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Temporal and spatial structure of multi-millennial temperature changes at high latitudes during the Last Interglacial

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ABSTRACT

The Last Interglacial (LIG, 129–116 thousand of years BP, ka) represents a test bed for climate model feedbacks in warmer-than-present high latitude regions. However, mainly because aligning different palaeoclimatic archives and from different parts of the world is not trivial, a spatio-temporal picture of LIG temperature changes is difficult to obtain.

Here, we have selected 47 polar ice core and sub-polar marine sediment records and developed a strategy to align them onto the recent AICC2012 ice core chronology. We provide the first compilation of high-latitude temperature changes across the LIG associated with a coherent temporal framework built between ice core and marine sediment records. Our new data synthesis highlights non-synchronous maximum temperature changes between the two hemispheres with the Southern Ocean and Antarctica records showing an early warming compared to North Atlantic records. We also observe warmer than present-day conditions that occur for a longer time period in southern high latitudes than in northern high latitudes. Finally, the amplitude of temperature changes at high northern latitudes is larger compared to high southern latitude temperature changes recorded at the onset and the demise of the LIG.

We have also compiled four data-based time slices with temperature anomalies (compared to present-day conditions) at 115 ka, 120 ka, 125 ka and 130 ka and quantitatively estimated temperature uncertainties that include relative dating errors. This provides an improved benchmark for performing more robust model-data comparison. The surface temperature simulated by two General Circulation Models (CCSM3 and HadCM3) for 130 ka and 125 ka is compared to the corresponding time slice data synthesis. This comparison shows that the models predict warmer than present conditions earlier than documented in the North Atlantic, while neither model is able to produce the reconstructed early Southern Ocean and Antarctic warming. Our results highlight the importance of producing a sequence of time slices rather than one single time slice averaging the LIG climate conditions.

1. Introduction

Due to numerous positive feedbacks, polar regions act as amplifiers of climate change (e.g. CAPE Last Interglacial Project Members, 2006; Masson-Delmotte et al., 2013; Nikolova et al., 2013). During the last decade, the Arctic has experienced the strongest warming trend observed at the Earth's surface, and further climate change is expected to produce large environmental changes in the near future including Arctic glaciers and Greenland ice sheet contributions to projected sea level rise (Church et al., 2013). By contrast, recent sea ice and temperature trends in and around Antarctica appear more complex, and this area is expected

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to respond on longer time scales to increased greenhouse gas emissions, with large uncertainties on associated sea level risks. The ability of climate models to correctly capture feedbacks involved in polar amplification remains uncertain and past climatic changes provide benchmarks against which the realism of climate models can be assessed (Braconnot et al., 2012; Schmidt et al., 2014). In particular, studying past warm periods such as recent interglacial periods, provide unique insights to assess polar amplification feedbacks in a range of temperature changes comparable to projected future changes (e.g. Otto-Bliesner et al., 2013).

The Last Interglacial period (hereafter LIG; 129–116 thousand of years BP, hereafter ka) is of particular interest since large parts of the globe were characterised by a warmer-than-present day climate (e.g. CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010). While orbital insolation was distinctly different to present-day (Laskar et al., 2004), atmospheric CO_2 concentration levels were close to pre-industrial values (Lüthi et al., 2008). The LIG is not an analogue for future climate change because orbital forcing is fundamentally different from anthropogenic forcing, and because the geographical pattern of LIG temperature changes strongly differ from those expected in the future (Masson-Delmotte et al., 2011a). Nonetheless, it offers an opportunity to assess the effect of warmer-than-present-day polar climate on climate-sensitive parts of the Earth system, most notably polar ice sheets and sea level. Previous work suggests that global sea level was 5.5–9 m higher than today (e.g. Kopp et al., 2009; Thompson et al., 2011). Combined with earlier evidence for LIG ice at the bottom of the Greenland ice sheet (e.g. GRIP members, 1993), the NEEM ice core data demonstrate the resilience of the central Greenland ice sheet to LIG local warming (NEEM community members, 2013). Ice sheet simulations compatible with NEEM elevation estimates suggest that the Greenland ice sheet contribution to the sea level rise should be in the range of 1.4–4.3 m (Robinson et al., 2011; Born and Nisancioglu, 2012; Masson-Delmotte et al., 2013; Quiquet et al., 2013; Stone et al., 2013). However, different input climates arising from climate simulations have been used as inputs for these ice sheet simulations. Also, the study of the LIG benefits from numerous snapshot and transient climatic simulations with state of the art General Circulation Models (GCMs; e.g. Bakker et al., 2013; Lunt et al., 2013; Nikolova et al., 2013; Otto-Bliesner et al., 2013; Langebroek and Nisancioglu, 2014; Paleoclimate Modelling Intercomparison Project, http://pmip3.lsce.ipsl.fr/). Altogether, this further motivates the evaluation of these GCMs against LIG climate reconstructions. In particular, data syntheses are required to document the magnitude and spatio-temporal structure of LIG temperature changes.

Several climatic data compilation initiatives have been conducted for the LIG (CLIMAP, 1984; Kaspar et al., 2005; CAPE Last Interglacial Project Members, 2006; Clark and Huybers, 2009; Turney and Jones, 2010; McKay et al., 2011). Turney and Jones (2010) averaged temperature estimates across the benthic foraminifera $\delta^{18}O$ and ice $\delta^{18}O$ plateau in marine and ice core records respectively, and across the period of maximum warmth in terrestrial sequences. They deduced a global annual LIG "maximum" warming above pre-industrial of about 2 °C and they identified earlier warming in Antarctica. McKay et al. (2011) used an alternative temperature-averaging method and calculated the mean sea surface temperature (SST) over a 5 ka period centred on the warmest temperature observed between 135 ka and 118 ka in marine records. They estimated a global annual mean SST warming of $+0.7 \pm 0.6$ °C relative to the late Holocene.

Otto-Bliesner et al. (2013) used these existing LIG temperature compilations to benchmark snapshot simulations performed at 125 and 130 ka with the CCSM3 GCM. However, both time slices are compared to a single data synthesis built assuming explicitly synchronous peak warmth. Recently, Bakker et al. (2014) proposed a comparison of temperature rates of change inferred from transient simulations as well as sea surface temperature (SST) from alkenone data and polar temperature syntheses, albeit without common chronologies. Both studies stress uncertainties associated with chronologies and temperature-averaging procedures. A temporal description of the LIG climate rather than an asynchronous compilation of LIG temperature optima could allow a detailed evaluation of these model simulations.

Indeed, current temporal representations inferred from marine sediment and ice core records remain limited so far by the lack of a common robust age scale over the LIG. Existing LIG syntheses are currently based on records taken on their original timescale, introducing absolute dating uncertainties that can reach several thousand years (e.g. Waelbroeck et al., 2008; Bazin et al., 2013; Veres et al., 2013). However, there is evidence that surface temperature peaks are not globally coincident. In particular, there is a significant delay in the establishment of peak interglacial conditions in the North Atlantic and Nordic Seas as compared to the Southern Ocean (Cortijo et al., 1999; Bauch and Erlenkeuser, 2008; Bauch et al., 2011; Van Nieuwenhove et al., 2011; Govin et al., 2012). Also, an early Antarctic warming has been reported (Masson-Delmotte et al., 2010). Thus, a compilation with a dynamic representation of the sequence of climatic events (several time slices) taking into account potential asynchronous temperature changes between the two hemispheres during the LIG is necessary. This requires synchronising palaeoclimatic records from different archives (e.g. ice cores and marine sediments).

The objectives of this study are twofold. First we document the magnitude and spatio-temporal structure of LIG temperature changes in the high latitudes of the two hemispheres. For that purpose, we describe a new data synthesis of air and sea surface temperature changes across the LIG in polar and sub polar regions associated with a coherent temporal framework between ice core and marine sediment records. Second, based on this new high latitude data compilation, we produce four data-based surface temperature anomaly time slices at 115 ka, 120 ka, 125 ka and 130 ka for which we propagate relative dating uncertainties and reconstructed temperature errors into the final temperature anomaly estimates. Using snapshot simulations performed for the 125 ka and 130 ka climatic conditions by the CCSM3 and HadCM3 models, we illustrate how these new time slices enable more robust model-data comparison to be performed in order to test state-of-the-art GCMs also used to perform future climate projections.

2. Material and methods

2.1. Palaeoclimatic data selection

We selected sites presenting a mean time-resolution of temperature reconstruction better than 2 ka and sufficient additional information (e.g. benthic and/or planktic $\delta^{18}O$ records, ash layers) to help integrate them with confidence into the common temporal framework. We selected five records of surface air temperature deduced from water stable isotopes measured along polar ice cores and 42 SST records from marine sediment cores located above 40°N and 40°S of latitude (Fig. 1). We obtained data through the PANGAEA database, from individual papers provided by principal investigators or extracted from published figures through digital image processing. Details for each selected record are given in Table A1.

- *Ice core records*:

We include local surface air temperature reconstructions for the East Antarctic EPICA Dome C (EDC), EPICA Dronning Maud Land