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Lake levels in Asia at the Last Glacial Maximum as indicators of hydrologic sensitivity to greenhouse gas concentrations

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ABSTRACT

Using monsoonal and arid Central Asia as a case study, we have compiled lake level information from proxy records for the Last Glacial Maximum (LGM) and compared these to the simulated hydrologic cycle from four 21 ka model experiments completed for the Paleoclimate Modeling Intercomparison Project, phase 2 (PMIP2). Our new review of proxy records indicates that lake levels were nearly all lower at LGM compared to the pre-industrial across Asia. This water-balance pattern is largely reproduced by all four models and results from decreased precipitation during the LGM. An offline lake energy balance model forced with output from the PMIP2 models shows that lake evaporation also significantly decreased at LGM, but that in most areas the change in lake evaporation is overshadowed by changes in precipitation. Based on the model experiments, higher LGM lake levels only existed in the dryland regions of Pakistan, Afghanistan and north of monsoonal East Asia (~45°N, ~90–120°E), which differs from previous studies that suggested that higher lake levels prevailed during the LGM in western China and arid Central Asia. A detailed atmospheric water budget analysis performed with output from the Community Climate System Model version 3 (CCSM3) indicates that a combination of atmospheric dynamics (i.e., convergence) and thermodynamics (i.e., the Clausius–Clayperon relationship) were responsible for decreases in LGM precipitation in Siberia and monsoonal Asia. Our results support the idea that monsoonal Asia will become wetter in the future due to increased atmospheric greenhouse gas concentrations, though more than atmospheric thermodynamics may be at play. The situation is more complex for arid Central Asia, though current trends towards wetter conditions there might be consistent with the pattern we observe and model for LGM.

1. Introduction

The Last Glacial Maximum (LGM) refers to the time of maximum extent of the ice sheets, between 26.5 and 19 ka BP, marking the peak of the Last Glacial period (Clark and Alan, 2002; Clark et al., 2009). During this time, land-based ice volume reaches its maximum, and these ice sheets profoundly impact the Earth's climate, causing drought, desertification, and a dramatic drop in sea levels (Yokoyama et al., 2000; Clark et al., 2009). While the greenhouse gas concentrations and sea levels are significantly different in comparison to present, the LGM orbital forcings are similar to today's (Otto-Bliesner et al., 2006). The global hydrologic cycle, the circulation of water in the climate system, is an integral part of the earth's climate system, which plays a role in determining the large-scale circulation and precipitation patterns (Hack et al., 2006). Lake level changes, in response to changes in the hydrologic cycle over the lake and its catchment, are highly sensitive to changes in the climate system. Therefore, lake level changes, between the LGM and the present, can be used as indicators of inland hydrologic sensitivity to different greenhouse gas concentrations.

A key projection of future hydrologic change under increased atmospheric greenhouse gas concentrations is that, in general, wet areas will become wetter and dry areas drier around the world (e.g., Meehl et al., 2007). Held and Soden (2006) presented the simple physical argument that this response is the result of increased lower-tropospheric water vapor, which is positively related to atmospheric temperature according to the Clausius–Clayperon relationship. In the absence of any dynamic (flow field) changes, this thermodynamic change is capable of enhancing atmospheric

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moisture convergence in wet areas and moisture divergence in dry areas. More recently, Seager et al. (2010) analyzed model simulations completed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report and concluded that changes in atmospheric dynamics, including shifts in the Intertropical Convergence Zone, Hadley circulation and mid-latitude transient eddies, must also play a role. Plus, regional responses can be different than global patterns (e.g., Held and Soden, 2006). One example of this might be the dry areas in Central Asia that have become wetter in the past few decades (Shi et al., 2007; Piao et al., 2010; Zhang et al., 2011). Given lowered atmospheric CO_2 levels and colder temperatures at LGM compared to today, this pattern appears to be the exact opposite of the projected future trend. Therefore, the LGM can be used as a reverse analog for the future and studying lake levels from the LGM may provide one way to test hypotheses about future patterns of hydrologic change. Quade and Broecker's (2009) preliminary review of global LGM lake level showed a strong hemispheric symmetry in lake expansion that occurred in current drylands during the LGM as well as lake contractions in the tropics, a conclusion supported by other studies (Street and Grove, 1979; Benson et al., 1990; Harrison et al., 1996; Farrera et al., 1999; Yu et al., 2003).

Monsoonal and Central Asia are ideal places to further test the hypothesis, wet areas will become wetter and dry areas drier, because these regions include tropical and sub-tropical areas influenced by the Asian summer monsoon and mid-latitude dryland areas to the west and north affected by the westerly winds (Zhang and Lin, 1992). Qin and Yu (1998) reported lake level changes in these regions during the LGM through compilations of sedimentological, biogeological and hydrological data. Compared with modern lake levels, East and South Asia were characterized by lower water levels, while the lake levels in China and Central Asia west of 100°E were relatively high during the LGM. Based on a compilation of lake data, Yu et al. (2003) obtained similar results and used model simulations to explore possible mechanisms behind LGM lake level change. However, both Qin and Yu (1998) and Yu et al. (2003) used lake level data mostly published in the 1990s, and dating uncertainties in many of these records make it difficult to precisely identify the LGM. Using newly published lake records as well as loess and pollen records, Herzschuh (2006) showed that the LGM was characterized by dry climate conditions in both monsoonal and Central Asia. Not only do questions remain about the pattern of lake level change at the LGM, but the previous modeling studies considered only precipitation and evapotranspiration changes as causes of lake level change (Qin and Yu, 1998; Yu et al., 2003). Lake surface evaporation, which was likely significantly decreased during the LGM, can play a significant role in the lake water balance and tends to change independently of drainage basin precipitation minus evaporation (Li and Morrill, 2010). Therefore, lake surface evaporation changes at LGM could severely limit the use of lake levels to test hypotheses about future precipitation changes. Yet another possible limitation of using the LGM to test these hypotheses is the fact that dynamical changes in the atmosphere forced by the presence of large continental ice sheets, a boundary condition irrelevant for the future, could have been responsible for some changes in atmospheric moisture.

In this study, we compile lake level information for the LGM from well-dated proxy records from monsoonal and Central Asia. We then compare these to lake water balance changes calculated using output from four 21 ka simulations from the Paleoclimate Modeling Intercomparison Project, phase 2 (PMIP2). We use our lake level compilation to contribute to the debate over the pattern of moisture changes in Asia at the LGM. Modeling changes in lake water balance allows us to consider the importance of lake surface evaporation changes in generating the observed lake level changes. Lastly, we present an analysis of the atmospheric moisture balance using one of the PMIP2 models to assess the relative influence of dynamical and thermodynamical factors. Our findings will address whether LGM lake levels offer a useful test of future hydrologic projections and, if so, what they imply about the response of the hydrologic cycle to greenhouse gas forcing.

2. Experimental design

2.1. PMIP2 model simulations

We used time slice simulations of pre-industrial (c. 1750 A.D. as defined by PMIP2) and of 21 ka from four coupled atmosphere–ocean models archived at the French Laboratoire des Sciences du Climat et l'Environnement (LSCE) as part of PMIP2 (Table 1). From the total of seven available models in the PMIP2 database, we excluded simulations from models of intermediate complexity and simulations with significant trends in global surface air temperature (>0.05 °C/century). All boundary conditions for these simulations were specified according to PMIP2 protocols. For the preindustrial (PI) simulations, orbital parameters were set to 1950 A.D. values. Atmospheric greenhouse gas concentrations came from ice core measurements for 1750 A.D. ($CO_2 = 280$ ppm, $CH_4 = 760$ ppb, $N_2O = 270$ ppb). Vegetation was prescribed to present-day distributions, and is model dependent since each group used different input datasets. Appropriate orbital parameters were used for the LGM, but these are not very different from forcing at PI and do not explain the large changes in climate. The more important forcings are atmospheric greenhouse gas concentrations ($CO_2 = 185$ ppm, $CH_4 = 350$ ppb, $N_2O = 200$ ppb), which result in a radiative forcing of the troposphere of -2.8 W/m^2 (Braconnot et al., 2007), and the presence of large continental ice sheets in the Northern Hemisphere. Ice sheet topography was prescribed according to Peltier (2004) and the land–sea masks were modified to be consistent with lowered sea level at 21 ka. Spin-up to LGM conditions was completed by various techniques of acceleration or asynchronous coupling of the atmosphere and ocean. More details about model boundary conditions and model results can be found in Braconnot et al. (2007).

The entire duration, one hundred years, of the output archived in the PMIP2 database was analyzed for each of the model simulations. We present results from each of the four models individually and as a multi-model ensemble. In general, an equally-weighted average of several models agrees better with observations than does any one model alone (Lambert and Boer, 2001). To generate ensembles, we bilinearly interpolated all model outputs to the coarsest model grid and took a simple average of the four outputs. We compared the ensemble mean difference between LGM and PI to the standard deviation of the four individual LGM–PI differences as a measure of model agreement and significance.

Table 1
PMIP2 models used.

Model name	Resolution of atmosphere lat° × lon° (levels)	Resolution of ocean lat° × lon° (levels)	References
CCSM3	∼2.8° × 2.8° (26)	∼1° × ∼1° (40)	Otto-Bliesner et al. (2006)
HadCM3M2	2.5° × 3.75° (19)	1.25° × 1.25° (20)	Gordon et al. (2000)
IPSL-CM4-V1-MR	2.5° × 3.75° (19)	0.5° × 2° (31)	Marti et al. (2005)
MIROC 3.2	∼2.8° × 2.8° (20)	0.5° × 1.4° (43)	K-1 Model Developers (2004)