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Southern Hemisphere westerly wind changes during the Last Glacial Maximum: paleo-data synthesis

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ABSTRACT

Changes in the strength and position of Southern Hemisphere westerly winds during the Last Glacial cycle have been invoked to explain both millennial and glacial–interglacial climate fluctuations. However, neither paleo models nor paleodata agree on the magnitude, or even the sign, of the change in wind strength and latitude during the most studied glacial period, the Last Glacial Maximum (LGM), compared to the recent past. This paper synthesizes paleo-environmental data that have been used to infer changes in LGM winds. Data compilations are provided for changes in terrestrial moisture, dust deposition, sea surface temperatures and ocean fronts, and ocean productivity, and existing data on Southern Hemisphere ocean circulation changes during the LGM are summarized. We find that any hypothesis of LGM wind and climate change needs to provide a plausible explanation for increased moisture on the west coast of continents, cooler temperatures and higher productivity in the Subantarctic Zone, and reductions in Agulhas leakage around southern Africa. Our comparison suggests that an overall strengthening, an equatorward displacement, or no change at all in winds could all be interpreted as consistent with observations. If a single cause related to the southern westerlies is sought for all the evidence presented, then an equatorward displacement or strengthening of the winds would be consistent with the largest proportion of the observations. However, other processes, such as weakening or poleward shifts in winds, a weakened hydrological cycle, extended sea-ice cover, and changed buoyancy fluxes, cannot be ruled out as potential explanations of observed changes in moisture, surface temperature, and productivity. We contend that resolving the position and strength of westerly winds during the LGM remains elusive based on data reconstructions alone. However, we believe that these data reconstructions of environmental conditions can be used in conjunction with model simulations to identify which processes best represent westerly wind conditions during the LGM.
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1. Introduction

The Southern Hemisphere westerly wind system is an important driver of the large scale ocean circulation and thus, of heat, salt, and nutrient transport in the global ocean (Toggweiler and Samuels, 1995; De Boer et al., 2008). Reconstructing the position and intensity of Southern Hemisphere westerly winds during the Last Glacial Maximum (LGM, 19,000–23,0000 calendar years ago) has gained particular importance because of the potential role of westerly winds in driving glacial–interglacial changes in the global ocean's heat and carbon cycling (Anderson et al., 2009). Changes in westerly winds are likely important to future changes in global ocean circulation (Beal et al., 2011; Downes et al., 2011), affecting the efficiency of the ocean CO_2 sink (Zickfeld et al., 2008). The ability to simulate the position and intensity of westerly winds for the LGM provides a challenging test of the flexibility of models to simulate winds under highly altered boundary conditions, and thus is essential for interpreting present and future changes in the carbon cycle.

Several studies using both terrestrial and marine paleo-evidence have attempted to reconstruct the position and strength of winds during the LGM, with somewhat contradictory results (Fig. 1; Table S1). Although paleo-evidence is often interpreted as equatorward shifts in winds, reconstructed changes in terrestrial moisture

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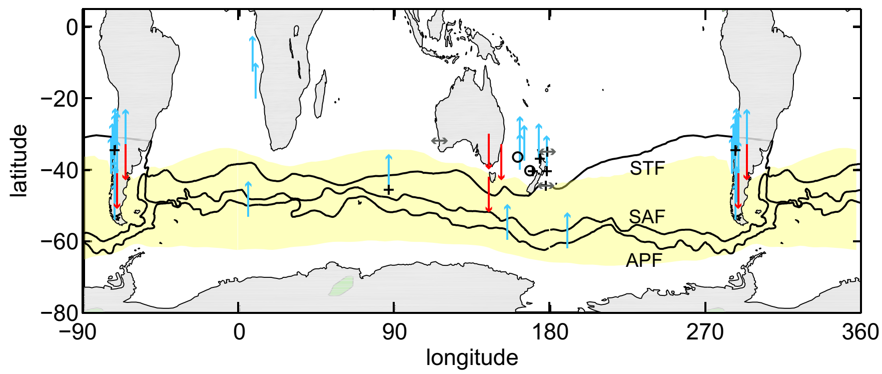

Fig. 1. Changes in the latitude and strength of the westerlies inferred in published studies based on moisture proxy paleo-data (Table 1). Blue arrows indicate equatorward and red arrows indicate poleward shifts, interpreted for the LGM relative to today. Sideways gray arrows indicate no shift. Black circles indicate no evidence for intensification while black pluses denote sites where intensification of westerlies during the LGM was inferred. Mean position of present-day westerlies (zonal component of mean surface wind >3 m/s, NCEP/NCAR Reanalysis 1) are indicated by the yellow shaded region, and modern-day fronts are indicated by the black lines (Orsi et al., 1995). Fronts shown include the southernmost branches of the APF (Antarctic Polar Front), SAF (Subantarctic Front), and the STF (Subtropical Front) and demarcate the positions of the PFZ (Polar Front Zone; between APF and SAF) and SAZ (Subantarctic Zone; between SAF and STF).

during the LGM have also been interpreted as showing poleward wind shifts (e.g. Wainer et al., 2005) or changes in the hydrological cycle unrelated to winds (e.g., Sime et al., 2013). Recent publications also suggest that temperature-dominated changes in the hydrological cycle may create wetter conditions in mid-latitudes and drying in tropical regions (Quade and Broecker, 2009), with the possibility of changed relationships between winds and precipitation during past climate periods (Cartwright et al., 2011). Shifts in oceanic fronts are also often cited as evidence for equatorward shifted winds, but interpreting the link between paleoceanographic data and the wind field is also not always straightforward. Other data associated with changes in the winds include proxies for Antarctic Intermediate Water (AAIW) formation, Antarctic Circumpolar Current (ACC) transport, and aeolian transport.

The number of studies inferring changes in glacial winds from paleoclimate indicators is vast, and interpreting paleo-indicators as wind shifts involves a chain of assumptions. Paleo-indicators are first linked to surrounding environmental conditions, and then these conditions are assumed to be similar enough to today to allow inferences about past wind changes. The abundance of information and complexities of interpretation make it increasingly difficult to gain an overview of what one might deduce from the paleo-record regarding LGM winds, especially for those not expert in paleo-data.

This paper synthesizes data relevant to changes to winds during the LGM in an easily accessible format. In Section 2, we describe how data on changes in terrestrial moisture, dust deposition, sea surface temperature (SST), ocean fronts, and export production during the LGM have been assembled. In Section 3, we describe observed changes from the data syntheses and then review assumptions needed to infer associated changes in winds. We also include literature summaries of other ocean circulation tracers which have been related to changes in winds during the LGM. In Section 4, we use these reconstructions to evaluate different scenarios for changes in winds during the LGM. A main contribution of this work is to bring together datasets of terrestrial moisture, dust deposition, ocean SSTs and fronts, and ocean productivity (Tables S2–S6) that can be used to evaluate model simulations. When taken together, these proxies provide insights regarding hemispherically consistent as well as regionally heterogenous changes that may be important to our understanding of winds.

A complementary approach for understanding LGM winds is to simulate them in climate models. Simulations from Atmosphere General Circulation Models (AGCMs) and Atmosphere-Ocean General Circulation Models (AOGCMs) produce different changes in Southern Hemisphere westerly wind position and intensity during the LGM. Simulated changes vary from equatorward and weaker (e.g., Kim et al., 2003; Rojas et al., 2009) to poleward and stronger winds (Wyrwoll et al., 2000; Shin et al., 2003; Otto-Bliesner et al., 2006; Rojas et al., 2009) during the LGM compared to today. Many inferred changes involve small shifts in latitude of the westerly winds maximum within a broad distribution of wind speeds. This can result in major differences in the conclusions drawn, even when the actual shift in winds at any given latitude is quite small. In our companion paper (Sime et al., 2013), the response of winds to LGM boundary conditions is simulated in an AGCM, and the importance of each boundary condition (i.e., SST, sea ice, etc.) is individually determined. We use the moisture data synthesized in this study to assess these and other AOGCM model simulations, providing insights into the merits of alternative explanations of how the winds changed.

These companion papers combine data synthesis, new AGCM model simulations, and data-model comparisons to provide a comprehensive review on the state of the Southern Hemisphere Westerlies during the LGM. This wider perspective enables us to improve our understanding of how winds change, and may help to reconcile apparent inconsistencies between data reconstructions and simulated changes in westerly winds during the LGM.

2. Data compilations

Our approach first involves compiling terrestrial and marine data on changes in terrestrial moisture balance on the continents during the LGM compared with today. We focus on plant available moisture (pollen), precipitation-evaporation balance (lake level), ice accumulation (glacier moraines), runoff (mineralogical data), and precipitation (beetle assemblages; speleothems). Then, we compile information on glacial–interglacial changes in dust deposition and marine indicators of sea-surface temperature (SST) and ocean fronts, biological productivity, and export production.

2.1. *Studied time interval and age control*

We focus on the LGM, 19,000–23,000 calendar years ago. We recognize that some terrestrial paleo-environmental evidence suggests that initial changes preceded the LGM by about 10,000 years in some regions, such as Africa, and that the LGM represents more of a transient phase prior to deglaciation (Gasse et al., 2008). Some studies also suggest that millennial scale climate variability

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