 1754-1764.

Cox, M.D., 1984. A primitive equation, 3 dimensional model of the ocean. GFDL Ocean Group Technical Report 1, Princeton NJ, USA, 143 pp.

Cox, P., Betts, R., Bunton, C., Essery, R., Rowntree, P.R. and Smith, J., 1999. The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. Climate Dynamics 15, 183-203.

Craig, H., and Gordon, L.I., 1965. Deuterium and oxygen 18 variations in the ocean and marine atmosphere. In: Tongiorgi, E. (ed.) Stable Isotopes in Oceanographic Studies and Paleotemperatures, Naz. Ric., Lab. Geol. Nucl., Pisa (1965), pp. 9–72.

Cronin, T.M., Whatley, R., Wood, A., Tsukagoshi, A., Ikeya, N., Brouwers, E.M. and Briggs, W.M., 1993. Microfaunal evidence for elevated Pliocene temperatures in the Arctic-Ocean. Paleoceanography 8, 161-173.

Csank, A.Z., Tripati, A., Patterson, W.P., Eagle, R.A., Rybczynski, N., Ballantyne, A.P. and Eiler, J., 2011. Estimates of Arctic land surface temperatures during the early Pliocene from two novel proxies. Earth and Planetary Science Letters, doi:10.1016/j.epsl.2011.02.030.

Cullen, H., D’Arrigo, R., Cook, E. and Mann, M.E., 2001. Multiproxy-based reconstructions of the North Atlantic Oscillation over the past three centuries. Paleoceanography 15, 27-39.

Cusack, S., Slingo, A., Edwards, J.M. and Wild, M., 1998. The radiative impact of a simple aerosol climatology on the Hadley Centre climate model. Quarterly Journal of the Royal Meteorological Society 124, 2517-2526.

D'Arrigo, R., Buckley, B. and Kaplan, S., 2003a. Interannual to multidecadal modes of variability in northern Labrador tree rings spanning the past four centuries. Climate Dynamics 20, 219-228.

D'Arrigo, R., Cook, E., Mann, M. and Jacoby, G., 2003b. Tree-ring reconstruction of the temperature and sea-level variability associated with the warm season Arctic Oscillation since AD 1650. Geophysical Research Letters 30, 1549.

Dowsett, H.J. and Cronin M.A., 1990. High eustatic sea-level during the Middle Pliocene – evidence from the Southeastern United-States Atlantic Coastal-Plain. Geology 18, 435-438.

Dowsett, H.J., Cronin, T.M., Poore, R.Z., Thompson, R.S., Whatley, R.C. and Wood, A.M., 1992. Micropaleontological evidence for increased meridional heat transport in the North Atlantic Ocean during the Pliocene. Science 258, 1133-1135.

Dowsett, H.J., Barron, J.A., Poore, R.Z., Thompson, R.S., Cronin, T.M., Ishman, S.E. and Willard, D.A., 1999. Middle Pliocene palaeoenvironmental reconstruction: PRISM2. US Geological Survey Open File Report, 99-535, see http://pubs.usgs.gov/openfile/of99-535.

Dowsett, H.J., Robinson, M.M. and Foley, K.M., 2009. Pliocene three-dimensional global ocean temperature reconstruction. Climate of the Past 5, 769-783.

Dowsett, H.J., Robinson, M.M., Haywood, A.M., Salzmann, U., Hill, D., Sohl, L., Chandler, M., Williams, M., Foley, K., Stoll, D.K., 2010. The PRISM3D paleoenvironmental reconstruction. Stratigraphy 7, 123-139.

Dowsett, H.J., Haywood, A.M., Valdes, P.J., Robinson, M.M., Lunt, D.J., Hill, D.J., Stoll, D.K. and Foley, K.M., this issue. Sea surface temperatures of the mid-Piacenzian Warm Period: A comparison of PRISM3 and HadCM3.

Dwyer, G.S. and Chandler, M.A., 2009. Mid-Pliocene sea level and continental ice volume based on coupled benthic Mg/Ca palaeotemperatures and oxygen isotopes. Philosophical Transactions of the Royal Society London A 367, 157-168

Edwards, J.M. and Slingo, A., 1996. Studies with a flexible new radiation code. I: choosing a configuration for a large-scale model. Quarterly Journal of the Royal Meteorological Society 122, 689-719.

Edwards, T.W.D. and Fritz, P., 1986. Assessing meteoric water composition and relative humidity from ^{18}O and ^{2}H in wood cellulose: paleoclimatic implications for southern Ontario, Canada. Applied Geochemistry 1, 715-723.

Evans, M.N., 2008. A reactor for high temperature pyrolysis and oxygen isotopic analysis of cellulose via induction heating. Rapid Communications in Mass Spectrometry 22, 2211-2219.

Fleming, R.F., 1994. Cretaceous pollen in Pliocene rocks: implications for Pliocene climate in the southwestern United States. Geology 22, 787-790.

Funder, S., Bennike, O., Böcher, J., Israelson, C., Petersen, K.S., and Símonarson, L.A., 2001. Late Pliocene Greenland – the Kap København formation in North Greenland. Bulletin of the Geological Society of Denmark 48, 117-134.

Gladstone, R.M., Ross, I., Valdes, P.J., Abe-Ouchi, A., Braconnot, P., Brewer, S., Kageyama, M., Kitoh, A., Legrande, A., Marti, O., Ohgaito, R., Otto-Bliesner, B., and Vettoretti, G., 2005. Mid-Holocene NAO: a PMIP2 model intercomparison Geophysical Research Letters 32, L16707.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B. and Wood, R.A., 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16, 147-168.

Gregory, D., Kershaw, R. and Inness, P.M., 1997. Parametrisation of momentum transport by convection II: tests in single column and general circulation models. Quarterly Journal of the Royal Meteorological Society 123, 1153-1183.

Gregory, D., Shutts, G.J. and Mitchell, J.R., 1998. A new gravity-wave-drag scheme incorporating anisotropic orography and low-level wave breaking: Impact upon the climate of the UK Meteorological Office Unified Model. Quarterly Journal of the Royal Meteorological Society 124, 463-493.

Haywood, A.M., Valdes, P.J. and Sellwood, B.W., 2000. Global scale palaeoclimate reconstruction of the middle Pliocene climate using the UKMO GCM: initial results. Global and Planetary Change 25, 239-256.

Haywood, A.M., Valdes, P.J., Sellwood, B.W. and Kaplan, J.O., 2002a. Antarctic climate during the middle Pliocene: model sensitivity to ice sheet variation. Palaeogeography, Palaeoclimatology, Palaeoecology 182, 93-115.

Haywood, A.M., Valdes, P.J. and Sellwood, B.W., 2002b. Magnitude of climate variability during middle Pliocene warmth: a palaeoclimate modelling study. Palaeogeography, Palaeoclimatology, Palaeoecology 188, 1-24.

Haywood, A.M. and Valdes, P.J., 2004. Modelling Pliocene warmth: contribution of atmosphere, oceans and cryosphere. Earth and Planetary Science Letters 218, 363-377.

Haywood, A.M., Chandler, M.A., Valdes, P.J., Salzmann, U., Lunt, D.J. and Dowsett, H.J., 2008. Comparison of mid-Pliocene climate predictions produced by the HadAM3 and GCMAM3 General Circulation Models. Global and Planetary Change 66, 208-224.

Haywood, A.M., Dowsett, H.J., Valdes, P.J., Lunt, D.J., Francis, J.E. and Sellwood, B.W., 2009. Introduction. Pliocene climate, processes and problems. Philosophical Transactions of the Royal Scoiety A 367, 3-17.

Haywood, A.M., Dowsett, H.J., Otto-Bliesner, B., Chandler, M., Dolan, A., Hill, D.J., Lunt, D.J., Robinson, M.M., Rosenbloom, N., Salzmann, U., Sohl, L.E., 2010. Pliocene Model Intercomparison Project (PlioMIP): Experimental Design & Boundary Conditions (Experiment 1). Geoscientific Model Development 3, 227-242.

Hill, D.J., Haywood, A.M., Hindmarsh, R.C.A. and Valdes, P.J., 2007. Characterizing ice sheets during the Pliocene: evidence from data and models. In Williams, M., Haywood, A.M., Gregory, F.J. and Schmidt, D.N. (eds.) Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies, The Micropalaeontological Society, Special Publications. The Geological Society, London, 517-538.

Hirschi, J.J.-M. and Sinha, B., 2007. Negative NAO and cold Eurasian winters: How exceptional was the winter of 1962/1963? Weather 62, 43-48.

Huber, N.K., 1981. Amount and timing of late Cenozoic uplift and tilt of the central Sierra Nevada, California – evidence from the upper San Joaquin River Basin. U.S. Geological Survey Professional Paper 1197, 28 pp.

Hurrell, J.W., 1995. Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation. Science 269, 676-679.

Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M., 2003. An overview of the North Atlantic Oscillation. In: The North Atlantic Oscillation: Climatic

Significance and Environmental Impact, Hurrell, J.W., Kushnir, Y., Ottersen, G., and Visbeck, M. (eds.) Geophysical Monograph Series 134, 1-35.

Hurrell, J.W. and Dickson, R.R., 2004. Climate variability over the North Atlantic. Marine Ecosystems and Climate Variation – the North Atlantic, Stenseth, N.C., Ottersen, G., Hurrell, J.W. and Belgrano, A. (eds.) Oxford University Press, 15-32.

Hurrell, J.W. and Deser, C., 2009. North Atlantic climate variability: The role of the North Atlantic Oscillation. Journal of Marine Systems 78, 28-41.

Jasperson, W.H., Nastrom, G.D and Fritts, D.C., 1990. Further study of terrain effects on the mesoscale spectrum of atmospheric motions. Journal of Atmospheric Science 47, 979-987.

Kennett, J.P. and Hodell, D.A., 1993. Evidence for relative climatic stability of Antarctica during the Early Pliocene: a marine perspective. Geografiska Annaler 75, 205-220.

Kitoh, A., 2002. Effects of large-scale mountains on surface climate – a coupled ocean-atmosphere General Circulation Model study. Journal of the Meteorological Society of Japan 5, 1165-1181.

Kohn, M., and Welker, J.M., 2005. On the temperature correlation of $\delta^{18}O$ in modern precipitation. Earth and Planetary Sciences Letters 231, 87-96.

Kraus, E.B. and Turner, J.S., 1967. A one dimensional model of the seasonal thermocline II. The general theory and its consequences. Tellus 19, 98-105.

Kress, A., Saurer, M., Buntgen, U., Treydte, K.S., Bugmann, H., and Siegwolf, R.T.W., 2009. Summer temperature dependency of larch budmoth outbreaks revealed by Alpine tree-ring isotope chronologies. Oecologia 160, 353-365.

Kürschner, W.M, Van der Burgh, J., Visscher, H. and Dilcher, D.L., 1996. Oak leaves as biosensors of late Neogene and early Pleistocene paleoatmospheric CO2 concentrations. Marine Micropaleontology 27, 299-312.

Leavitt, S.W. and Danzer, S.R., 1993. A method for the batch processing of small wood samples to holocellulose for stable carbon isotope analysis. Annals of Chemistry 65, 87-89.

Lisiecki, L.E. and Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography 20, PA1003.

Lozier, M.S., Leadbetter, S., Williams, R.G., Roussenov, V., Reed, M.S.C. and Moore, N.J., 2008. The spatial pattern and mechanisms of heat-content change in the North Atlantic. Science 319, 800-803.

Lü, J.-M., Kim, S.-J., Abe-Ouchi, A., Yu, Y., Ohgaito, R., 2010: Arctic Oscillation during the Mid-Holocene and Last Glacial Maximum from PMIP2 Coupled Model Simulations. Journal of Climate 23, 3792–3813.

Lunt, D.J., Foster, G.L., Haywood, A.M., Stone, E.J., 2008. Late Pliocene Greenland glaciation controlled by a decline in atmospheric CO_2 levels. Nature 454, 1102-1105.

Lunt, D.J., Haywood, A.M., Foster, G.L. and Stone, E.J., 2009. The Arctic cryosphere in the mid-Pliocene and the future. Philosophical Transactions of the Royal Society A 367, 49-67.

Lunt, D.J., Haywood, A.M., Schmidt, G.A., Salzmann, U., Valdes, P.J. and Dowsett, H.J., 2010. Earth system sensitivity inferred from Pliocene modelling and data. Nature Geoscience 3, 60-64.

Markwick, P.J., 2007. The palaeogeographic and palaeoclimatic significance of climate proxies for data-model comparisons. In Williams, M., Haywood, A.M., Gregory, F.J. and Schmidt, D.N. (eds.) Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies, The Micropalaeontological Society, Special Publications. The Geological Society, London, 251-312.

Matthews, E., 1985. Prescription of land-surface boundary conditions in GISS GCM II: a simple method based on high-resolution vegetation data bases. NASA Report No. TM 86096, 20 pp.

Matthews Jr., J.V., and Ovenden, L.E., 1990. Late Tertiary plant macrofossils from localities in Arctic/Subarctic North America: a review of the data. Arctic 43, 364-392.

Matthews Jr., J.V., Westgate, J.A., Ovenden, L.E., Carter, L.D., and Fouch, T., 2003. Stratigraphy, fossils, and age of sediments at the upper pit of the Lost Chicken gold mine: new information on the late Pliocene environment of east central Alaska. Quaternary Research 60, 9-18.

MacDonald, G.M., and Case, R.A., 2005. Variations in the Pacific Decadal Oscillation over the past millennium. Geophysical Research Letters 32, L08703, doi:10.1029/2005GL022478.

McMillan, M.E., Heller, P.L. and Wing, S.L., 2006. History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau. Geological Society of America Bulletin 118, 393-405.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C., 2007. Global Climate Projections, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis.Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Miller, R.L., Schmidt, G.A. and Shindell, D.T., 2006. Forced annular variations in the 20th century Intergovernmental Panel on Climate Change Fourth Assessment Report models. Journal of Geophysical Research 111, D18101, doi:10.1029/2005JD006323.

Moucha, R., Forte, A.M., Rowley, D.B., Mitrovica, J.X., Simmons, N.A. and Grand, S.P., 2008. Mantle convection and the recent evolution of the Colorado Plateau and the Rio Grande Rift valley. Geology 36, 439-442.

Naish, T.R. and Wilson, G.S., 2009. Constraints on the amplitude of Mid-Pliocene (3.6-2.4Ma) eustatic sea-level fluctuations from the New Zealand shallow-marine sediment record. Philosophical Transactions of the Royal Society London A. 367, 169-187.

Osborn, T.J., 2004. Simulating the winter North Atlantic Oscillation: the roles of internal variability and greenhouse gas forcing. Climate Dynamics 22, 605-623.

Paeth, H., Hense, A., Glowienka-Hense, R., Voss, R. and Cubasch, U., 1999. The North Atlantic Oscillation as an indicator for greenhouse-gas induced regional climate change. Climate Dynamics 15, 953-960.

Pagani, M., Liu, Z., LaRiviere, J. and Ravelo, C., 2009. High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations. Nature Geoscience 3, 27-30.

Pagani, M., Liu, Z., LaRiviere, J. and Ravelo, A.C., 2010. High Earth-system sensitivity determined from Pliocene carbon dioxide concentrations. Nature Geosciences 3, 27-30.

Percival D.B. and Walden A.T., 1993. Spectral Analysis for Physical Applications. Cambridge University Press, Cambridge UK, 583 pp.

Pope, V.D., Gallani, M.L., Rowntree, P.R. and Stratton, R.A., 2000. The impact of new physical parameterisations in the Hadley Centre Model. Climate Dynamics 16, 123-146.

Porter, T.J., Pisaric, M.F.J., Kokelj, S.V. and Edwards, T.W.D., 2009. Climate signals in delta C-13 and delta O-18 of tree-rings from White Spruce in the Mackenzie Delta Region, Northern Canada. Arctic Antarctic and Alpine Research 41, 497-505.

Rauthe, M., Hense, A. and Paeth, H., 2004. A model intercomparison study of climate change-signals in extratropical circulation. International Journal of Climatology 24, 643-662.

Raymo, M.E., Grant, B., Horowitz, M. and Rau, G.H., 1996. Mid-Pliocene warmth: stronger greenhouse and stronger conveyor. Marine Micropaleontology 27, 313-326.

Reynolds-Henne, C.E., R.T.W. Siegwolf, K.S. Treydte, J. Esper, S. Henne, and M. Saurer., 2007. Temporal stability of climate-isotope relationships in tree rings of oak and pine (Ticino, Switzerland). Global Biogeochemical Cycles 21, GB4009.

Richter, S.L., Johnson, A.H., Dranoff, M.M., LePage, B.A. and Williams, C.J., 2008. Oxygen isotope ratios in fossil wood cellulose: Isotopic composition of Eocene- to Holocene-aged cellulose. Geochimica et Cosmochimica Acta 72, 2744-2753.

Rind, D. and Chandler, M., 1991. Increased ocean heat transports and warmer climate. Journal of Geophysical Research 96, 7437-7461.

Ringler, T.D. and Cook, K.H., 1998. Understanding the seasonality of orographically forced stationary waves: Interaction between mechanical and thermal forcing. Journal of the Atmospheric Sciences 56, 1154-1174.

Robinson, M.M., 2009. New quantitative evidence of extreme warmth in the Pliocene Arctic. Stratigraphy 6, 265-275.

Robinson, M.M., Valdes, P.J., Haywood, A.M., Dowsett, H.J., Hill, D.J. and Jones, S.M., this issue. Bathymetric controls on Pliocene North Atlantic and Arctic sea surface temperature and deepwater production.

Robinson, W.J. and Evans, R., 1980. A microcomputer-based tree-ring measuring system. Tree-Ring Bulletin 40, 59-64.

Rodwell, M.J., 2003. On the predictability of North Atlantic climate. In: The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Hurrell, J.W., Kushnir, Y., Ottersen, G., and Visbeck, M. (eds.) Geophysical Monograph Series 134, 173-192.

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, 432-447.

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 292, 201-211.

Sloan, L.C., Crowley, T.J. and Pollard, D., 1996. Modeling of middle Pliocene climate with the NCAR GENESIS general circulation model. Marine Micropaleontology 27, 51-61.

Sohl, L.E., Chandler, M.A., Schmunk, R.B., Mankoff, K., Jonas, J., Foley, K.M. and Dowsett, H.J., 2009. PRISM3/GISS topographic reconstruction. U.S. Geological Survey Data Series 419, 6 pp.

Thompson, D.W.J. and Wallace, J.M., 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophysical Research Letters 25, 1297-1300.

Thompson, D.W.J., Wallace, J.M. and Hegerl, G.C., 2000. Annular modes in the extratropical circulation. Part II: Trends. Journal of Climate 13, 1018-1036.

Thompson, D.W.J., Lee, S. and Baldwin, M.P., 2003. Atmospheric processes governing the Northern Hemisphere Annular Mode/North Atlantic Oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, S., Visbeck, M. (Eds.), The North Atlantic Oscillation, Climatic Significance and Environmental Impact. AGU Geophysical Monograph, 134, pp. 81-112.

Thompson, R.S. and Fleming, R.F., 1996. Middle Pliocene vegetaton: Reconstructions, paleoclimatic inferences and boundary conditions for climate modelling. Marine Micropaleontology 27, 27-49.

Thomson, D.J., 1982. Spectrum estimation and harmonic analysis. Proceedings of the Institute of Electrical and Electronics Engineers 70, 1055-1096.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D. and Frank, D.C., 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. Science 324, 78-80.

Tucker, D.F. and Crook, N.A., 1999. The generation of a mesoscale convective system from mountain convection. Monthly Weather Review 127, 1259-1273.

Vachon, R.W., Welker, J.M., White, J.W.C. and Vaughn, B.H., 2010. Moisture source temperature and precipitation δ18O-temperature relationships across the United States. Water Resources Research 46, W07523, doi:10.1029/2009WR0085

Visbeck, M., Marshall, J., Haine, T. and Spall, M., 1997. On the specification of eddy transfer coefficients in coarse resolution ocean circulation models. Journal of Physical Oceanography 27, 381-402.

Wardlaw, B.R. and Quinn, T.M., 1991. The record of Pliocene sea-level change at Enewetak Atoll. Quaternary Science Reviews 10, 247-258.

Welker, J.M., Rayback, S. and Henry, G.H.R., 2005. Arctic and North Atlantic Oscialltion phase changes are recorded in the isotopes ($\delta^{18}O$ and $\delta^{13}C$) of *Cassiope tetragona* plants. Global Change Biology 11, 997-1002.

Williams, M., Haywood, A.M., Harper, E.M., Johnson, A.L.A., Knowles, T., Leng, M.J., Lunt, D.J., Okamura, B., Taylor, P.D. and Zalasiewicz, J., 2009. Pliocene climate and seasonality in North Atlantic shelf seas. Philosophical Transactions of the Royal Society A 367, 85-108.

Wilson, M.F and Henderson-Sellers, A., 1985. A global archive of land cover and soils data for use in general circulation models. International Journal of Climatology 5, 119-143.

Winograd, I.J., Szabo, B.J., Coplen, T.B., Riggs, A.C. and Kolesar, P.T., 1985. Two-million-year record of deuterium depletion in Great Basin ground waters. Science 227, 519-522.

Figure Captions

Fig. 1. Pre-industrial and mid-Pliocene boundary conditions used within the climate model simulations. (a) Pre-industrial orography and (b) the difference between mid-Pliocene and pre-industrial orography, outside of ice sheet regions. (c) Pre-industrial and (d) mid-Pliocene ice sheet coverage. (e) A representation of pre-industrial vegetation, derived from Matthews (1985) and included here as a direct comparison to (f) PRISM2 mid-Pliocene vegetation reconstruction (Dowsett et al., 1999). CO2 is set to 280ppmv in pre-industrial and 400ppmv in mid-Pliocene simulations.

Fig. 2. Characterisation of Northern Hemisphere variability in the standard pre-industrical and mid-Pliocene simulations, PREIND and PRISM2. (a) Standardised AO indices calculated from PCA of the winter mslp north of 20°N. (b) NAO indices calculated using the Paeth et al. (1999) technique, standardised to the PREIND simulation. (c) Mean Atlantic mslp in the Northern Hemisphere.

Fig. 3. First component EOFs of mslp north of 20°N for (a) the standard pre-industrial simulation, PREIND and (b) the standard mid-Pliocene simulation, PRISM2. Significant changes occur over the Pacific and Atlantic centres of NAM.

Fig. 4. Mean Atlantic mslp in the Northern Hemisphere for each of the climate model simulations. Solid lines represent mid-Pliocene simulations, while dashed lines are pre-industrial. Green lines are vegetation perturbation simulations, blue lines ice sheet perturbations, red lines altered CO_2 and orange lines perturbed orography simulations. The major changes in Atlantic mslp occur when orography is changed.

Fig. 5. Frequency spectra of Pliocene tree-ring width and $\delta^{18}O$ isotope data compared to modern NAO and AO indices. Fossil wood comes from the Beaver Pond site on Ellesmere Island, shown on inset map.

Table Caption

Table 1. List of climate model simulations within each of the standard, perturbed pre-industrial and perturbed mid-Pliocene experiments. Superscript identifiers denote the non-standard boundary condition in each simulation.

Table 2. Key atmospheric parameters in the HadCM3 simulations. PREIND values are absolute, but all others are relative to PREIND.

Table 3. Key oceanic parameters in the HadCM3 simulations. PREIND values are absolute, but all others are relative to PREIND.