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Context

# How cold were the tropics and subtropics at the Last Glacial Maximum?

The spatial pattern and magnitude of tropical and subtropical sea surface temperatures (SSTs) at the Last Glacial Maximum (LGM) have been a major challenge for many years. The range of the LGM tropical and subtropical cooling remains a major source of uncertainties for our understanding of the LGM climate. The global SST reconstruction for the LGM is an important ocean surface boundary condition for LGM climate simulations. One widely used surface boundary condition for many previous LGM climate simulations is the Climate, Long-Range Investigation, Mapping and Prediction (CLIMAP) reconstruction, which is based on the distribution of species of various fossil groups. The CLIMAP LGM reconstruction shows a moderate cooling (1–2 °C) over most of the tropical Pacific and warming over the subtropical Pacific relative to the present. This reconstruction, however, is at odds with a variety of terrestrial proxies indicating much colder LGM conditions over the tropics. Climate models forced with the CLIMAP SST often simulate conditions over tropical land areas (Rind and Peteet, 1985) that are inconsistent with the LGM land data.

Recent geochemical estimates of LGM tropical SSTs based on Mg/Ca ratios from planktonic foraminifera indicate much colder conditions relative to the CLIMAP reconstruction (Lea et al., 2000; Stott et al., 2002). The discrepancies between the CLIMAP SSTs and many other proxy estimates suggest that the CLIMAP SST reconstruction may have inherent warm biases. To address the controversy between the LGM terrestrial and oceanic cooling at low latitudes, one previous modeling study (Yin and Battisti, 2001) prescribed colder tropical SSTs relative to the CLIMAP reconstruction, with resulting simulated colder surface temperature over land that is in better agreement with the terrestrial evidence at the LGM. However, the prescribed cooling is arbitrary and the prescribed SST gradients are not based on realistic faunal and floral gradients.

The article by Hostetler et al. (2006) in this issue of *Quaternary Science Reviews* represents a critical step toward resolving the long-term debate of the LGM tropical cooling. Hostetler, Pisias and Mix identify two major possible biases in the transfer functions for faunal-based SST reconstructions: low sensitivity in the transfer functions at regions with very warm SSTs, and underestimation of SSTs at regions with strong upper ocean vertical temperature gradients. They employ a creative statistical approach to adjust the hypothetical CLIMAP SST biases during the LGM, based on the two identified fundamental biases in the transfer functions. In comparison with the CLIMAP reconstruction, the bias-adjusted SSTs are much colder at low latitudes, especially around the western Pacific warm pool and the subtropical Pacific, consistent with many recent geochemical estimates. Meanwhile this bias adjustment method maintains the SST gradients derived from faunal and floral gradients. Hostetler et al. (2006) further test the sensitivity of the climate system to the bias-adjusted ocean surface boundary conditions with an atmosphere general circulation model (AGCM). When forced with the prescribed bias-adjusted SSTs, the simulated magnitude of the LGM cooling over land is stronger and shows a better agreement with terrestrial proxy estimates relative to CLIMAP, thus helping to resolve the tropical cooling discrepancy between land and ocean at the LGM.

The systematic statistical method developed in Hostetler et al. (2006) for the bias-correction to the faunal-based SST reconstruction provides a new perspective on resolving the debate of the LGM cooling. The estimate of the magnitude of the LGM tropical cooling is very important to our understanding of the climate sensitivity and future climate change. For example, what does the tropical cooling at the LGM tell us about the climate sensitivity to atmospheric greenhouse gas concentrations? The atmospheric $CO_2$ levels at the LGM were about 30% lower than modern preindustrial values. With imposed low atmospheric greenhouse gas concentrations at the LGM, some simulations of the LGM climate from the Paleoclimate Modeling Intercomparison Project (PMIP) (Pinot et al., 1999) using AGCMs coupled to a mixed layer ocean model obtained much colder tropical SST relative to the CLIMAP, indicating high climate sensitivity to greenhouse gases. On the other hand, the moderate tropical cooling derived from CLIMAP SST reconstructions suggests relative low climate sensitivity to greenhouse gases. Future studies focusing on the synthesis of the bias-adjusted CLIMAP SSTs with other proxy evidence will help to narrow the uncertainties of low-latitude cooling during the LGM, and thus reduce the uncertainties of future climate changes in

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response to changes in atmospheric greenhouse gas concentrations.

In the AGCM simulation by Hostetler et al. (2006), the prescribed bias-adjusted SSTs produce a positive mass balance over the northern hemisphere ice sheets, and lead to greater cooling in the northern hemisphere and less cooling in the southern hemisphere, relative to the case with prescribed CLIMAP SSTs. This interhemispheric contrast in the simulated response (greater cooling in the northern hemisphere and less cooling in the southern hemisphere) may result in a southward shift of the Intertropical Convergence Zone (ITCZ) over the Pacific and the Atlantic in a fully coupled ocean-atmosphere system. There is no coupled feedback in the AGCM simulations with SSTs specified as the ocean surface boundary conditions. Would the bias-adjusted SST pattern be maintained with the AGCM-simulated response if the atmosphere–ocean system were fully coupled? How will the results be affected by the coupled feedback involving realistic ocean dynamics and air–sea interactions?

The bias-adjusted CLIMAP SSTs in Hostetler et al. (2006) agree well with many recent geochemical SST estimates, except that from core V21–30 in the eastern tropical Pacific. The LGM SST estimated by the Mg/Ca method at core V21–30 (south of the equator in the eastern tropical Pacific) shows a weaker cooling (1.2 °C, Koutavas et al., 2002). Meanwhile, the same Mg/Ca method indicates that LGM SSTs from the western Pacific warm pool and from north of the equator in the eastern tropical Pacific were much colder (Lea et al., 2000; Stott et al., 2002). These results suggest that relative to present, the LGM north–south SST contrast across the equator in the eastern tropical Pacific and east–west SST contrast in the southern tropical Pacific were reduced, indicating an El Niño–like pattern in the southern tropical Pacific and a southward shift of the Pacific ITCZ during the LGM (Koutavas et al., 2002; Stott et al., 2002). The question is how to reconcile the bias-adjusted CLIMAP SSTs derived from faunal transfer functions with the reduced north–south SST contrast in the eastern tropical Pacific and the reduced east–west SST contrast in the southern tropical Pacific estimated by the Mg/Ca method. A more accurate estimate of the LGM tropical Pacific SST contrast is crucial to our understanding of the ITCZ position and the ocean circulation in the tropical Pacific at the LGM.

## References

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