Evaluation of Eemian and Holocene Climate Trends: Combining Marine Archives with Climate Modelling

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Abstract In an attempt to assess trends of Holocene sea-surface temperature (SST), two proxies have been compiled and analyzed in light of model simulations. The data reveal contrasting SST trends, depending upon the proxy used to derive Holocene SST history. To reconcile these mismatches between proxies in the estimated Holocene SST trends, it has been proposed that the Holocene evolution of orbitally-driven seasonality of the incoming radiation is the first-order driving mechanism of the observed SST trends. Such hypothesis has been further tested in numerical models of the Earth system with important implications for SST signals ultimately recorded by marine sediment cores. The analysis of model results and alkenone proxy data for the Holocene indicate a similar pattern in temperature change, but the simulated SST trends underestimate the proxy-based SST trends by a factor of two to five. SST trends based on Mg/Ca show no correspondence with model results. We explore whether the consideration of different growing seasons and depth habitats of the planktonic organisms used for temperature reconstruction could lead to a better agreement of model results with alkenone data on a regional scale. We found that invoking shifts in the living season and habitat depth can remove some of the model–data discrepancies in SST trends. Our results indicate that modeled and reconstructed temperature trends are to a large degree only qualitatively comparable, thus providing at present a challenge for the interpretation of proxy data as well as the model sensitivity to orbital forcing.

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1 Introduction

In order to examine sea-surface temperature (SST) trends caused by growing emissions of greenhouse gases and how they induce a significant impact on the Earth's climate, we need the knowledge about the variability of the natural system. Unfortunately, the instrumental record with a large-scale coverage of data goes back only to the time when human industrialisation started. Information beyond the instrumental record covering the last 150 years can only be obtained indirectly from two strategies. On the one hand, they can be derived from proxies that record past climate and environmental conditions. On the other hand, the past climate can be simulated using comprehensive models of the climate system under appropriate external forcing. Numerical climate models are clearly able to simulate a broad suite of phenomena in the current climate system, but their reliability on longer time-scales requires additional evaluation. Only climate records derived from paleoenvironmental proxies enable the test of these models because they provide records of climate variations that have actually occurred in the past.

2 Materials and Methods

a. Data: The proxy data work undertaken was focused on updating the global database for proxy-derived Holocene SST records, i.e., an SST synthesis based on alkenone-derived SST estimation, and a synthesis effort compiling the SST records derived from foraminiferal Mg/Ca was carried out (Leduc et al. 2010a).
b. Complex models: We use and evaluate a suite of atmosphere-ocean circulation models to evaluate the temperature evolution. We concentrate on ECHO-G (Lorenz and Lohmann 2004) and COSMOS (Fischer and Jungclaus 2010, 2011; Pfeiffer and Lohmann 2013), but use also data from time slice experiments as compiled in PMIP2 and PMIP3 (Lohmann et al. 2013).
c. Conceptual model and theoretical framework: A concept for the physical understanding of insolation-driven temperature variability on orbital timescales is developed. Based at this concept, the temperature evolution of the interglacials related to local insolation forcing is estimated (Laepple and Lohmann 2009).
d. Data-model and intermodel comparisons: We used several statistical techniques to compare data with models. We also participated on model intercomparisons (e.g., Lunt et al. 2013).

3 Key Findings

For the mid-Holocene, high obliquity results in more high-latitude summer insolation at the expense of low-latitude summer insolation. Obliquity explains most of the variance in the annual insolation, and the effect is symmetric between the hemispheres but asymmetric between the tropics and high latitudes. The seasonal template model (Laepple and Lohmann 2009) largely reproduces the Holocene temperature trends as simulated by coupled climate models and provides a theoretical framework for our project.

Our multi-proxy mapping reveals contrasting Holocene SST trends, depending upon the proxy used. To reconcile these mismatches between proxies, we find that foraminiferal Mg/Ca and alkenones paleothermometers may be skewed toward specific seasons (Leduc et al. 2010a) (Fig. 1). Following on a seasonality hypothesis, a first attempt to test and quantify the degree to which SST databases are seasonally-skewed was conducted in data-model comparisons aiming at filtering model output for different seasons and compare it to the SST database (Leduc et al. 2010a; Lohmann et al. 2013).

Using the coupled atmosphere-ocean general circulation model COSMOS with applied orbital forcing, we investigate the climate evolution and variability of the last two interglacial periods, the mid-Holocene (6 thousand years (ka) before present (BP)) and the Last Interglacial (LIG) (125 ka BP). Earth's orbital parameters in these two periods lead to an increase in the Northern Hemisphere's seasonal insolation

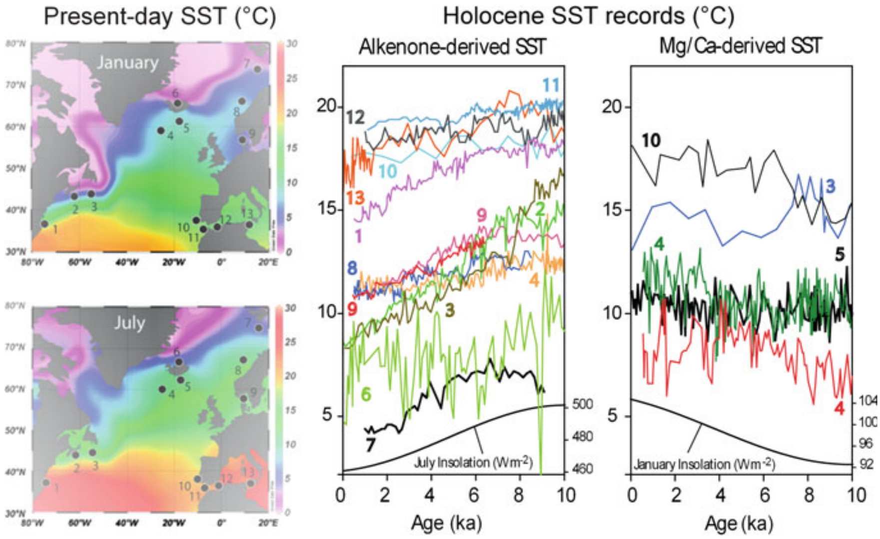

Fig. 1 *Left panels* modern-day seasonal anomalies in SST in the North Atlantic Ocean (in °C) and locations of marine sediment cores corresponding to the records shown in *right panels*. *Right panels* records for paleo-SST covering the last 10 ka and estimated from alkenone unsaturation index and planktonic foraminifera Mg/Ca measurements. Adapted from Leduc et al. (2010a)

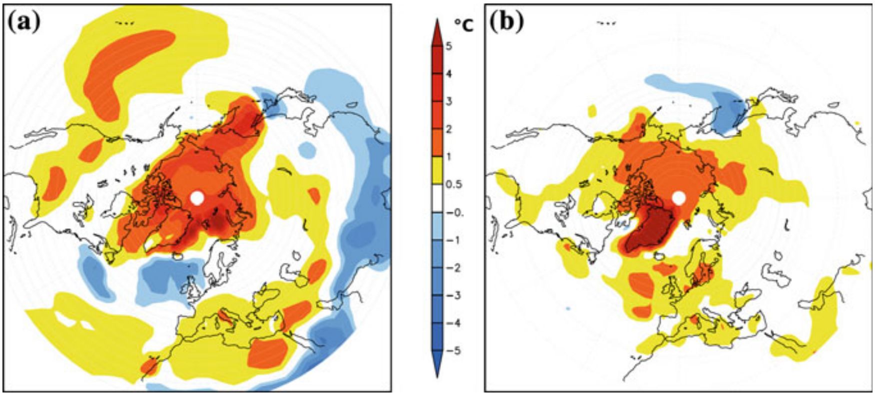

Fig. 2 Annual mean surface temperature anomalies for: **a** LIG minus the preindustrial control simulation, **b** LIG with reduced GIS by 1,300 m minus LIG. For the run with reduced GIS, the surface area and albedo have been consistently adapted

cycle. In high northern latitudes, an insolation-induced temperature increase is further enhanced by increased ocean heat transport and reduced sea-ice cover, resulting in an intensified ocean heat release (Fischer and Jungclaus 2010, 2011).

During the LIG, the northern high latitudes showed summer temperatures higher than those of the late Holocene, and a significantly reduced Greenland Ice Sheet (GIS). We perform sensitivity studies for the height and extent of the GIS at the beginning of the LIG (130 ka BP) using COSMOS. Our study shows that a strong Northern Hemisphere warming is caused by increased summer insolation (Fig. 2a). Reduced GIS elevation by 1,300 m contributes to a further warming of the LIG (Fig. 2b). These changed model boundary conditions lead to an effect of similar amplitude over high latitudes (up to 7 °C) compared to the run with orbital forcing only (Pfeiffer and Lohmann 2013).

Another goal of our project was to provide new records of SST variability over the last 3 millennia to evaluate Holocene transient simulations prescribed with solar variability, volcanic forcing, and greenhouse gas concentrations. A new high-resolution record from the Benguela upwelling system has been generated. The SST record pointed out that SST evolution over the past millennia in major upwelling systems were negatively correlated with temperature changes observed over larger regional scales because land-ocean interactions intensify Ekman pumping in response to a regional warming (Leduc et al. 2010b). In subsequent projects, we will further examine the role of external forcing onto climate trends and how they are recorded in proxy data.

Coupled general circulation models have been utilized to estimate the possible range of amplitudes for future climate change. Validation of these models by simulating interglacial climate states is essential for understanding the sensitivity of the climate system to external forcing. As a key issue in the ‘Interdynamic’ priority program of the German science foundation, we evaluated the interglacial dynamics by analyzing reconstructed and modeled SST trends *in tandem*. From our data-model comparison, we conclude that the SST sensitivity to orbital forcing seems to be underestimated in the models relative to the paleoclimate proxy data. More work is required to establish if such discrepancies can be caused by too simplistic interpretations of the proxy data, or by underestimated long-term feedbacks in climate models.

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