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Modelling the climatic diversity of the warm interglacials

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ABSTRACT

The climate response to peak interglacial forcing during Marine Isotopic Stages (MIS) 1, 5, 9, 11 and 19 is examined using the Community Climate System Model 3. We determine which interglacial provides the closest analogue to peak MIS1 climate as well as how the variations in forcing between these interglacials translate into different surface climate responses.

Simulated surface temperature, precipitation and sea-ice cover confirm that MIS5 and 9 are ineffective analogues of peak MIS1 climate given their relatively large astronomical and greenhouse forcing. Conversely, MIS11 and 19 are in much closer agreement with MIS1, although MIS11 exhibits the closest resemblance particularly during boreal summer. This is attributed to a greater similarity in the latitudinal distribution of insolation over the middle latitude northern hemisphere continents. This region is the most sensitive to insolation change given the absence of ice-sheet dynamics in our model.

First-order surface temperature differences between the interglacials are explained by the sensitivity of the direct radiative responses to astronomical and greenhouse forcing. These include higher temperature sensitivity over land versus ocean, at high versus low latitudes and during June–July–August versus December–January–February. Sensitivity of indirect dynamical responses to insolation and greenhouse forcing also contribute to surface temperature differences between the interglacials. These include negative sea-level pressure anomalies in the North Pacific and Southern Oceans, which invigorate the meridional exchange of subpolar and subtropical air. Additionally, intense cooling and sea-ice expansion in the Nordic Seas, observed only in MIS1, 5 and 19, results in the largest variability exhibited between the interglacials. The manifestation of this cooling only after 800 years of simulation emphasises the importance of long model integrations. The examination of these features provides a framework for understanding the primary climatic differences between the warm interglacials and emphasises regions where proxies may provide effective validation of climate models.

1. Introduction

Determining interglacial diversity, primarily as a function of duration, intensity and internal variability has become a focal point for researchers trying to better understand our current interglacial (e.g. Tzedakis et al., 2009). The focus on interglacials over the past ~800 ka has been driven mainly by the availability of data – thus favouring Marine Isotopic Stages (MIS) 1 and 5 (e.g. Kukla et al., 2002; Bartlein et al., 2011) – as well as by similarities in forcing to MIS1 (Berger and Loutre, 2003).

Several interglacials have been espoused as analogues to MIS1 based on their astronomical characteristics, seasonal insolation patterns or their similarity to predicted anthropogenic warming. Early studies assumed MIS5 to be a good analogue for the future of the Holocene (Kukla et al., 1972). However, based on astronomically driven variations in insolation MIS11 was shown to be a closer analogue, having both closer duration and climatic stability to the current interglacial than MIS5 (Berger and Loutre, 2003). Subsequently, Ruddiman (2007) pointed out that, based on obliquity and precession phasing as well as summer caloric half year insolation, MIS9 was in fact a closer MIS1 analogue. However, complicating the MIS9–MIS1 analogy is the large greenhouse forcing during MIS9, which was greater than all other interglacials and greater than MIS1 by 36 ppmv CO_{2eq} (Yin and Berger, 2012). This makes causal relationships for climatic differences between MIS9 and 1 potentially difficult to delineate. Ruddiman also noted that the amplitude of the precession cycle was considerably larger during MIS9 than MIS1. Since precession is modulated by eccentricity with 100 and 400 ka harmonics, minima in the 400 ka eccentricity cycle provide the closest phasing of precession to MIS1, which is currently in an

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eccentricity minimum (Berger, 1978). The most recent interglacials to experience such eccentricity minima and thus similar precessional amplitudes to MIS1 are MIS11 and 19, at approximately 405 and 780 ka respectively. Of these, MIS19 shows closer obliquity and precession phasing to MIS1 (Yin and Berger, 2010) and the recent extension of the CO_2 record to 800 ka (Luthi et al., 2008) reveals near-identical greenhouse forcing (Yin and Berger, 2012). Thus, MIS19 is currently viewed by many as the closest astronomical – and likely climatic – analogue to MIS1 in terms of duration and peak intensity (Tzedakis, 2010; Yin and Berger, 2012).

Despite these developments, there has been little comparison of the peak climates of these warm interglacials within a physically robust framework. Previous climate modelling has primarily focused on MIS1 and 5 due to the desire to couple modelling scenarios with observations (e.g. Groll et al., 2005; Braconnot et al., 2007; Kaspar and Cubasch, 2007; Fischer and Jungclaus, 2010). This focus has recently been expanded by simulations of MIS1 through 19 using an Earth system model of intermediate complexity (Yin and Berger, 2010, 2012). Importantly, Yin and Berger (2012) distinguished the relatively warm interglacials from the relatively cool interglacials and isolated the individual contributions from insolation and CO_2 to these climates. However, these studies were of a broad scope, quantifying the gross climatic responses to greenhouse and astronomical forcing. In this study we utilise an atmosphere–ocean General Circulation Model (GCM) to elicit the climate responses to peak interglacial forcing during the relatively warm interglacials MIS1, 5, 9, 11 and 19. We determine which interglacial provides the closest analogue of peak surface climate during MIS1 as well as the mechanisms which dominate surface temperature variability between the interglacials. This will enable us to better understand specifically how variations in astronomical and greenhouse forcing between interglacials translate into climatic differences. The use of a GCM permits an emphasis on regional climate variations and integrates relatively realistic atmospheric responses to astronomical forcing, which have been shown to involve complex circulations not necessarily represented in simpler models (e.g. Hall et al., 2005). Thus this study focuses on one criterion for identifying an MIS1 analogue – the intensity of peak climate – and leaves the analysis of interglacial duration and internal variability to future work.

2. Model description and experiment design

To model the interglacials we utilize the Community Climate System Model 3 (CCSM3), which comprises separate models of the atmosphere, ocean, land and sea-ice (Collins et al., 2006). The atmospheric GCM in the CCSM3 resolves 26 vertical levels in hybrid coordinates and has a horizontal T31 resolution equivalent to approximately $3.75 \times 3.75°$ in longitude and latitude. The land model shares the same horizontal resolution as the atmospheric GCM and resolves 10 soil layers and up to five snow layers. The ocean GCM resolves 25 vertical layers in z-coordinates and has a horizontal resolution of approximately $3 \times 1.5°$ in longitude and latitude respectively, with higher meridional resolution at the equator and coarser resolution at middle latitudes. The sea-ice model is dynamical and shares the same horizontal resolution as the ocean GCM. A coupler coordinates communication between the models and ensures flux conservation. Global ocean salinity is conserved via a river routing model which diverts excess water to the oceans. For more information the reader is referred to Collins et al. (2006).

For our control case we use a pre-industrial simulation (PI), in which an orbital year of 1950 is prescribed along with pre-industrial ozone and aerosol concentrations. Chlorofluorocarbons are set to zero and the solar constant is set to 1365 W/m^2. The interglacial simulations are forced with identical boundary conditions to PI except for their greenhouse gas concentrations and astronomical parameters (eccentricity, obliquity and precession) which are detailed in Table 1. Our choice of astronomical parameters for the interglacials follows that of Yin and Berger (2012). We are interested in the peak astronomical forcing during each interglacial, which coincides approximately with dates where northern

Table 1
Experiment details.

	PI	MIS1	MIS5	MIS9	MIS11	MIS19
Date	1950 AD	12 ka	127 ka	334 ka	409 ka	788 ka
Eccentricity[a]	0.01672	0.019608	0.039378	0.031539	0.019322	0.026196
Obliquity[a]	23.446	24.152	24.040	24.239	23.781	24.003
CO_2 (ppm)[b]	280	267	287	295	285	260
CH_4 (ppb)[c]	760	659	724	794	713	728
N_2O (ppb)[d]	270	272	262	287	285	303

[a] Berger (1978).
[b] Luthi et al. (2008).
[c] Loulergue et al. (2008).
[d] Schilt et al. (2010).

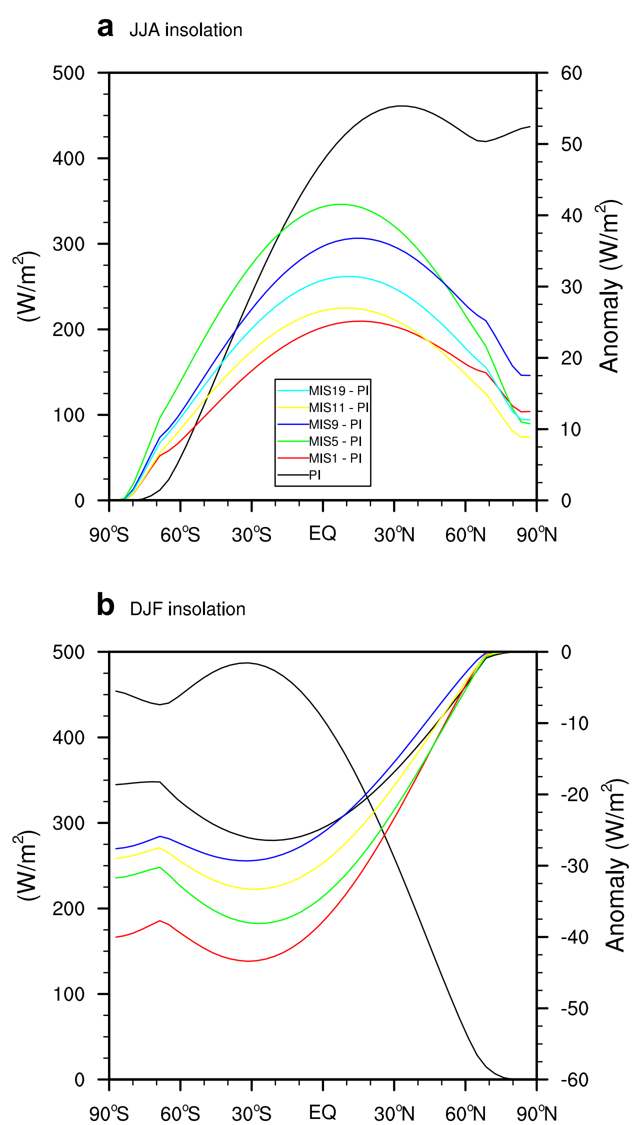

Fig. 1. (a) June–July–August (JJA) and (b) December–January–February (DJF) insolation anomalies relative to PI. PI insolation in black (left axis).