The glacial North Atlantic Oscillation

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Abstract

Based upon coupled climate simulations driven by present day and glacial boundary conditions, we demonstrate that the glacial North Atlantic Oscillation was characterized by four distinct centres of action and thus by an atmospheric circulation that differed radically in terms of its internal variability from modern conditions. Moreover, we show that although simulated modern climate supports a coupled atmosphere-ocean mode characterized by a timescale near 30 years (so-called Atlantic Multidecadal Oscillation, AMO), this mode is predicted to be absent under LGM conditions.

1. Introduction

It has long been recognized that the North Atlantic Oscillation (NAO) exerts a strong influence upon wintertime climate over North America and Eurasia (*Rogers* [1990], *Wallace and Gutzler* [1981]), as well as on marine, terrestrial and freshwater ecosystems (*Ottersen* [2001]). Despite its importance, the issue as to how the NAO has changed in the past or will vary in the future is unknown (*Cook* [2003]). For example, it is as yet unresolved as to whether NAO derived extratropical climate variability at Last Glacial Maximum (LGM) was stronger or weaker than it is at present. Climate simulations (e.g. *Justino et al.* [2005], *Peltier and Solheim* [2004], *Shin et al.* [2003], *Hewitt et al.* [2001]) have demonstrated that mean climate state at LGM was significantly different as compared to today, which raises the possibility that a distinct form of polar climate variability may also have existed during the glacial period.

While it has long been recognized that the NAO owes its essential existence to atmospheric dynamical processes (*Thompson et al.* [2003]), results of global coupled model (GCM) simulations driven by present day boundary conditions suggest a modification of this view (*Rodwell et al.* [1999], *Timmermann et al.* [1998]). In particular, it has been suggested (*Rodwell et al.* [1999]) that a large fraction of the inter-annual to inter-decadal variability of the winter NAO may be reconstructed on the basis of sea surface temperature (SST) variations. These issues may be further investigated in detail using GCM integrations designed to reproduce LGM climate. The presence of glacial ice sheets (Fig. 1b) exerts a strong influence upon the glacial wintertime atmospheric circulation over the North Atlantic due both to the mechanical forcing associated with the marked change in surface topography, and with the thermal forcing related to enhanced ice albedo feedback which in turn may result in a significantly modified spatial and temporal variability of the NAO.

2. The model and the coupled climate

The coupled atmosphere-ocean-sea-ice model employed in this study is the NCAR-CSM (*Kiehl et al.* [1998]). The atmospheric general circulation model is the low resolution version of CSM 1.4 that incorporates 18 vertical levels and 96 by 48 longitude and latitude grid points (T31). The dynamics of the ocean are described on 25 vertical levels on a 3 degree by 3 degree grid. In order to investigate the *glacial NAO* two model simulations have been performed: A modern simulation driven by present day boundary conditions (MOD) and a second experiment for the LGM (*Peltier and Solheim* [2004], *Peltier and Solheim* [2002]). In order to allow intercomparison of model simulations of LGM climate, the Paleoclimate Modelling Intercomparison Project (PMIP, http://www-lsce.cea.fr/pmip) has established a protocol for setting the four major boundary conditions that are required for the purpose of such analyses as follows: (I) orbital parameters are to be fixed to those corresponding to 21000 years ago, (II) ice sheet topography and albedo are to be fixed according to the ICE-4G or ICE-5G models (*Peltier* [1994], *Peltier* [2004]), (III) the land-sea mask and paleo sea level are also to be fixed according to the ICE-4(5)G models, (IV) the concentrations of the radiatively active atmospheric trace gases (CO_2, CH_4 and N_2O) are also to be adjusted based upon estimates from the Vostok ice core.

The MOD (LGM) experiment was run to equilibrium for 2000 (2500) years (*Peltier and Solheim* [2004], *Peltier and Solheim* [2002]) and the analyses discussed herein are based upon the last 500 years of each simulation. The annually and globally averaged SST in the MOD and LGM simulations are respectively near 18.5°C and 14.5°C. SST anomalies in the polar and mid-latitude regions, however, may reach values as high as -9°C. Obvious by inspection of Fig. 1b is the substantial increase of the sea-ice in the NH under LGM conditions. These modifications of surface ocean conditions lead to a significant reduction in the strength of NADW production and a simultaneous reduction in the depth to which NADW penetrates (*Peltier and Solheim* [2004], *Peltier and Solheim* [2002]). In addition, the inclusion of the LGM boundary conditions drastically changes the sea level pressure (SLP) distribution as compared to the modern simulation (Fig. 2a). Figure 2b shows that over the extratropical region an increase in the predicted glacial SLP develops that is primarily due to enhanced surface cooling and the attendant increase of atmospheric stability. Accompanying the increase in SLP in the LGM simulation there is also a predicted weakening of the Aleutian and Icelandic lows as a result of increased sea-ice extent that insulates the atmosphere from the underlying warmer ocean, thus cutting off the transfer of heat from the ocean to the atmosphere (see Fig. 1b).

3. Temporal and spatial climate variability

In what follows we investigate the temporal and spatial structure of the NAO based on empirical orthogonal function (EOF) and spectral analysis. The NAO is herein displayed in terms of its amplitude (Fig. 3a,d), obtained by regressing the hemispheric sea level pressure anomalies upon the leading principal component (PC) time series from the North Atlantic domain (20°-70°N, 90°W-40°E). The leading pattern of variability in the MOD simulation (Fig. 3a,b) is characterized by the existence of a well known characteristic dipolar structure over the North Atlantic, which is

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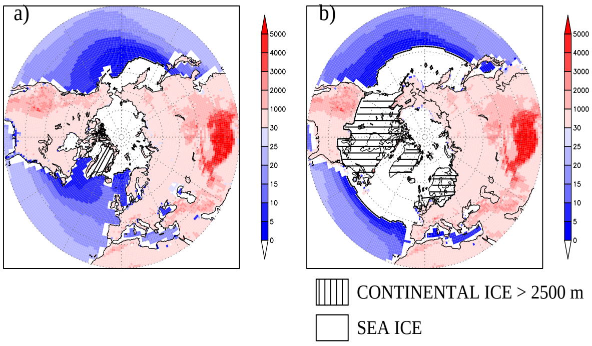

Figure 1. Northern Hemisphere planetary topographic height [m], SST [°C] and ice cover. Values smaller than 30 pertain to SST and larger than 30 to topographic height. The panel (a) for MOD simulation and (b) for LGM simulation. Ice on the surface of the continents is specified according to the ICE-4G model (*Peltier* [1994]).

dominated by two areas of strongest out-of-phase variability located over Iceland and the Azores/Iberian Peninsula. The first EOF accounts for 54% of the total variance. In addition to the characteristic surface pressure pattern, the predicted NAO under modern climate conditions also exhibits a prominent characteristic temporal variability. This is clearly shown by the power spectrum (Fig. 3b) of the first PC time series of SLP obtained by applying the Multi-Taper method (MTM) (*Thomson* [1982]). From Figure 3b it is evident that the NAO exhibits a significant concentration of power at interannual timescales of 2-4 years and at a multidecadal timescale near 30 years period which is dominant. This result agrees with previous analyses based on coupled model simulations (*Timmermann et al.* [1998], *Delworth et al.* [1993], *James and James* [1989]) as well as with results based on climate reconstructions (*Mann et al.* [1998], *Cook et al.* [1998], *Rogers* [1984]) from tree-rings and other proxies insofar as the existence of the multi-decadal signal is concerned. To provide an initial investigation of the interplay between the atmosphere and the ocean which supports the multi-decadal signal, the power spectrum for the first PC time series of SST calculated in the North Atlantic domain has also been computed (Fig. 3c). The spectrum of the SST is almost "red" (i.e., power increasing with period) but also clearly reveals the strong concentration of power at the same timescale near 30 years. Given this we may conclude that the interannual variability of the NAO is associated with the behavior of the atmosphere alone. At longer time scales, however, it is equally clear that air-sea coupling is significantly involved (*Rodwell et al.* [1999], *Timmermann et al.* [1998]).

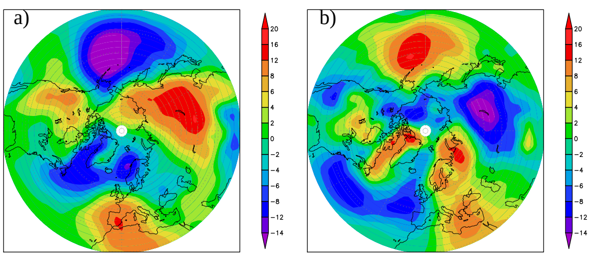

Figure 2. Distribution of eddy mean sea level pressure [hPa] (i.e., the sea level pressure with the zonal mean removed) in winter (DJF) for MOD simulation (a). (b) is the respective anomalies between the LGM and MOD simulations.

In order to study the *glacial NAO* identical EOF analyses were performed on the results obtained from the LGM simulation. These results reveal a markedly different picture compared to the results obtained from the modern simulation (Figs. 3d-f). The first EOF in the LGM run explains 59% of the total variance. It is interesting to note, moreover, that the surface pressure field is characterized by the existence of a quadrapolar structure with distinct centres of action over North America/Labrador Sea, over Siberia, over the Mediterranean Sea/Iberian Peninsula and over the North Pacific/Aleutian Islands (Fig. 3d). This result demonstrates that the north-south dipole of SLP anomalies over the North Atlantic that is characteristic of the present day NAO is shifted into an approximately east-west alignment in the LGM simulation. According to a simple quasi-geostrophic assumption, this SLP pattern would be associated with strongly meridional wind anomalies over the North Atlantic instead of the more zonal nature of the anomalous wind characteristic of the NAO under modern conditions (see the arrows on Fig. 3a,d indicating the lines of strongest SLP gradient which are approximately normal

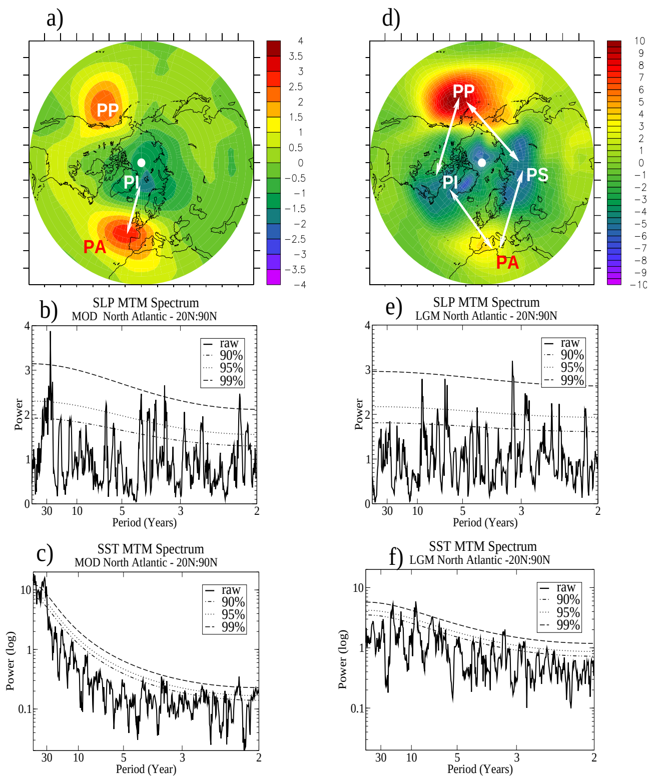

Figure 3. Figure 3. Leading EOF of SLP anomalies in DJF in the North Atlantic sector (20°-90°N, 90°W-40°E) for the MOD simulation (a) and the LGM simulation (d). The patterns are displayed as amplitudes (hPa) by regressing hemispheric SLP anomalies upon the standardized first principal component time series. Please note that figures a) and d) are shown with distinct labels. PI, PA, PS and PP are the main centres of action over Iceland, Azores, Siberia and the North Pacific, respectively. (b) and (e) are the MTM power spectrum for the first PC of SLP in the MOD and LGM simulations. (c) and (f) are the same as in (b) and (d) but calculated for SST. Also shown is the corresponding confidence levels (smooth lines), 90%, 95% and 99% for significance relative to the null hypothesis (red noise).

to the directions of anomalous wind). One should keep in mind that the present day westerly flow over the North Atlantic is not meridional in the glacial simulation but rather is shifted into a southwesterly-northeasterly orientation. Furthermore, over Eurasia a different atmospheric flow configuration is expected to be characteristic of high latitude variability as compared to modern conditions. When the EOF analysis is extended to include the SLP field for the entire polar region, rather than being restricted to the North Atlantic sector, we obtain a leading EOF that is essentially identical to the pattern shown on Figure 3a,d (not shown). We therefore assert that the LGM form of the Arctic Oscillation also has the same quadrapolar structure as the NAO.

The leading EOF in the LGM simulation also differs from its MOD counterpart over mid-latitudes. Whereas the southern centre of action is located near the Azores in the MOD simulation, this centre is shifted eastward over the Mediterranean region in the LGM simulation (*Peltier and Solheim* [2002]). Moreover, it is important to note the appearance of larger amplitude SLP anomalies over the North Pacific and their in-phase relationship with the changes over the Mediterranean region. This demonstrates that the topographic forcing and ice albedo feedback are both crucial to generating the quadrapolar form of the atmospheric variability, primarily due to the attendant modifications of the stationary and transient waves. Indeed, it has been shown previously that the LGM atmospheric circulation was characterized by highly significant changes of both transient and stationary waves (e.g. *Rind* [1987]) which are clearly reflected in the temporal and spatial variability of the NAO.

The incorporation of LGM boundary conditions also induces a distinct temporal variability of the *glacial NAO* as compared to the MOD simulation (Fig. 3e). The power spectrum of the *glacial NAO* is almost white but reveals somewhat enhanced variance near a period of 3 years. No other peak in the spectrum is significant at the 99% level. Additionally, Figures 3b,e demonstrate that the slightly enhanced power at 4-5 year periods in the MOD simulation is somewhat weaker in the LGM run. The latter experiment does reveal, however, an intensification in the sub-decadal period range from 5-10 years. The most striking difference between the LGM and MOD spectra of SLP, however, is the absence of the 30 year cycle in the LGM run. It should also be noted that the 30 year peak is entirely absent from the spectrum defined by the first PC time series of the North Atlantic SST calculated from the glacial simulation (Fig. 3f). To provide additional evidence for the link between the atmosphere and the underlying ocean we computed the power spectrum of the strength of the Atlantic meridional overturning circulation (MOC) for both the present day and the LGM simulations (not shown). In agreement with spectral analyses of the present day SST and SLP, the spectrum of the present day MOC shows a significant peak with a period of approximately 30 years. This signal is entirely absent from the results of the spectral analysis performed for the Atlantic MOC under LGM conditions (not shown).

Computations of the lagged regression between the present day MOC index and the SLP anomalies over the North Atlantic show that, at lag 0, a weakening of the MOC is accompanied by a positive amplitude phase of the NAO. This differs from previous analyses (e.g. *Carsten and Jung* [2001]) that show positive correlation. The anti-phase relantionship in our MOD simulation seems to be associated with a substantial increase of precipitation in the areas of deep water formation during positive phases of the NAO (not shown). Turning to analyses of the LGM conditions, it is interesting to note the high correlation (up to 0.6) between the leading PC of SST and SLP. In fact, this high correlation between SST and SLP is associated with the extensive sea-ice concentration that is captured in the EOF analysis of the glacial SST. This is evident by the high anti-correlation (-0.9) between the first PC of SST and the first PC of sea-ice. On the basis of these analyses it is reasonable to assume that the *glacial NAO* is not modulated by changes in the strength of the MOC, but rather is linked to the variability in sea-ice extent. This is illustrated on Fig. 4b that shows the high correlation between the SLP and sea-ice variability. Moreover, it is also clear that under MOD conditions (Fig. 4a) there is no substantial correlation between present day sea-ice variability and the first PC of SLP.

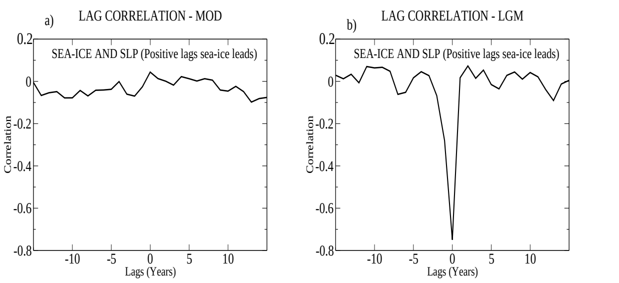

Figure 4. Figure 4. Lag correlation coefficient between the first PC of SLP and the correspond PC of sea-ice concentration for MOD simulation (a) and LGM simulation (b).

4. Summary and concluding remarks

Based on coupled climate simulations performed under present day and glacial boundary conditions, our analyses provide evidence that under modern climate conditions there exists a coupled climate mode characterized by a timescale of approximately 30 years. This marked feature of the modeled present day climate is completely absent in our simulation of LGM climate. The NCAR-CSM model predicts substantial changes in the form and the temporal variability of the *glacial NAO* as compared to the modern NAO. These changes are clearly caused by the presence of the Laurentide and Scandinavian ice sheets which induce profound changes of the stationary waves, sea-ice extent and the oceanic meridional overturning circulation. The *glacial NAO* is characterized by four centres of action located over North America/Labrador Sea, over Siberia, over the Mediterranean Sea/Iberian Peninsula and over the North Pacific. While during the positive phase of the modern NAO a strong westerly flow develops over the Atlantic Ocean, in the *glacial NAO* an enhanced southerly wind develops over this region, whereas cyclonic winds dominate the atmospheric flow over Siberia.

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