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Warm climate isotopic simulations: what do we learn about interglacial signals in Greenland ice cores?

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ABSTRACT

Measurements of Last Interglacial stable water isotopes in ice cores show that central Greenland $\delta^{18}O$ increased by at least 3‰ compared to present day. Attempting to quantify the Greenland interglacial temperature change from these ice core measurements rests on our ability to interpret the stable water isotope content of Greenland snow. Current orbitally driven interglacial simulations do not show $\delta^{18}O$ or temperature rises of the correct magnitude, leading to difficulty in using only these experiments to inform our understanding of higher interglacial $\delta^{18}O$. Here, analysis of greenhouse gas warmed simulations from two isotope-enabled general circulation models, in conjunction with a set of Last Interglacial sea surface observations, indicates a possible explanation for the interglacial $\delta^{18}O$ rise. A reduction in the winter time sea ice concentration around the northern half of Greenland, together with an increase in sea surface temperatures over the same region, is found to be sufficient to drive a >3‰ interglacial enrichment in central Greenland snow. Warm climate $\delta^{18}O$ and δD in precipitation falling on Greenland are shown to be strongly influenced by local sea surface condition changes: local sea surface warming and a shrunken sea ice extent increase the proportion of water vapour from local (isotopically enriched) sources, compared to that from distal (isotopically depleted) sources. Precipitation intermittency changes, under warmer conditions, leads to geographical variability in the $\delta^{18}O$ against temperature gradients across Greenland. Little sea surface warming around the northern areas of Greenland leads to low $\delta^{18}O$ against temperature gradients (0.1–0.3‰ per °C), whilst large sea surface warmings in these regions leads to higher gradients (0.3–0.7‰ per °C). These gradients imply a wide possible range of present day to interglacial temperature increases (4 to >10 °C). Thus, we find that uncertainty about local interglacial sea surface conditions, rather than precipitation intermittency changes, may lead to the largest uncertainties in interpreting temperature from Greenland ice cores. We find that interglacial sea surface change observational records are currently insufficient to enable discrimination between these different $\delta^{18}O$ against temperature gradients. In conclusion, further information on interglacial sea surface temperatures and sea ice changes around northern Greenland should indicate whether +5 °C during the Last Interglacial is sufficient to drive the observed ice core $\delta^{18}O$ increase, or whether a larger temperature increases or ice sheet changes are also required to explain the ice core observations.

1. Introduction

Stable water isotope measurements, $\delta^{18}O$ and δD, in polar ice cores provide valuable information on past temperature. A main control on the distribution of $\delta^{18}O$ (and equivalently, for this case, δD) in preserved ice in Greenland is local temperature (Dansgaard, 1964). Thus the stable water isotopic content of ice cores can be used as an indicator of past temperature.

Understanding Last Interglacial temperature across Greenland could help with assessing the impacts of a shrunken Greenland ice sheet (*e.g.* Letreguilly et al., 1991; Chen et al., 2006; Velicogna,

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2009; Vinther et al., 2009; Colville et al., 2011), and may offer an opportunity to understand how aspects of the Earth system (*e.g.* sea ice and ocean temperatures) behave in a period of Arctic warmth (*e.g.* Cuffey and Marshall, 2000; Johnsen et al., 2001; NGRIP Project Members, 2004; Masson-Delmotte et al., 2006; Vinther et al., 2009; Turney and Jones, 2010; Masson-Delmotte et al., 2010).

The current longest well dated undisturbed Greenland ice core record of $\delta^{18}O$ published is 123 ka long and is from NorthGRIP (NGRIP Project Members, 2004). However the peak of the Last Interglacial is thought to have occurred between 125 and 130 thousand years before present (ka), most likely at about 126 ka (Otto-Bliesner et al., 2006; Masson-Delmotte et al., 2011). The NorthGRIP record therefore contains no isotopic information from the early part of the Last Interglacial. The high $\delta^{18}O$ value at 123 ka nevertheless suggests that the temperature in the Last Interglacial part of the record was substantially warmer than at any time in the Holocene.

In order to make the link between climate change and $\delta^{18}O$ responses, it is necessary to understand climatic impacts on $\delta^{18}O$ across Greenland. Greenland $\delta^{18}O$ measurements have been traditionally converted into temperature using the linear relationship (*e.g.* $\delta^{18}O = aT + b$, where T is the surface temperature) derived from spatial information (Dansgaard, 1964; Jouzel et al., 1994, 1997). Spatial observations of $\delta^{18}O$ and temperature show a strong linear relationship with a gradient, for inland sites, of about 0.7–0.8‰ per °C (Johnsen et al., 1995; Sjolte et al., 2011). However, since evaporation conditions, transport pathways, and site elevation changes also effect $\delta^{18}O$, there are many reasons why temporal gradients, and hence the interpretation of temperature shifts through time, may differ from the spatial gradients (see also *e.g.* Dansgaard, 1964; Jouzel et al., 1997; Noone and Simmonds, 2004; Helsen et al., 2007; Schmidt et al., 2007; Noone, 2008; Sime et al., 2008; Cuffey and Paterson, 2010).

Alternative information that can be used to help understand how the $\delta^{18}O$ record has varied with past Greenland temperature is available from the temperature profile measured in the borehole (Cuffey et al., 1995; Johnsen et al., 1995; Dahl-Jensen et al., 1998), and from measurements of the isotopic composition of the air trapped in ice (Severinghaus et al., 1998; Severinghaus and Brook, 1999; Capron et al., 2010; Kobashi et al., 2011). The temporal gradients obtained in these studies are generally significantly smaller than the spatial gradients. Values range from 0.23 to 0.55‰ per °C, with most values falling around 0.3‰ per °C. Interestingly, despite this evidence, papers discussing the Last Interglacial record have nevertheless generally used the 0.7‰ per °C gradient (which implies that +3.5‰ in $\delta^{18}O$ might be interpreted as equivalent to +5 °C shift in temperature) to infer past temperature shifts (*e.g.* NGRIP Project Members, 2004).

For a past warmer interglacial climate, where the temperature information from the borehole and isotopic measurements from trapped air are not available, a possible alternative test of temporal gradients is to calculate $\delta^{18}O$ and temperature values over a range of climates using an isotopically enabled general circulation model (GCM) (*e.g.* Jouzel et al., 1994; Sime et al., 2008). For cold climate shifts, the isotopic signal in ice cores in Greenland seem to be more biased towards summer snow (Krinner and Werner, 2003); though it is worth noting that the sign and magnitude of this biasing or precipitation intermittency change effect does vary between models. Similar biasing issues also appear to occur in Antarctica under warmer climates (Sime et al., 2009b). Model based results have thus been used as an explanation of low (0.3–0.4‰ per °C) $\delta^{18}O$ against temperature gradients for past climate cold-shifts across Greenland (Krinner et al., 1997; Werner et al., 2000).

For Greenland, the temperature and isotopic increases simulated across Greenland using an ocean–atmosphere GCM forced only by interglacial orbital and greenhouse gas forcing are very small; the Masson-Delmotte et al. (2011) isotopic shift amounts to less than 20% of the observed interglacial isotopic shift. The implies that these simulations are not yet in good agreement with observational constraints, and that it is difficult to use only these orbitally-driven simulations to help understand interglacial $\delta^{18}O$ in ice cores. Here we therefore complement the Masson-Delmotte et al. (2011) orbital approach with the detailed investigation of isotopic climate simulations warmed by greenhouse gas forcing. In using this method we are not trying to use the greenhouse gas (GHG) driven simulations as a direct analogue for Last Interglacial, rather the approach allows investigation of the isotopic response to patterns of sea surface warming and sea ice change.

In overview, the manuscript first compiles Last Interglacial Greenland isotopic and Atlantic and Arctic sea surface observations. Secondly, we present a brief discussion of the isotopic models and GHG driven simulations. Third, simulation results are presented in two parts. Present day simulation results are compared to present day Greenland observations, then the warmer simulation results are presented and discussed. Fourth, we consider what we can learn from the warmer simulation results, in the context of Last Interglacial sea surface observations, about the interpretation of Last Interglacial ice in Greenland cores. Finally, the last section summarises our findings and draws together some conclusions.

2. Interglacial observations from Greenland and its surrounding region

In comparison with present day, Holocene, or even last glacial conditions, the amount of information about the Last Interglacial peak (around 125–130 ka) is rather limited (*e.g.* Johnsen et al., 2001; MARGO Project Members, 2009; Leduc et al., 2010). An overview of the currently available Last Interglacial observations for Greenland ice cores, and for near Greenland sea surface condition observations, is provided below. Note, observations of present day temperature, accumulation, and $\delta^{18}O$ from ice core tops and other surface sites across Greenland are provided in Appendix B.

2.1. Interglacial Greenland ice core observations

There is currently no complete record of the Last Interglacial from Greenland ice cores. However, there are four publicly available Greenland stable water isotope ice core records that may feature some Last Interglacial ice (Fig. 1b). The $\delta^{18}O$ isotopic records from NGRIP, GRIP, Renland, DYE3, and Camp Century show similar variations over the majority of the Last Glacial period. This strongly suggests that the upper parts of these cores depict continuous undisturbed climatic records. However, the lack of agreement between their bottom parts implies that stratigraphic disturbances perturb their respective depth–age relationships. See Fig. 1 for positions and $\delta^{18}O$ records. Fig. 1a also shows the maximum difference in $\delta^{18}O$ between present day (0–3 ka average) and the 'Last Interglacial' maximum (the highest value in Fig. 1b which occurs before 100 ka).

Of the available Greenland ice core records, NGRIP is the only site which provides a continuous undisturbed climatic record back to the Last Interglacial. However, bedrock was reached at 3085 m and the deepest ice is thought to be 123 ka old (NGRIP Project Members, 2004; Landais et al., 2005). Thus, the NGRIP ice core probably does not record the maximum peak of the Last Interglacial. At GRIP the lowest 10% of the core, older than 110 ka, has a disturbed stratigraphy (Landais et al., 2003; Suwa et al., 2006). While the observed $\delta^{18}O$ at the bottom of the core suggests the presence of interglacial ice (Fig. 1), there is doubt whether peak interglacial $\delta^{18}O$ values are represented (GRIP Project Members,