JOURNAL OF QUATERNARY SCIENCE (2010) **25**(6) 839–843

(www.interscience.wiley.com) DOI: 10.1002/jqs.1423

Rapid Communication

Does the Agulhas Current amplify global temperatures during super-interglacials?

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Turney, C. S. M. and Jones, R. T. 2010. Does the Agulhas Current amplify global temperatures during super-interglacials? *J. Quaternary Sci.*, **Vol. 25** pp. 839–843. ISSN 0267-8179.

ABSTRACT: Future projections of climate suggest our planet is moving into a 'super-interglacial'. Here we report a global synthesis of ice, marine and terrestrial data from a recent palaeoclimate equivalent, the Last Interglacial (ca. 130–116 ka ago). Our analysis suggests global temperatures were on average $\sim$1.5°C higher than today (relative to the AD 1961–1990 period). Intriguingly, we identify several Indian Ocean Last Interglacial sequences that suggest persistent early warming, consistent with leakage of warm, saline waters from the Agulhas Current into the Atlantic, intensifying meridional ocean circulation and increasing global temperatures. This mechanism may have played a significant positive feedback role during super-interglacials and could become increasingly important in the future. These results provide an important insight into a future 2°C climate stabilisation scenario. Copyright © 2010 John Wiley & Sons, Ltd.
Supporting information may be found in the online version of this article.

KEYWORDS: abrupt future climate change; El Niño–Southern Oscillation (ENSO); Southern Ocean; Southern Hemisphere westerlies; thermohaline circulation.

Introduction

Since the late 1980s it has become increasingly recognised that the world climate system is considerably more sensitive to anthropogenic emissions of greenhouse gases (GHG) than previously thought. The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) projects under a range of emission scenarios that global temperatures will increase over the next century between 1.1 and 6.4°C, accompanied by a sea-level rise of 18–59 cm (Meehl *et al.*, 2007). Worryingly, the AR4 estimates already appear conservative (Rahmstorf *et al.*, 2007).

Critically, past changes in the climate system can provide valuable insights into the future (Jansen *et al.*, 2007; PALSEA, 2010). While past periods may not be complete analogues for anthropogenic-driven climate change, the mechanisms that operated at different times can provide analogues of processes in the future. Future projections of climate driven by anthropogenic emissions of GHG suggest our planet is moving into a 'super-interglacial' state: a sustained period warmer than present (Overpeck *et al.*, 2005). There remains, however, considerable uncertainty over the mechanisms of change. Fortunately, there are several Late Pleistocene super-interglacials preserved in natural archives that can provide valuable insights into a range of processes (Masson-Delmotte *et al.*, 2010). Driven by orbital variations and carbon feedbacks, these periods may provide several important constraints on the future behaviour of the climate system. For instance, one intriguing observation is the apparent decoupling between inferred global temperatures and GHG during greatest warming (Masson-Delmotte *et al.*, 2010). Arguably one of the best super-interglacials for investigating this conundrum is the Last Interglacial (LIG), spanning the period ca. 130–116 ka ago and characterised by solar insolation anomalies caused by the changing Earth's orbit (Harrison *et al.*, 1995; Otto-Bliesner *et al.*, 2006). There is some uncertainty, however, regarding the global temperature during this period, with estimates ranging from 0.1 to >2°C warmer than present (CLIMAP Project Members, 1984; White, 1993; Hansen, 2005; Rohling *et al.*, 2008).

Greatly reduced Arctic sea ice area, changes in ice sheet topography and freshwater influences on the Atlantic Meridional Ocean Circulation (AMOC) have all been proposed as possible feedbacks for driving higher temperatures, but no consensus has been reached (Otto-Bliesner *et al.*, 2006;

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Masson-Delmotte *et al.*, 2010). Accompanying these changes, recent estimates of sea level corrected for changes in gravity, solid Earth deformation and other effects have suggested the LIG was 6.6–9.4 m higher than today, rising some 6–9 mm a^{-1} (Kopp *et al.*, 2009) – at least double the current global average. To better understand the mechanisms and sensitivity of the Earth system to radiative forcing, it is critical that a better constrained temperature estimate is obtained for this period.

Here we provide global and regional estimates of temperature during the LIG and present evidence that the Agulhas Current increased global warming through the enhanced delivery of warm, salty water into the Atlantic Ocean, intensifying AMOC and partially decoupling the climate system from the carbon cycle.

Methods

Although numerous qualitative reconstructions of the LIG have been reported (Trauth *et al.*, 2003; Sirocko *et al.*, 2005; Brook *et al.*, 2006; Kieniewicz and Smith, 2007; Van Nieuwenhove *et al.*, 2008), the magnitude of inferred changes around the globe is problematic to interpret. As an alternative strategy, we have compiled a global dataset comprising 263 published ice, marine and terrestrial sequences spanning the LIG that also contain a quantified estimate of annual temperature. Data were obtained from individual site reports, supplemented by records archived by the NOAA Paleoclimatology Program (www.ngdc.noaa.gov/paleo/paleo.html) and Pangaea database (www.pangaea.de) (see online supporting information for site locations and sources). Because of dating uncertainties over this period, sea surface (obtained using a combination of Sr–Ca, $U^{k'}_{37}$, Mg–Ca, diatom and radiolarian transfer functions) and ice core (using $\delta^{18}O$) temperature estimates were taken across the isotopic plateau associated with the LIG; terrestrial temperature estimates (based on pollen, macrofossil and Coleoptera) were developed over the period of maximum warmth and assumed to be broadly synchronous with the ocean and ice $\delta^{18}O$ plateau. Where uncertainties were not reported for individual marine temperature reconstructions, conservative estimates were assumed (see online supporting information) (Barrows *et al.*, 2007). To develop a robust comparison to today, mean annual terrestrial temperatures for each palaeosite location were taken from the AD 1961–1990 estimate from the nearest 0.5° × 0.5° grid cell (www.cru.uea.ac.uk/cru/data/hrg.htm; New *et al.*, 1999); contemporary ocean records were obtained over the same period from the nearest 2° × 2° grid cells (www.esrl.noaa.gov/psd/data/gridded/; Smith and Reynolds, 1998). Differences between the LIG and today were averaged within gridded boxes 45° latitude by 30° longitude, followed by zonal, hemispheric and global averaging.

Results and Discussion

Importantly, the different proxies used in this study all have limitations and/or potential biases (Jones and Mann, 2004). To minimise these, we have only utilised records that report annual averages, have more than four data points across the LIG and used conservative estimates of the uncertainties where none were reported. Furthermore, due to the inherent problems with dating LIG sequences, we averaged the temperature estimates across the isotopic plateau in the marine and ice records (though this resulted in removing the very earliest high Antarctic temperatures from our reconstruction) and the period of maximum warmth in terrestrial sequences, to provide a first-order estimate of the global climate at this time.

Our results suggest the world was 1.5 ± 0.1°C warmer than the period AD 1961–1990 (Fig. 1). Although the uncertainty of this reconstruction almost certainly does not capture all the bias in our dataset (including the poor spatial coverage in some parts of the world), this analysis implies global temperatures were ~1.9°C higher than pre-industrial levels (Smith and Reynolds, 2005). The available data also indicate there was a strong latitudinal temperature gradient, with greater warming at high latitudes (>60°) relative to tropical regions (0–30°) (most probably related to ice albedo sensitivity) and imply a reduced

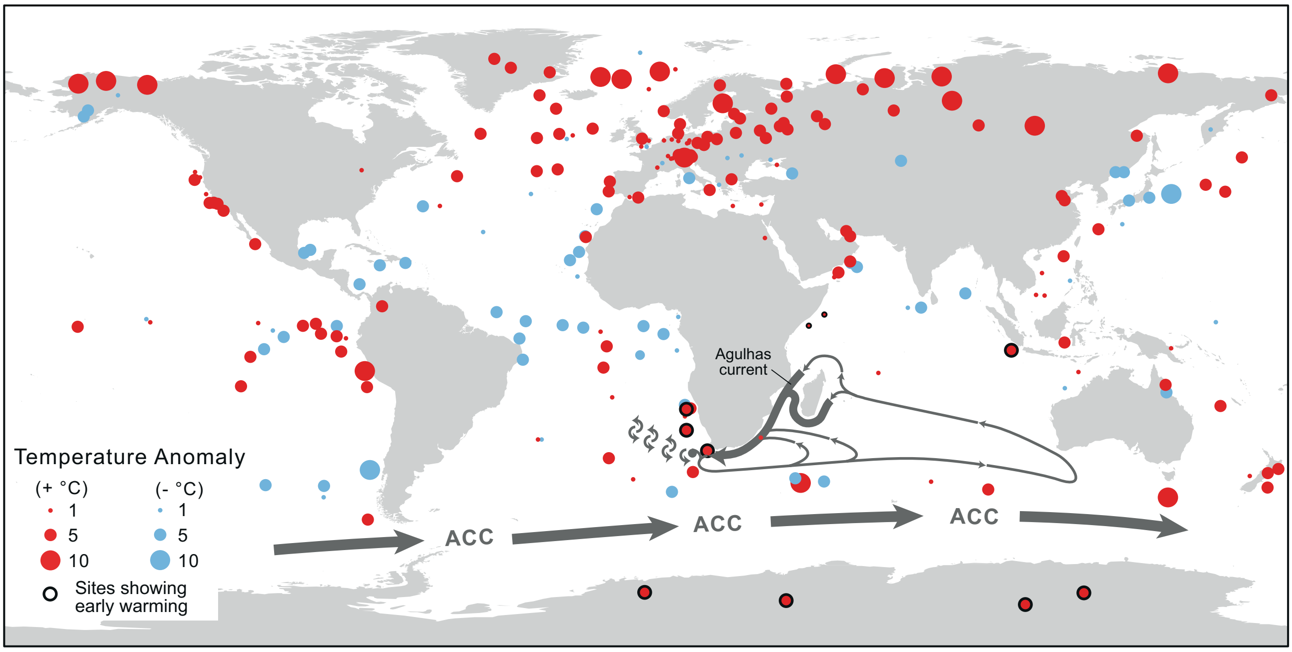

Figure 1 Temperature anomalies (relative to AD 1961–1990) in 263 Last Interglacial ice, marine and terrestrial sequences. The location of the Antarctic Circumpolar Current (ACC) and the Agulhas Current are shown. Sites suggesting local early warming are shown with bold circles. This figure is available in colour online at www.interscience.wiley.com/journals/jqs

zonally averaged latitudinal gradient of ~1.6°C, consistent with previous estimates (CAPE–Last Interglacial Project Members, 2006; Otto-Bliesner *et al.*, 2006; Sime *et al.*, 2009).

The amplitude and spatial scale of the LIG warming closely match the AR4 low-emission B1 scenario, which projects temperatures to rise between 1.1°C and 2.9°C by the end of this century (relative to AD 1900–1999) (IPCC, 2007). Regional patterns may also be discerned that have direct relevance to future change. One of the key uncertainties in tropical regions is the future pattern of sea surface temperature (SST) change. Some global models of future change suggest warming with relatively higher temperatures in the east Pacific relative to the west, leading to long-term patterns of rainfall change akin to those experienced during El Niño events (Collins and CMIP Modelling Groups, 2005). In contrast, other models produce La Niña-like patterns in which the west Pacific warms more than the east, leading to very different impacts on tropical landmasses. The uncertainty in tropical SSTs feeds through into major uncertainties in the impacts on tropical ecosystems and services, such as the Amazon rainforest (Cox *et al.*, 2004). Today, colder than modern SSTs in the eastern Pacific are indicative of a La Niña state (Nederbragt and Thurow, 2005; Wilson *et al.*, 2010). Although the data are sparse in the tropics, warmer eastern boundary currents in the Pacific are suggestive of more pervasive El Niño conditions during the LIG. Intriguingly, some of the data suggest spatially complex temperature trends in sites from the same immediate areas, and it is presently unclear whether this reflects high natural variability or problems with the reconstructions from specific sites and/or methods. Future work is urgently required in these areas to resolve this issue.

A striking feature within the highest-resolved marine records is a concentration of LIG sites along the southern African coastline and across the wider Indian Ocean that preserve a stratigraphic lead in 'local' annual warming over the shift to interglacial δ^{18}O values (Fig. 1), regardless of the dating uncertainty of individual sequences. Importantly, this trend is also observed in other records that preserve seasonal (i.e. winter and/or summer temperatures) trends in temperature (e.g. Chen *et al.*, 2002). This pattern of early warming is consistent with inferred temperatures preserved in Antarctic ice core records but is in marked contrast to annual and seasonal trends in the North Atlantic region (Fig. 2). One possibility is that this reflects the time taken to transmit the global ice volume component of the δ^{18}O through the world's oceans. However, no such lead in temperature is observed at other extremes of the ocean circulation system, such as the North Pacific (Bard *et al.*, 1994). Instead, our observations imply that temperatures increased across the Indian Ocean and Antarctica before significant global ice melt.

Today, the Indian Ocean is dominated by the Agulhas Current, which makes a significant contribution to the AMOC by the transportation of highly saline, warm water into the Atlantic through the shedding of 'rings' that become detached during retroflection into the Indian Ocean (Rouault *et al.*, 2009). Critically, this input is strongly controlled by the latitude of subtropical ocean masses and the Antarctic Circumpolar Current (ACC), which are in turn influenced by the core location of Southern Hemisphere westerly airflow (Sijp and England, 2009). During glacial periods, westerly winds were several degrees north of today (Hesse, 1994; Turney *et al.*, 2006), accompanied by a latitudinal shift of similar magnitude in the subtropical front and ACC (Bard and Rickaby, 2009), potentially shutting off Agulhas Current leakage into the Atlantic and resulting in reduced AMOC, depressing upwelling of carbon-rich deep waters around Antarctica (Sijp and England, 2009).

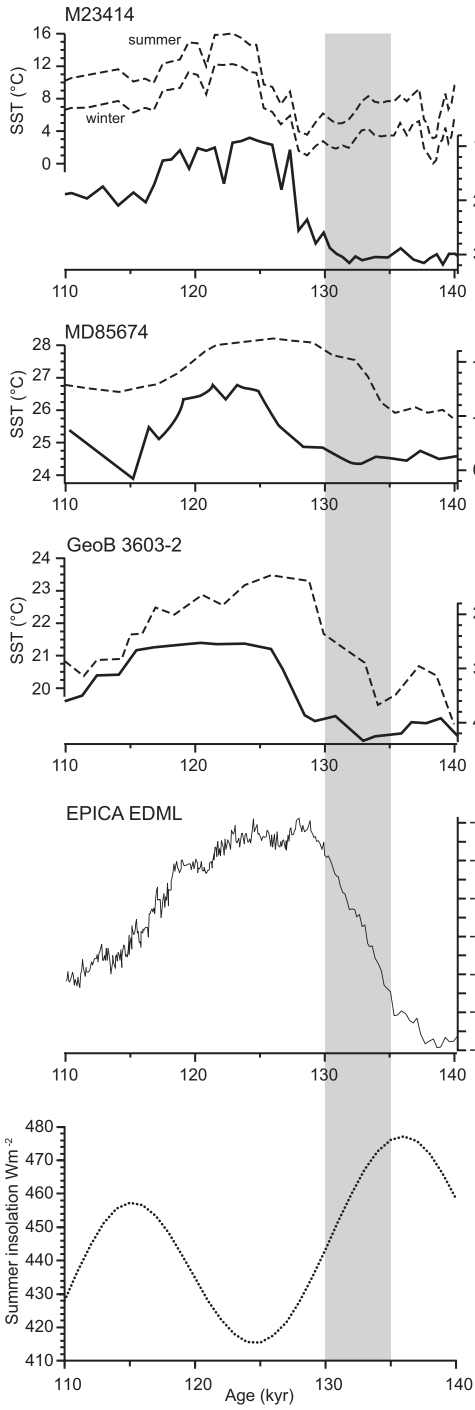

Figure 2 Comparison between selected North Atlantic (site M23414-9: Kandiano *et al.*, 2004) and Indian Ocean (MD85674: Bard *et al.*, 1997; GeoB 3603-2: Schneider *et al.*, 1999) marine cores and the EPICA EDML Antarctic ice record (EPICA, 2006) over the common period 140–110 ka ago. Dashed lines denote temperature and solid lines δ^{18}O. Summer insolation for 80° S is also shown (Laskar *et al.*, 2004). The grey column spans the common period of early warming over Antarctica and the Indian Ocean

Our results support the contention that during the LIG, orbital changes drove early warming over the Southern Ocean and Antarctic region during the 135 ka summer insolation maximum (Fig. 2), reducing sea ice extent (Kim *et al.*, 1998) and therefore the latitudinal temperature gradient. In contrast to Peeters *et al.* (2004), who proposed a Northern Hemisphere forcing of Agulhas leakage, we suggest that insolation forcing over the Southern Ocean and Antarctica led to a poleward shift in westerly airflow, causing a southward migration of the ACC and subtropical front. This scenario would have allowed the resumption and increase of Agulhas leakage into the Atlantic, intensifying AMOC through the delivery of highly saline warm water, amplifying global temperatures. Model results suggest that an approximate 50% retreat in the Southern Ocean sea ice margin during the termination of glacial conditions would have been sufficient to cause an abrupt resumption of AMOC through the delivery of warm, saline water from the Indian Ocean (Knorr and Lohmann, 2003). These results suggest a similar mechanism may have played a role during the termination of other glacial periods, including the onset of the present interglacial (Walker *et al.*, 2009), and during centennial-scale climate changes through the Holocene (Turney *et al.*, 2005).

Importantly, over the past two decades, increasing Atlantic leakage of the Agulhas has been observed (Rouault *et al.*, 2009), paralleled by a poleward shift in Southern Hemisphere westerly airflow (Biastoch *et al.*, 2009) as Antarctic temperatures increase (Steig *et al.*, 2009). Our results suggest the Agulhas Current may act as a significant positive feedback in the climate system, driving higher temperatures into the next super-interglacial. These results are consistent with modelling studies where reduced inflow of warm, saline Agulhas water led to a reduction in the strength of the AMOC (Sijp and England, 2009). Furthermore, if our estimate of global temperatures during the LIG is broadly correct and was higher than pre-industrial levels by ~1.9°C, this leads us to question whether a 2°C target for stabilising global temperatures should be considered 'safe' (cf. Meinshausen, 2006).

Conclusions

The Last Interglacial is an excellent example of a super-interglacial, a period warmer than today, where sea levels were 6.6–9.4 m higher than today, providing a valuable insight into the future climate system. Unfortunately, previous estimates of global and regional temperatures have been highly uncertain. Here we have compiled 263 quantified ice, marine and terrestrial records spanning the Last Interglacial. Although only a first approximation of published datasets, our results suggest this period was approximately 1.5°C warmer than AD 1961–1990 (~1.9°C relative to pre-industrial levels). A comparison between the reconstructed temperature and δ^{18}O trends in the highest-resolved records preserves a stratigraphic lead in 'local' warming over the shift to interglacial conditions around the southern African coastline. These results imply an enhanced leakage of the Agulhas Current into the Atlantic Ocean, injecting warm, saline water into the meridional ocean circulation and amplifying global warming during this super-interglacial. The above observations suggest the LIG can provide important insights into the mechanisms of future climate and whether a 2°C stabilisation scenario can be considered 'safe'.

Acknowledgements We thank numerous colleagues for their data and valuable input while discussing these ideas, including Peter Cox and Andrew Nicholas. Andrew Cowley and Sue Rouillard kindly helped prepare Figs 1 and 2. Two anonymous referees greatly improved the quality of the manuscript. C.S.M.T. would like to thank the Philip Leverhulme Prize which helped to support his contribution to this work.

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