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A multi-model analysis of moisture changes during the last glacial maximum

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ABSTRACT

This study investigates terrestrial moisture changes and associated mechanisms during the last glacial maximum (LGM; approximately 21,000 calendar years ago) using multi-model simulations from the Paleoclimate Modelling Intercomparison Project phase 3 (PMIP3). Considering that terrestrial moisture is not determined solely by precipitation, an aridity index (AI) is employed for measuring the terrestrial moisture by combining the effects of both precipitation and potential evapotranspiration (PET), where the latter represents atmospheric water demand and is greatly decreased mainly by the intense cooling during the LGM. Compared to the preindustrial period, the magnitude of global mean terrestrial moisture change is small, as the wetness brought by decreased PET counteracts the dryness induced by decreased precipitation. Regionally, the moisture changes depend on the different combinations of changes in precipitation and PET: (i) drying occurs where precipitation deceases and PET hardly changes, such as the northern tropical Americas and Southeast Asia; (ii) wetting is found in regions with precipitation increases and PET decreases (e.g., northwestern Africa and the central Andes), and their contributions are comparable; (iii) in particular, wetting can also occur in regions of decreased precipitation if a sufficient decrease in PET also occurs (i.e., southeastern North America and the northern and southern parts of eastern Asia), with the latter wetting effect reversing the former drying effect. The multi-model median field is consistent with available paleo-records in southern North America, the northern tropical Americas, the Andes, northwestern Africa, the southern Iberian Peninsula, southwestern Africa, the central part of eastern Asia, and Java but disagrees with proxies in Australia, central Brazil, southeastern Africa, the northern Iberian Peninsula, and the southern part of eastern Asia.

1. Introduction

The last glacial maximum (LGM), approximately 21,000 calendar years before present, is a key period for understanding glacial climates on an orbital scale. The LGM allows an estimation of climate responses to lower atmospheric greenhouse gas (GHG) concentrations (Petit et al., 1999) and the expansion of large ice sheets in the Northern Hemisphere with an associated sea level decrease of approximately 125 m (Peltier, 2004). The primary response is strong cooling, with a cooling of 0.7–2.7 °C over the ocean (MARGO Project Members, 2009) and 3–8 °C over the land (Holden et al., 2010; Annan and Hargreaves, 2013). The largest cooling of 21–25 °C is shown by ice core records in central Greenland (Cuffey et al., 1995; Johnsen et al., 1995; Dahl-Jensen et al., 1998). On one hand, such extreme cold may have weakened the hydrological cycle (Held and Soden, 2006; Quade and Broecker, 2009), with the atmospheric water-holding capacity suppressed and the regional subsidence enhanced. These conditions are unfavorable for precipitation (Boos, 2012), thus desiccating the land. On the other hand, strong cooling can wet the land by decreasing the atmospheric water demand and thus increasing the amount of water remaining in the soil (Allen et al., 1998). Thus, a scientific question that attracts us is how the glacial terrestrial moisture conditions differed from those of the present day.

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Terrestrial moisture conditions during the LGM have been inferred from multiple proxies, including relative abundances of pollen or diatoms (Bartlein et al., 2011; Izumi and Bartlein, 2016), lake levels from geomorphic and stratigraphic records (Kohfeld and Harrison, 2000; Yu et al., 2001), stable isotopes in speleothems, and the activity of dunes (Fitzsimmons et al., 2013). Relative to the present day, desiccation has been shown over East and Central Asia (Yu et al., 2000; Herzschuh, 2006; Li and Morrill, 2013), Southeast Asia (DiNezio and Tierney, 2013), western Siberia (Tarasov et al., 1999), Europe (Peyron et al., 1998; Bartlein et al., 2011; Moreno et al., 2012), the tropical Americas (Farrera et al., 1999; Sylvestre, 2009), southeastern Africa (Kohfeld et al., 2013; Jiang et al., 2015), and Australia (Fitzsimmons et al., 2013; Reeves et al., 2013), while the opposite holds for southwestern North America (Kohfeld and Harrison, 2000; Bartlein et al., 2011), northwestern and southwestern Africa (Kohfeld and Harrison, 2000; Bartlein et al., 2011), and the high Andes (Vizy and Cook, 2005; Sylvestre, 2009). For eastern North America south of the Laurentide Ice Sheet, a new pollen reconstruction (Izumi and Bartlein, 2016) that considers the sensitivity of the plant to low CO_2 concentrations suggests that the LGM climate was less dry and more similar to the present day than that reconstructed by the conventional statistical approach (Bartlein et al., 2011). Note that knowledge is limited by the spatial scarcity of paleo-data, and the extent to which the site-based data represent large-scale features is ambiguous. In addition, these data can depict only features of climate change, whereas they remain difficult to provide direct physical mechanisms alone, which need to be identified by climate simulations.

Previous modelling studies have done much to interpret the proxy-inferred moisture during the LGM. In particular, the LGM has been one of the target periods for simulations from the Paleoclimate Modelling Intercomparison Project (PMIP) in recent decades. Different PMIP models are forced with a common set of boundary conditions, which allows research using multiple models. Thus, the altering of LGM moisture conditions associated with global (Yan et al., 2016) and regional (Berman et al., 2016; Tian and Jiang, 2016; Chevalier et al., 2017) hydrological cycles is frequently explained using PMIP models. Most of the studies focus on precipitation changes. It is shown that the wetness in the Iberian Peninsula and the North American Southwest is accompanied by the southward shift of the westerly storm track (Kageyama et al., 1999; Laîné et al., 2009; Ludwig et al., 2016), the dryness in Southeast Asia is intensified by the exposure of the Sunda Shelf (DiNezio and Tierney, 2013), and the dryness in East Asia is linked to the suppressed subtropical high (Yanase and Abe-Ouchi, 2007) as well as the increased meridional temperature gradient and the decreased land–sea thermal contrast (Jiang et al., 2015).

However, it is far from convincing to determine whether a region is wetter or drier solely from the point of precipitation changes, as these modelling studies have done. Farrera et al. (1999) have inferred that the wetness shown at high elevations may be due more to the strong cooling than to the precipitation increase. Indeed, other than precipitation, both energy (radiation, heat and pressure) and aerodynamic factors (relative humidity and wind speed) are also responsible for the regional hydrological cycle through altering the atmospheric demand of water vapor (Fisher et al., 2011). Hence, the specific moisture change during the LGM needs to be analyzed, particularly considering changes in both precipitation and atmospheric water demand. Here, we employ a quantitative aridity index (AI), which is defined as a ratio between annual precipitation and potential evapotranspiration (PET). PET measures the amount of terrestrial water that evaporates from a sufficient water surface and represents the atmospheric water demand, while precipitation represents the water supply to the land; together, these factors determine the amount of water remaining in the land. This index in particular is adopted to produce the map of arid regions by the Food and Agriculture Organization of the United Nations (FAO), the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the United Nations Environment Programme (UNEP) (UNESCO, 1979; Middleton and Thomas, 1997) and has been widely used in studies of aridity (e.g., Sherwood and Fu, 2014; Huang et al., 2016).

In the present work, we perform an analysis of LGM moisture changes using climate simulations run with models that participated in the third phase of PMIP (PMIP3), which was included in the Coupled Model Intercomparison Project Phase 5 (Taylor et al., 2012). We aim to address the following issues: (i) How and to what extent did the LGM moisture change on global and regional scales? (ii) What were the mechanisms responsible for the moisture change? (iii) Are the simulations reconciled with paleo-records? The following section describes the data and method. The results are presented in section 3. Sections 4 and 5 provide a discussion and conclusions, respectively.

2. Data and methods

2.1. Model and observation data

The analysis is based on all available general circulation models participating in the PMIP3 experiments, including five fully coupled atmosphere–ocean models and four fully coupled atmosphere–ocean–vegetation models. The basic information about the models and the related boundary conditions are listed in Tables 1 and 2, and more details can be found at http://pmip3.lsce.ipsl.fr/. The preindustrial period is the baseline for comparison with the LGM. The LGM conditions differ from those of the preindustrial period mainly through reduced atmospheric GHG concentrations, larger ice sheets over continents, and lower sea levels. The orbital configuration is little changed, resulting in negligible climate changes in annual average states (Harrison et al., 2016; Yan et al., 2016). The models have been run for hundred years with these pre-defined boundary conditions. The last 50 years of simulations are taken to represent the equilibrium climate states for the preindustrial and LGM periods, the differences between which are analyzed in this study. Since the median field can avoid individual outliers in a collection of models and generally outperforms individual models (Gleckler et al., 2008), the multi-model median is emphasized in the following analysis. The uncertainty linked to model dependence is measured by the inter-model spread or consistency among the models.

The model performance for the modern climate is assessed based on monthly observation and reanalysis data from 1981 to 2010. The precipitation data are taken from the Precipitation Reconstruction over Land (PREC/L) dataset developed by the Climate Prediction Center (Chen et al., 2002). The dataset is derived from gauge observations at more than 17,000 stations collected in two individual datasets: the Global Historical Climatology Network version 2 (GHCN2) and the Climate Anomaly Monitoring System (CAMS). The other variables are obtained from the National Centers for Environment Prediction – Department of Energy (NCEP–DOE) Atmospheric Model Intercomparison Project (AMIP-II) reanalysis (NCEP-2) (Kanamitsu et al., 2002). Both types of data are referred to as observations hereafter for convenience. All data from the simulations and observations are interpolated into the same horizontal grids with one half-degree resolution using the bilinear approach.

2.2. Estimation of moisture conditions

The estimation of the terrestrial moisture conditions is based on the AI (Middleton and Thomas, 1997), which is defined as follows: