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Temperature trends during the Present and Last Interglacial periods – a multi-model-data comparison

P. Bakker [a,*], V. Masson-Delmotte [b], B. Martrat [c], S. Charbit [b], H. Renssen [a], M. Gröger [d,1], U. Krebs-Kanzow [e], G. Lohmann [f], D.J. Lunt [g], M. Pfeiffer [f], S.J. Phipps [h], M. Prange [i], S.P. Ritz [j], M. Schulz [i], B. Stenni [k], E.J. Stone [g], V. Varma [i]

[a] VU University Amsterdam, Department of Earth Sciences, Faculty of Earth and Life Sciences, Amsterdam, Netherlands
[b] Laboratoire des Sciences du Climat et de l'Environnement (IPSL/CEA-CNRS-UVSQ, UMR 8212), Gif-sur-Yvette, France
[c] Department of Environmental Chemistry, Institute of Environmental Assessment and Water Research, Spanish Council for Scientific Research, Barcelona, Spain
[d] Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany
[e] Department of Geology, Kiel University, Kiel, Germany
[f] Alfred Wegener Institute for Polar and Marine Research, Germany
[g] Bristol Research Initiative for the Dynamic Global Environment (BRIDGE), School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, UK
[h] ARC Centre of Excellence for Climate System Science and Climate Change Research Centre, University of New South Wales, Sydney, Australia
[i] MARUM – Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Klagenfurter Strasse, 28334 Bremen, Germany
[j] Climate and Environmental Physics, Physics Institute, and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[k] University of Trieste, Dept. of Mathematics and Geosciences, Weiss 2, 34128 Trieste, Italy

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ABSTRACT

Though primarily driven by insolation changes associated with well-known variations in Earth's astronomical parameters, the response of the climate system during interglacials includes a diversity of feedbacks involving the atmosphere, ocean, sea ice, vegetation and land ice. A thorough multi-model-data comparison is essential to assess the ability of climate models to resolve interglacial temperature trends and to help in understanding the recorded climatic signal and the underlying climate dynamics. We present the first multi-model-data comparison of transient millennial-scale temperature changes through two intervals of the Present Interglacial (PIG; 8–1.2 ka) and the Last Interglacial (LIG; 123–116.2 ka) periods. We include temperature trends simulated by 9 different climate models, alkenone-based temperature reconstructions from 117 globally distributed locations (about 45% of them within the LIG) and 12 ice-core-based temperature trends from Greenland and Antarctica (50% of them within the LIG). The definitions of these specific interglacial intervals enable a consistent inter-comparison of the two intervals because both are characterised by minor changes in atmospheric greenhouse gas concentrations and more importantly by insolation trends that show clear similarities.

Our analysis shows that in general the reconstructed PIG and LIG Northern Hemisphere mid-to-high latitude cooling compares well with multi-model, mean-temperature trends for the warmest months and that these cooling trends reflect a linear response to the warmest-month insolation decrease over the interglacial intervals. The most notable exception is the strong LIG cooling trend reconstructed from Greenland ice cores that is not simulated by any of the models. A striking model-data mismatch is found for both the PIG and the LIG over large parts of the mid-to-high latitudes of the Southern Hemisphere where the data depicts negative temperature trends that are not in agreement with near zero trends in the simulations. In this area, the positive local summer insolation trend is counteracted in climate models by an enhancement of the Southern Ocean summer sea-ice cover and/or an increase in Southern Ocean upwelling. If the general picture emerging from reconstructions is realistic, then the model-data mismatch in mid and high Southern Hemisphere latitudes implies that none of the models is able to resolve the correct balance of these feedbacks, or, alternatively, that interglacial Southern

* Corresponding author.
E-mail address: pbakker@coas.oregonstate.edu (P. Bakker).
[1] Now at Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden.

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Hemisphere temperature trends are driven by mechanisms which are not included in the transient simulations, such as changes in the Antarctic ice sheet or meltwater-induced changes in the overturning circulation.

1. Introduction

It has long been recognised that changes in the astronomical configuration of the Earth's orbit are a primary driver of long-term climate variations (Milankovitch, 1941). Past changes in the latitudinal and seasonal distribution of incoming top-of-the-atmosphere solar radiation (referred to as insolation in this manuscript) can be accurately calculated (Berger, 1978; Berger and Loutre, 1991; Laskar et al., 2004). The response of the climate system to this astronomical forcing includes a diversity of feedbacks involving the atmosphere, ocean, sea ice, vegetation and land ice (Braconnot et al., 2012; PALAEOSENS Project Members, 2012). Palaeoclimate information can be used to assess the realism of the representation of these feedbacks within numerical climate models. Systematic model-data comparisons performed within the Paleoclimate Modelling Intercomparison Project (PMIP) have focused on time-slice experiments such as those performed by Braconnot et al. (2007) for the middle of the Present Interglacial period (PIG-period) and by Lunt et al. (2013) for the thermal maximum of the Last Interglacial period (LIG-period; note that throughout the text PIG-period and LIG-period refer loosely to the two interglacial periods, while PIG and LIG will be used to indicate the specific target intervals defined in Section 2.1). During the last decade, progress has been made in the documentation of past climate variability based on time series from geological archives (e.g. deep-sea sediments, ice cores, lake sediments) resulting in a large number of proxy-based temperature reconstructions for the PIG-period (e.g. Wanner et al., 2008; Lohmann et al., 2013; Marcott et al., 2013) and, to a lesser extent, for the LIG-period (Andersen et al., 2004; CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; McKay et al., 2011), with improved age models (e.g. Waelbroeck et al., 2008; Masson-Delmotte et al., 2011b). In parallel, increasing computational capacity, as well as the development of more computationally efficient climate models, has made it feasible to perform multi-millennial climate simulations (Bakker et al., 2013; Langebroek and Nisancioglu, 2013; Lohmann et al., 2013). These lines of progress now allow an investigation of PIG-period and LIG-period multi-millennial temperature trends, e.g. multi-millennial linear temperature changes, based on multiple reconstructions and simulations. The assessment of the ability of climate models to reproduce climate trends during periods warmer than today is strongly motivated by the context of projected global warming. Indeed, while there is no direct analogy between the physics of greenhouse gas versus astronomical forcing, the LIG-period is characterised by Northern Hemisphere (NH) continental summer temperatures that are similar to those expected for the coming centuries (Masson-Delmotte et al., 2010b).

The PIG-period (~12 ka until the present-day; throughout this manuscript we will use [ka] to indicate kiloyears before 1950) and the LIG-period (~130–115 ka) are both warm interglacial periods with distinct $\delta^{18}O$ values in both ice-core and deep-sea-sediment records. Extensive research has resulted in a large number of proxy-based temperature reconstructions for the PIG-period (e.g. Wanner et al., 2008; Lohmann et al., 2013; Marcott et al., 2013) and (to a lesser extent) for the LIG-period (Andersen et al., 2004; CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; McKay et al., 2011). For most mid-to-high latitude NH regions, the temperature evolution of the PIG-period is characterised by a gradual 1 °C decrease of the summer temperature from the early part of the interglacial to the pre-industrial situation. This multi-millennial temperature trend has been attributed to insolation changes (Wanner et al., 2008; Renssen et al., 2009). However, there are significant spatial differences in the magnitude and timing of the early PIG-period temperature maximum, and therefore in the PIG-period temperature trends, which are related for instance to the cooling effect of remnants of NH glacial ice sheets (Renssen et al., 2009). Lohmann et al. (2013) have recently shown that climate models underestimate reconstructed sea surface temperature (SST) changes over part of the PIG-period and that overall the model-data disagreement becomes smaller if seasonal biases in the proxy-based temperature trends are taken into account.

Climate reconstructions from the LIG-period show that maximum temperatures were roughly 2–5 °C higher than at present in, respectively, the mid- and high-latitudes of the NH (CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; McKay et al., 2011; Sánchez-Goñi et al., 2012) during the early part of the LIG-period (>~126 ka; Sánchez-Goñi et al., 2012; Shackleton et al., 2003). In Antarctica, LIG-period peak warmth (temperature anomalies of at least 4 °C; Sime et al., 2008; Masson-Delmotte et al., 2011b), was shown to occur earlier than at NH high latitudes (Masson-Delmotte et al., 2010a; Govin et al., 2012). However, the number of climate reconstructions available for the LIG-period is much smaller than for the PIG-period. Moreover, mainly because the LIG-period lies outside the time span covered by ^{14}C dating techniques or ice-core layer counting, climate reconstructions are hampered by important issues related to assigning absolute ages and, as a consequence, to aligning different time series.

In addition to proxy-based reconstructions, transient climate-model experiments are helpful for analysing the PIG-period and LIG-period climates. If forced by the best estimate of millennial-scale astronomical and greenhouse gas (GHG) forcing scenarios at hand, simulations allow us to *i*) provide a global picture of the surface temperature evolution and *ii*) to investigate the role of external forcings and climate feedbacks in shaping the seasonal evolution of temperature. Earlier model-data comparisons focused on equilibrium simulations (Lunt et al., 2013). Beyond this approach, the transient nature of the simulations presented here enables us to *i*) describe the dynamical temperature response to the evolution of the astronomical forcing in the PIG-period and the LIG-period and *ii*) to take into account feedbacks from parts of the climate system which have a long (>1 ka) response time such as the deep ocean. A model inter-comparison of transient simulations covering the later part of the PIG-period, 6 ka to present, has been described in an earlier review study by Wanner et al. (2008). Their main findings are a decrease in summer temperatures at mid and high NH latitudes while winter temperatures decrease north of 60°N and increase at the mid latitudes of the NH. Results from the equatorial region and the Southern Hemisphere (SH) tend to differ between the different simulations. In a more recent model inter-comparison of transient PIG-period simulations, Varma et al. (2012) found a consistent cooling trend over Antarctica and the adjacent ocean between 7 and 0.25 ka. Model inter-comparison