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# Sensitivity of Pliocene Arctic climate to orbital forcing, atmospheric $CO_2$ and sea ice albedo parameterisation

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ABSTRACT

General circulation model (GCM) simulations of the mid-Pliocene Warm Period (mPWP, 3.264 to 3.025 Myr ago) do not reproduce the magnitude of Northern Hemisphere high latitude surface air and sea surface temperature (SAT and SST) warming that proxy data indicate. There is also large uncertainty regarding the state of sea ice cover in the mPWP. Evidence for both perennial and seasonal mPWP Arctic sea ice is found through analyses of marine sediments, whilst in a multi-model ensemble of mPWP climate simulations, half of the ensemble simulated ice-free summer Arctic conditions. Given the strong influence that sea ice exerts on high latitude temperatures, an understanding of the nature of mPWP Arctic sea ice would be highly beneficial.

Using the HadCM3 GCM, this paper explores the impact of various combinations of potential mPWP orbital forcing, atmospheric $CO_2$ concentrations and minimum sea ice albedo on sea ice extent and high latitude warming. The focus is on the Northern Hemisphere, due to availability of proxy data, and the large data–model discrepancies in this region. Changes in orbital forcings are demonstrated to be sufficient to alter the Arctic sea ice simulated by HadCM3 from perennial to seasonal. However, this occurs only when atmospheric $CO_2$ concentrations exceed 300 ppm. Reduction of the minimum sea ice albedo from 0.5 to 0.2 is also sufficient to simulate seasonal sea ice, with any of the combinations of atmospheric $CO_2$ and orbital forcing. Compared to a mPWP control simulation, monthly mean increases north of 60°N of up to 4.2 °C (SST) and 9.8 °C (SAT) are simulated.

With varying $CO_2$, orbit and sea ice albedo values we are able to reproduce proxy temperature records that lean towards modest levels of high latitude warming, but other proxy data showing greater warming remain beyond the reach of our model. This highlights the importance of additional proxy records at high latitudes and ongoing efforts to compare proxy signals between sites.



## 1. Introduction

The mid-Pliocene Warm Period (mPWP, 3.264 to 3.025 Myr ago, Dowsett et al., 2010) is widely characterised as a period of sustained warmth in Earth's history (Haywood and Valdes, 2004; Haywood et al., 2013), with mean annual temperatures thought to be 2–3 °C higher than the pre-industrial era. Estimates of mid-Pliocene $pCO_2$ have typically been within the range of 365–415 ppm (Pagani et al., 2010; Seki et al., 2010), but other studies have suggested that it may have been lower, around 270–300 ppm (Zhang et al., 2013; Badger et al., 2013). GCM simulations of the mPWP have not reproduced the magnitude of high-latitude warming of sea surface and surface air temperatures (SSTs and SATs) indicated by proxy data (e.g. Dowsett et al., 2011; Salzmann et al., 2013). A detailed understanding of forcings which have a strong effect on high latitude climates is therefore important, as their representation in models may have a strong impact on the simulated climates of the past, present and future.

The representation of sea ice in models is one such example. Sea ice can enhance perturbations to the climate via feedback processes such as albedo, in addition to acting as an insulator between the ocean and the atmosphere (Kellogg, 1975; Maykut, 1978; Curry et al., 1995). Previous studies have attempted to reduce the discrepancy between mid-Pliocene high latitude temperature estimates derived from proxy data and model simulated temperatures through reduced sea ice cover. This has been done by artificially removing it year-round in an atmosphere-only simulation (Ballantyne et al., 2013), or by changes to the parameterisation of some sea ice processes (Howell et al., 2014).

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Understanding of the state of Arctic sea ice from proxy data in the mid-Pliocene remains limited. Based on the presence of iron grains in marine sediments (located at 87.5°N, 138.3°W), Darby (2008) concludes that the Arctic has had perennial sea ice for the past 14 million years. Analysis of $IP_{25}$, a sea ice proxy biomarker (Belt et al., 2007; Brown et al., 2014), in two cores (located at 80.2°N, 6.4°E and 80.3°N, 8.1°E) by Knies et al. (2014) shows that the mid-Pliocene minimum sea ice margin was located to the north of these two sites. Cronin et al. (1993), Moran et al. (2006) and Polyak et al. (2010) show evidence from ostracode assemblages and ice rafted debris that appear to suggest that the mid-Pliocene Arctic sea ice cover was seasonal in nature.

The Pliocene Modelling Intercomparison Project (PlioMIP) has compared the output of the simulation of the mPWP by GCMs from eight different modelling groups (Haywood et al., 2013). Howell et al. (2015) showed that variability in the ensemble simulation of mid-Pliocene Arctic sea ice is high in the summer months, where four of the models simulate ice-free summers, and the other four, including HadCM3, maintain at least some sea ice coverage year-round.

Model simulations of the mPWP, such as those performed for PlioMIP, typically represent the mid-Pliocene through a fixed atmospheric $CO_2$ concentration, usually $\sim 400$ ppm, and orbital configuration typically identical to modern (Haywood et al., 2011). However, the mPWP time slab is ∼240,000 years long, across which there may have been variations in $pCO_2$, as well as changes in orbital forcing, which will have affected the state of the Arctic sea ice cover.

This paper focuses on two main issues. It explores the sensitivity of modelled mid-Pliocene Arctic sea ice in HadCM3 to variations in orbital configuration, atmospheric $CO_2$ concentration and sea ice albedo parameterisation, in isolation as well as in combinations of these factors. In addition, through focusing on those simulations where there is the most extreme reductions in sea ice, this paper investigates the extent to which such large changes can influence the outcomes of data–model comparison, and if they are capable of bringing model and data results into closer agreement.

## 2. Methods

### 2.1. Model description

The simulations carried out in this paper were run using HadCM3 (Hadley Centre Coupled Climate Model version 3), a coupled atmosphere–ocean GCM from the UK Met Office. The model incorporates sea ice and vegetation components in addition to the atmosphere and ocean components (Gordon et al., 2000).

The ocean component contains 20 vertical levels, and has a horizontal resolution of 1.25° × 1.25°, which gives a grid box at the equator of approximately 139 km × 139 km. Vertical levels are distributed to allow greater resolution closer to the surface (Gordon et al., 2000). The atmosphere component of the model contains 19 vertical levels with a horizontal resolution of 2.5° × 3.75° (latitude × longitude), giving six ocean boxes for every atmosphere grid box. Schemes incorporated in the atmosphere component include a radiation scheme representing effects of minor trace gases (Edwards and Slingo, 1996), a land surface scheme capable of representing the effects of soil moisture melting and freezing (Cox et al., 1999) and a gravity wave drag parameterisation (Gregory et al., 1998).

Parameterisations of ice drift and leads, combined with a basic thermodynamic scheme, are the basis of the sea ice model in HadCM3 (Cattle and Crossley, 1995; Gordon et al., 2000). The thermodynamic scheme is based on the zero-layer model from Semtner (1976), developed from the one-dimensional sea ice model described in Maykut and Untersteiner (1971). Ice dynamics are based on parameterisations described by Bryan (1969). Sea ice advection is derived from the mean current speeds in the top 100 m of the ocean, which are based on windstress in HadCM3 (Gordon et al., 2000). The parameterisation of sea ice concentration is based on Hibler (1979). For SATs between −10 °C and 0 °C, sea ice albedo is a linear function of the temperature. Albedo is 0.8 at −10 °C and colder, and 0.5 at 0 °C. Salinity of sea ice is constant, at 0.6‰.

**Table 1**
Combinations of orbital configuration (with eccentricity, precession and obliquity values), $pCO_2$ and minimum sea ice albedo of the 30 simulations. The control simulation is highlighted in bold.

| Experiment name | Orbital equivalent (kyr BP) | Eccentricity/ precession/ obliquity | Atmospheric $CO_2$ concentration (ppmv) | Minimum albedo |
|---|---|---|---|---|
| Mod_300_0.5 | Modern | 0.016702 | 300 | 0.5 |
| **Mod_400_0.5** | | 0.01628 | 400 | 0.5 |
| Mod_500_0.5 | | 23.439 | 500 | 0.5 |
| Mod_300_0.2 | | | 300 | 0.2 |
| Mod_400_0.2 | | | 400 | 0.2 |
| Mod_500_0.2 | | | 500 | 0.2 |
| Jan_300_0.5 | 3057 | | 300 | 0.5 |
| Jan_400_0.5 | | 0.053487 | 400 | 0.5 |
| Jan_500_0.5 | | −0.02318 | 500 | 0.5 |
| Jan_300_0.2 | | 22.914 | 300 | 0.2 |
| Jan_400_0.2 | | | 400 | 0.2 |
| Jan_500_0.2 | | | 500 | 0.2 |
| Mar_300_0.5 | 3140 | 0.040574 | 300 | 0.5 |
| Mar_400_0.5 | | 0.02343 | 400 | 0.5 |
| Mar_500_0.5 | | 22.719 | 500 | 0.5 |
| Mar_300_0.2 | | | 300 | 0.2 |
| Mar_400_0.2 | | | 400 | 0.2 |
| Mar_500_0.2 | | | 500 | 0.2 |
| Jul_300_0.5 | 3037 | 0.051086 | 300 | 0.5 |
| Jul_400_0.5 | | −0.04239 | 400 | 0.5 |
| Jul_500_0.5 | | 23.642 | 500 | 0.5 |
| Jul_300_0.2 | | | 300 | 0.2 |
| Jul_400_0.2 | | | 400 | 0.2 |
| Jul_500_0.2 | | | 500 | 0.2 |
| Sep_300_0.5 | 3053 | 0.054281 | 300 | 0.5 |
| Sep_400_0.5 | | 0.03551 | 400 | 0.5 |
| Sep_500_0.5 | | 22.947 | 500 | 0.5 |
| Sep_300_0.2 | | | 300 | 0.2 |
| Sep_400_0.2 | | | 400 | 0.2 |
| Sep_500_0.2 | | | 500 | 0.2 |

### 2.2. Experimental design

Including the control, thirty simulations of the mid-Pliocene are run. These comprise all combinations of five orbital configurations, three concentrations of atmospheric $CO_2$, and two minimum sea ice albedo values. These are summarised in Table 1, which also describes the notation used to identify individual simulations. In addition to the mid-Pliocene simulations, a simulation with pre-industrial boundary conditions was also run. Each simulation was run for 500 years, spun off from the same 500 year control run, which was sufficient to ensure all simulations reached an equilibrium state. Climatological averages are based on the last 30 years, and the boundary conditions used are derived from PRISM3D, a reconstruction of mPWP sea surface and deep ocean temperatures, in addition to sea level, topography, vegetation and ice sheet reconstructions (Dowsett et al., 2010), following the PlioMIP alternate experimental design outlined in Haywood et al. (2011).

#### 2.2.1. Orbital configurations

In addition to the control (orbit identical to modern), simulations of the mPWP were run with four alternative orbital config-