Interannual variability in the tropical Pacific and associated atmospheric teleconnections during the last glacial period

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Simulations of the climate of Marine Isotope Stages 2 and 3 suggest pronounced ENSO variability during the Heinrich Stadial 1 period when the Atlantic overturning circulation was weaker. Our model results also highlight the nonstationarity of ENSO teleconnections through time.

A well-known example of coupled ocean-atmosphere interaction on interannual timescales is the El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific. Consensus is still lacking about how ENSO will behave under future climate conditions, even in the latest generation of comprehensive climate models (Guilyardi et al. 2012).

Major goals of paleoclimatic research are to provide constraints on the possible range of changes in response to modified boundary conditions and to identify possible feedback and amplification mechanisms in the climate system. In this context, climate models are valuable tools for investigating different climate scenarios that have occurred in the past. Most ENSO studies, however, are limited to the two priority periods specified by the Paleoclimate Modeling Intercomparison Project (PMIP): the Mid-Holocene, and the Last Glacial Maximum (LGM; e.g. Zheng et al. 2008). However, proxy data from the tropical Pacific (e.g. Stott et al. 2002; Leduc et al. 2009; Dubois et al. 2011) suggest that ENSO also changed on millennial timescales, e.g. in association with pronounced abrupt climate changes related to the Dansgaard-Oeschger stadials and interstadials during Marine Isotope Stage 3 (MIS3, 59-29 ka BP).

Modeling ENSO for different glacial climate states

The first modeling studies that addressed MIS3 were limited to intermediate complexity models (e.g. Ganopolski and Rahmstorf 2001; van Meerbeeck et al. 2009; Ganopolski et al. 2010), a regional model approach (e.g. Barron and Pollard 2002), or an atmosphere-only setup (Sima et al. 2009), unsuitable to capture the complexity of ENSO dynamics. Recently, the first simulations of MIS3 climate in a comprehensive coupled climate model were accomplished with the US National Center of Atmospheric Research's CCSM3 model (Merkel et al. 2010). The study used a timeslice approach with a focus on a period of relatively regular Dansgaard-Oeschger variability around 35 ka BP. When 35 ka BP boundary conditions (greenhouse gas concentrations, orbital parameters, continental ice sheet distributions) are prescribed, the model simulates a very weak Atlantic meridional overturning circulation (AMOC) of about 7 Sv, which is much weaker than the preindustrial value of 12 Sv, but also weaker than the ~10 Sv simulated for the LGM. Therefore, we consider the simulated 35 ka BP climate as a stadial climate state. The counterpart of an interstadial climate state is induced in the model by a 0.1 Sv freshwater extraction from the North Atlantic over ~300 model years, thereby forcing a resumption of the AMOC to ~14 Sv.

Our set of experiments also includes a simulation of a Heinrich Stadial 1 scenario. This is set up by imposing a freshwater perturbation of about 0.2 Sv to a simulated LGM ocean state over 360 model years. This is motivated by earlier studies which mimic past Heinrich events by hosing freshwater into the modern ocean and thereby demonstrate that a slowdown of the AMOC may have a pronounced impact on the tropical Pacific (e.g. Timmermann et al. 2007).

One of our major findings was that interannual (about 1.5-8 years) variability in sea surface temperatures (SST) of the eastern tropical Pacific was distinctly increased in our Heinrich Stadial 1 simulation compared to pre-industrial times, whereas variability in our LGM and MIS3 simulations was systematically reduced, albeit only weakly (Fig. 1). Modern ENSO dynamics studies show that stronger ENSO variability is dynamically linked to a weaker annual cycle of SST and to a weaker meridional asymmetry of SST across the equator in the eastern tropical Pacific (Guilyardi 2006; Xie 1994). Our model results show that these relationships also hold for the different simulated glacial climate states. In particular, our Heinrich Stadial 1 simulation exhibits a much weaker north-south contrast in eastern tropical Pacific SST than under

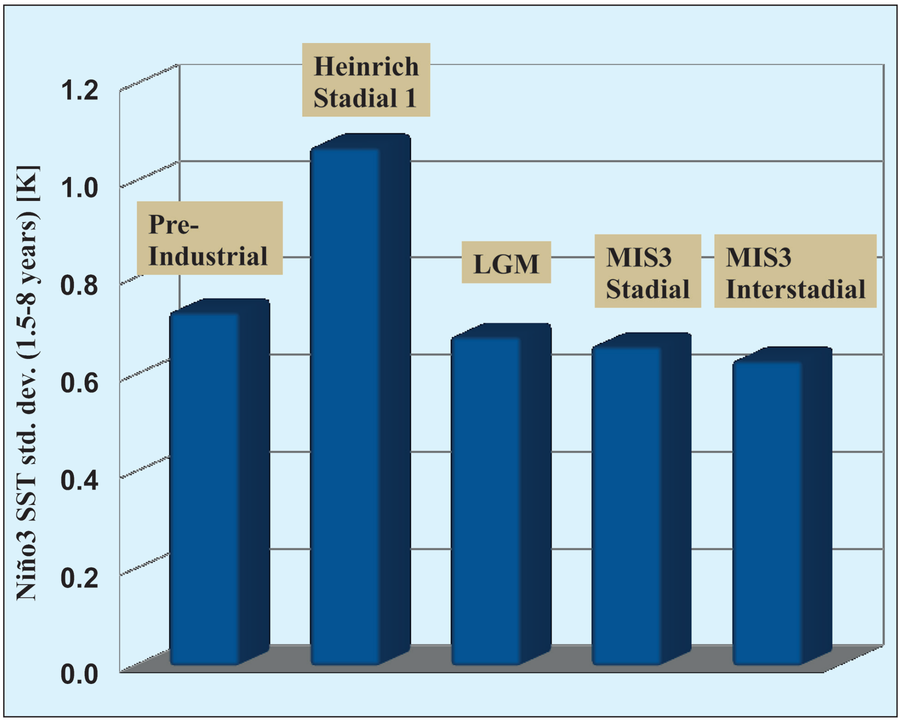

Figure 1: ENSO variability of sea surface temperature in the eastern tropical Pacific (Niño3 region: 150°W-90°W, 5°S-5°N) for different simulated climatic states.

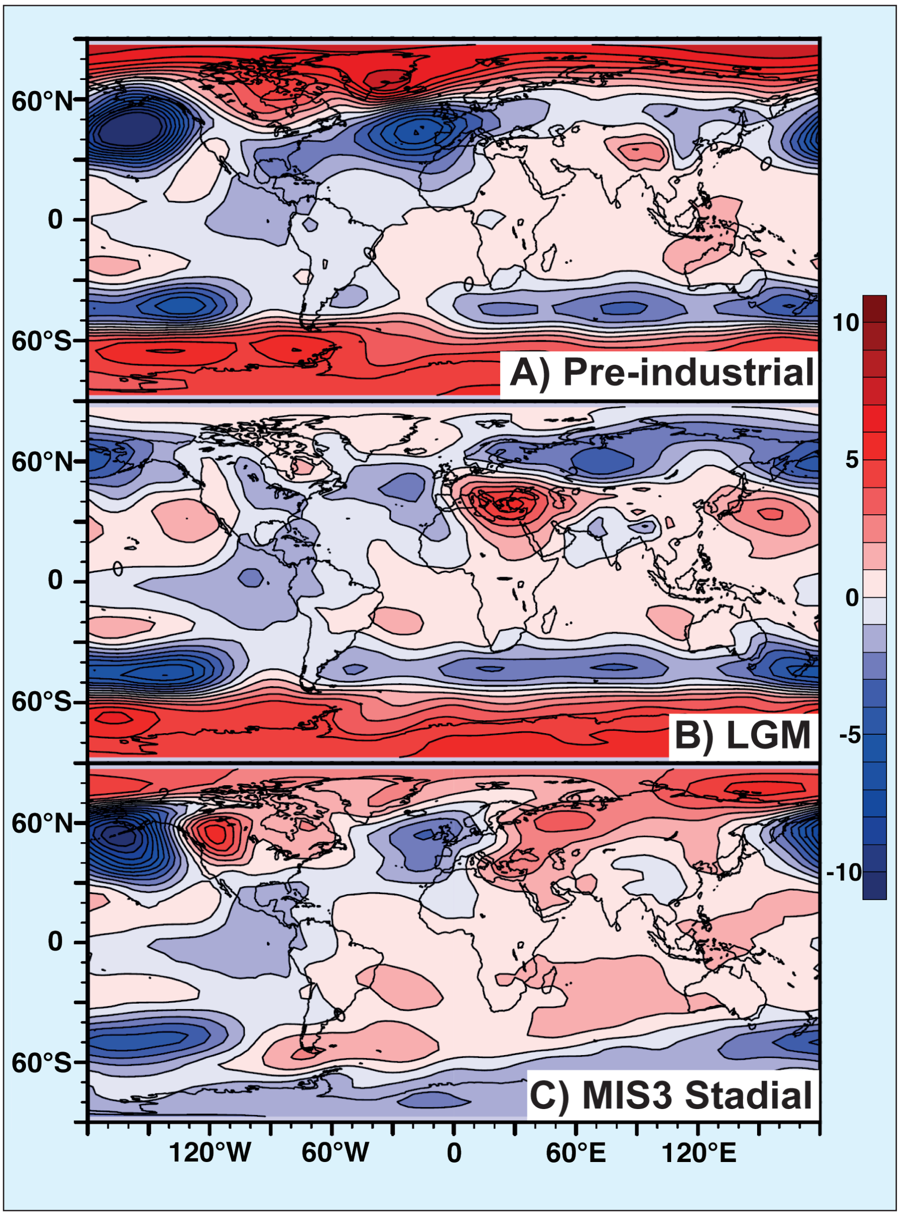

Figure 2: ENSO teleconnections during boreal winter (Dec.-Feb.): El Niño minus La Niña composites of sea level pressure [hPa] for ***(A)*** *pre-industrial control climate,* ***(B)*** *Last Glacial Maximum (LGM), and* ***(C)*** *Marine Isotope Stage 3 (MIS3) stadial climate. Figure modified from Merkel et al. 2010.*

modern conditions. This is attributed to an atmospheric signal communication from the strongly cooled North Atlantic into the tropical Pacific.

Model-data comparison

Further insights into tropical Pacific variability can be achieved through model-data intercomparison. Felis et al. (2012) present findings from a fossil coral retrieved during IODP Expedition 310 near Tahiti. The coral has been dated to Heinrich Stadial 1. Its fast growth rate allows sampling at monthly resolution and provides a unique opportunity to investigate interannual SST variability in the southwestern tropical Pacific during that period. The coral record exhibits pronounced variability at interannual ENSO frequencies during Heinrich Stadial 1, consistent with the basin-wide increase in ENSO variability in our Heinrich Stadial 1-analogue simulation. At the Tahiti location, the coral and the model are also quantitatively consistent, as both suggest a strengthening of interannual SST variability by 20-30% compared to modern conditions.

Modern and past ENSO teleconnections

Modern ENSO is well known for its atmospheric teleconnections of near-global extent. Understanding how teleconnections operate, both in the atmosphere and the ocean, is particularly relevant for the validity of paleoclimatic reconstructions, as they generally assume that atmospheric teleconnection patterns are stable. This may be particularly critical in the interpretation of proxy records not stemming from the core ENSO region. A composite analysis of atmospheric patterns (e.g. of sea level pressure) during all El Niño and La Niña events in the different simulations revealed obvious deviations from the modern spatial distribution of anomalies (Fig. 2). In particular, the teleconnections to the North American continent and the North Atlantic region seem to be strongly altered in terms of amplitude and spatial structure in the LGM and MIS3 simulations. This difference is probably caused by the presence of the glacial continental ice sheets and the glacial cooling of the North Atlantic, which both affect the position of the upper-tropospheric jetstream and atmospheric storm tracks, and thus the tropical-extratropical signal propagation. The typical intensification of the Aleutian low forced by El Niño (Fig. 2a) seems to be present during the LGM but is less pronounced, and the atmospheric bridge to the North Atlantic region seems to be interrupted, as no clear large-scale pattern is simulated there (Fig. 2b). The MIS3 stadial conditions (Fig. 2c) bear more resemblance to the control simulation over the North Pacific, whereas over the North Atlantic, the ENSO influence is clearly reduced, similar to the LGM situation. This points to a complex interplay of atmospheric dynamics with the various forcings in the different climatic states.

The need to learn more about glacial climatic states

In summary, our modeling study confirms that ENSO variability responds to various glacial climatic states. However, ENSO variability does not appear to be linearly linked to the strength of the AMOC. This calls for more detailed analyses, for instance in the form of glacial hosing studies in a multi-model approach (Kageyama et al. 2013). The different roles of the AMOC and the various glacial boundary conditions with respect to their impact on ENSO need to be further disentangled. Likewise, we emphasize that the concept of stationary teleconnections should only be applied to past climatic states with caution as they may be altered by different past boundary conditions and forcings internal and external to the climate system.

Selected references

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http://www.pages-igbp.org/products/newsletters/ref2013_2.pdf

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