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Atmospheric simulations of southern South America's climate since the Last Glacial maximum

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ABSTRACT

This study investigates the simulated present and past climate of southern South America through the use of the PSU/NCAR MM5 mesoscale model forced by Princeton GFDL global atmosphere-ocean model data. This approach is taken to obtain climate data with sufficiently high resolution to resolve the steep mountain ranges of the southern Andes, which generate large amounts of orographic precipitation. Results indicated that the region experienced northward shifted low level westerlies at and before 9000 years before present and shifts in upper level winds associated with the midlatitude jet culminated about 9000 years ago. A simple energy balance model indicates that the lower equilibrium line altitudes in the southern Andes during the Last Glacial maximum persisted into the early Holocene, resulting in an expansion of the area receiving net snow accumulation, particularly in eastern parts of the Andes mountains. Changes in simulated winds and precipitation in the lee of the southern Andes are consistent with Laguna Potrok Aike climate proxies.

1. Introduction

The Andean mountains of southern South America (SSA) are between 1500 and 3500 m high and represent the only significant topographic barrier to the Southern Hemisphere midlatitude jet, acting to dry the atmosphere in this region more efficiently than any other mountain range (Smith and Evans, 2007). There are extremely large precipitation gradients in the region, with less than 300 mm per year in the eastern semi-arid steppe of Argentina and upwards of 7000 mm per year on the windward side of the Chilean Andes (Warren and Sugden, 1993). Outlet glaciers extent to the ocean and the Patagonian steppe from several large icefields which lie at the apex of these mountains. The region is known to have been significantly more glaciated during the Last Glacial maximum (LGM), with major glacial re-advances occurring until the early Holocene (Clapperton, 1994). Growth or retreat of glaciers in SSA over the past 21,000 years is affected to a large degree by the position of the midlatitude jet stream and the low level westerlies (LLWs), which control the location and intensity of orographic precipitation.

An understanding of the climatic conditions which established enlarged southern Andean icefields during the LGM is key to establishing a link between atmosphere model solutions and proxy records from the area. Past studies have suggested that temperatures over tropical South America during the LGM were up to 7° cooler than today's (Bush and Philander, 1999; Kim et al., 2003). However, models have also indicated that surface temperatures over the Pacific from the coast of Antarctica to roughly 40°S were only 1–2°C cooler than today's. The extent of SSA's cooling during the LGM is also not clear from proxies (Schäbitz et al., 2013) and due to the absence of significant cooling associated with the Younger Dryas, Ackert et al. (2008) concluded that glacial expansion in the southern Andes must have taken place as a result of increases in precipitation. Hence, cycles of glacial recession and growth may have resulted from changes in the position of the midlatitude jet which was likely situated further north repeatedly until the early Holocene (Clapperton, 1994).

Analysis of monthly mean LLWs and precipitation data has revealed that wet periods and periods of up-sloping winds are temporally correlated, on both sides of the Andes (Garreaud, 2007). Although the LLWs ensure that east facing slopes are extremely dry, most of the area's precipitation is still associated with winds out of the southwest (Mayr et al., 2007). Laguna Potrok Aike, a maar lake situated in the semi-arid Patagonian steppe (51°58′58″S, 70°22′42″W) with annual precipitation of only 200 mm year^{-1}, currently lies in a closed basin of about 200 km^2. The area has been characterized by a negative water budget (net evaporation where open water is present) and so lake level is related to the precipitation

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of the drainage basin containing the lake (Ohlendorf et al., 2013). As part of the Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO), an international initiative within the framework of the International Continental Scientific Drilling Project (ICDP), sediment cores were obtained. Plant and animal microfossils contained in the sediment provide clues about the region's past winds, temperatures, and precipitation (Wille et al., 2007).

The following analysis seeks to quantify the specific changes in the climatic forcings which resulted in the region's LGM glacial expansion through the use of both global and mesoscale atmospheric modelling and establish a link with paleoclimate proxies. The following text is organized into three sections. The next section describes the configuration of models used in the experiment. Following this is a detailed analysis of the numerical modelling results and how they relate to other paleoclimate experiments and the sediment record from Laguna Potrok Aike. Finally, conclusions that can be drawn from the results are presented.

2. Methodology

2.1. Global model setup

Many of the atmosphere–land surface interactions controlling the surface water fluxes of a region can be investigated using geophysical fluid dynamics (GFD) models. This study will use computational GFD to compare simulations with differing atmospheric CO_2 concentrations (known from ice cores (Monnin et al., 2001)), differing global ice sheet coverage (Peltier, 1994), and differing orbital parameters that affect the latitudinal distribution of insolation (Berger, 1992).

A global atmospheric general circulation model is dynamically and thermodynamically coupled with a global ocean general circulation model and will be referred to as the GCM. The atmospheric component (Gordon and Stern, 1982), developed at the Geophysical Fluid Dynamics Laboratory in Princeton (GFDL), is a spectral model with rhomboidal truncation at 30 zonal waves. This gives the model an equivalent spatial resolution of 3.75° longitude by 2.25° latitude (at the equator). The model contains 14 terrain-following sigma levels with the lowest sigma level approximately 30 m above ground in a standard atmosphere. Precipitation is determined to be snow if the temperature at the level of condensation is below freezing, a method which handles the surface energy balance during periods of wet snowfall well. The albedo of snow covered grid cells depends on surface temperature and snow depth, with snow depth determined by surface hydrology (see Manabe (1969) for further details). Large ice sheets such as those of Greenland and Antarctica have a fixed albedo of 0.6 and their areal extent and elevation is constant during model integration. Surface fluxes over the ocean are calculated at 1-day intervals through the use of the Modular Ocean Model version 2 (see Pacanowski, 1991), run with a spatial resolution comparable to the atmospheric model. Sea ice is simulated using the thermodynamic model of Fanning and Weaver (1996) and the two general circulation models exchange boundary information once per day.

Five 68-year GCM integrations are analyzed. The first, a control simulation, has carbon dioxide concentrations and orbital parameters set to fit modern, i.e. pre-industrial, levels. The others having orbital forcing parameters, surface boundaries (including land surface coverage and continental ice sheet extent and elevation), and CO_2 concentration parameters corresponding to the time periods 6000, 9000, 16,000, and 21,000 years before present. The 5 datasets are referred to as the control, 6 kbp, 9 kbp, 16 kbp, and LGM simulations. The simulations are spun up for four months as atmosphere-only simulations with modern specified sea surface temperatures to adjust to the radiative forcing. The atmosphere is then coupled to the ocean model, which then also responds to the radiative forcing over a period of approximately ten years. Results are analyzed after this spin-up period.

Numerous studies have been performed on the atmospheric conditions which sustain large ice-sheets such as the Laurentide, the Antarctic, and the Greenland ice-sheets under the differing radiative balances which governed climates of Earth's past (Otto-Bliesner and Brady, 2006; Pritchard et al., 2008), but few studies of smaller glaciers and ice-fields have been performed. This is largely because of the inability of low resolution GCMs to quantify changes in mountainous regions, where elevation varies significantly over small distances. Furthermore, semi-permanent synoptic features are affected by specific terrain features such as elevation and albedo; therefore model resolution also plays some role. Hence, a higher resolution model is not only necessary to quantify climate changes in mountainous topography with isolated high elevation regions, but also to quantify the effects of the topography on the Southern Hemisphere westerlies.

2.2. Mesoscale model setup

One approach to acquiring higher spatial resolution climate data from a GCM, and the one that is pursued in this study, is to use

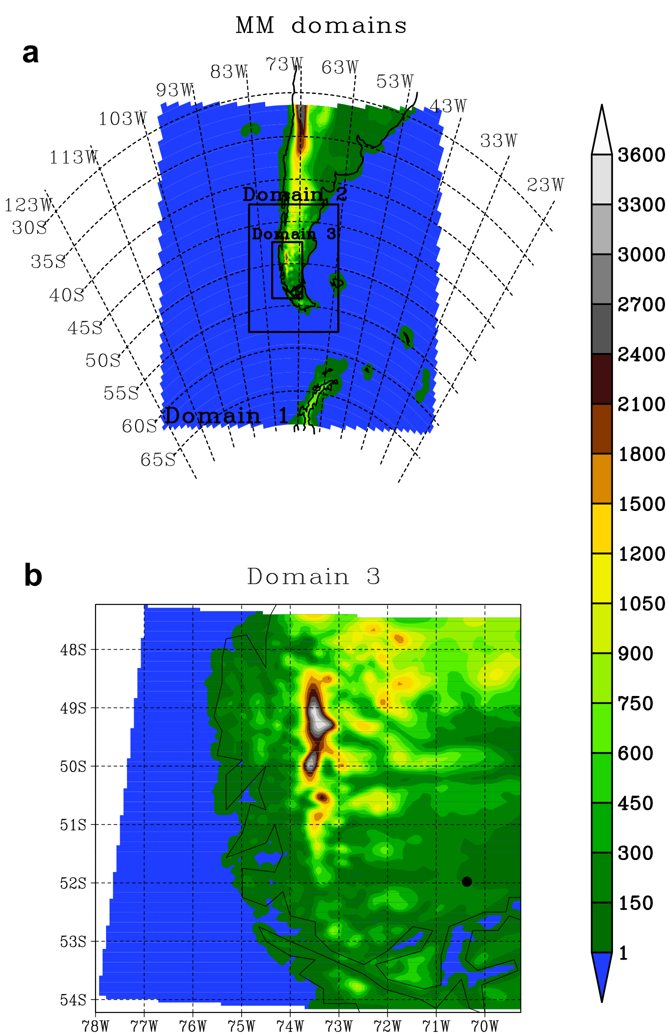

Fig. 1. The 3 regional model domains and topography. b) Topography in domain 3, with the location of Laguna Potrok Aike marked by the black dot. Coloured contours show elevation in metres.