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[1] The mid-Holocene (6000 years before present) North Atlantic Oscillation (NAO) from nine models in the Paleoclimate Modeling Intercomparison Project Phase 2 is studied, primarily through principal component analysis of winter time North Atlantic sea level pressure (SLP). Modeled mid-Holocene NAO and mean SLP show small changes compared to pre-industrial control runs, with a shift in mean state towards a more positive NAO regime for three of the models. Modeled NAO variability shows little change, with a small increase for some models in the fraction of time spent in the NAO-negative phase during the mid-Holocene. Proxy based reconstructions of the NAO indicate a more positive NAO regime compared to present day during the mid- Holocene. We hypothesise that there was a small NAO+ like shift in mean state during the mid-Holocene. **Citation:** Gladstone, R. M., et al. (2005), Mid-Holocene NAO: A PMIP2 model intercomparison, *Geophys. Res. Lett.*, *32*, L16707, doi:10.1029/2005GL023596.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is the most prominent mode of variability in the Northern Hemisphere winter climate [*Wanner et al.*, 2001]. Although many aspects of European climate are closely correlated to the NAO [*Hurrell and Van Loon*, 1997; *Dickson et al.*, 2000], the driving physical mechanisms are not well understood. Climate models simulate this pattern with varying degrees of success [*Stephenson and Pavan*, 2003] and it remains uncertain whether they correctly represent changes in different climate regimes.

1.1. The PMIP2 Experiments

[3] Here we examine the mid-Holocene NAO using an ensemble of nine models (Table 1) from the Paleoclimate Modeling Intercomparison Project Phase 2 (PMIP2). Throughout this paper, mid-Holocene is defined as 6 thousand years before present (6ky BP).

[4] A key motivation for PMIP2 is to test state of the art climate models that are being used to predict future climate sensitivity against past climate states reconstructed from proxy data [*Harrison et al.*, 2002]. Here we investigate the response of modeled 6ky BP sea level pressure (SLP) over the North Atlantic region under the PMIP2 6ky BP boundary conditions (*Joussaume et al.* [1999], see also PMIP2 website http://www-lsce.cea.fr/pmip2). The main change in northern hemisphere forcing at 6ky BP is stronger insolation seasonality due to the precessional cycle. Icesheets, CO_2 and vegetation distribution are identical to the pre-industrial control experiment.

[5] Two advantages of PMIP2 over PMIP, for phenomena that vary on interdecadal timescales, such as the NAO, are the use of coupled ocean-atmosphere models and increased run length (100 years post-spinup for most models in the current study, Table 1).

1.2. Proxies for Mid-Holocene NAO

[6] Reliable proxies for NAO-like changes through the Holocene are sparse. Holocene precipitation changes reconstructed from a Greenland ice-core [*Knasper et al.*, 1995] and a glaciolacustrine study of Norwegian glaciers [*Nesje et al.*, 2001] have been interpreted as implying a centennial to millennial oscillation between positive and negative NAO regimes [*Brown*, 2003]. The largest negative peak in winter precipitation from *Nesje et al.* [2001] occurs at 10ky BP.

[7] B. A. S. Davis et al. (manuscript in preparation, 2005) identify a correlation between the winter-time European latitudinal temperature gradient and NAO, using temperatures reconstructed from pollen data [*Davis et al.*, 2003]. Their findings suggest a strongly negative NAO regime during the early Holocene (9–12ky BP) rising to a slightly positive NAO regime during the mid-Holocene, then decreasing to pre-industrial NAO.

[8] EOF analysis of alkenone based SST reconstructions [*Rimbu et al.*, 2003, 2004] suggests a strongly positive NAO regime during the early Holocene decreasing to a negative NAO regime at 2 ky BP (positive at 6ky BP).

[9] In summary, available proxies suggest a small long term trend to a more positive NAO regime at 6ky BP and possibly also centennial to millennial scale oscillations throughout the Holocene. There is disagreement over the NAO regime during the early Holocene.

2. Model Results

2.1. Mean Climate

[10] There is considerable variation in the December to February (DJF) change (6ky–0ky BP) in mean SLP across

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Table 1. Summary of PMIP2 Models Used in This Study[a]

Id	PMIP2 name	Model Designation	Length	Reference
HadCM3	UBRIS-HadCM3M2	UK Meteorological Office Unified Model run at Bristol University (UK)	100	*Gordon et al.* [2000]
CCSM	CCSM3	Community Climate System Model run at the National Center for Atmospheric Research, Boulder, Colorado	100	B. L. Otto-Bliesner et al. (Last Glacial Maximum and Holocene climate in CCSM3, submitted to *Journal of Climate*, 2005)
FOAM	FOAM	Fast Ocean Atmosphere Model run at Bristol University	100	*Jacob et al.* [2001]
GISS	GISSmodelE	Goddard Institute for Space Studies (USA)	50	*Schmidt et al.* [2005]
MIROC	MIROC3.2	CCSR, NIES and FRCGC (Japan)	100	*K-1 Model Developers* [2004]
MRI-fa	MRI-CGCM2.3.4fa	Meteorological Research Institute (Japan) coupled GCM with flux adjustments	100	S. Yukimoto et al. (The Meteorological Research Institute coupled GCM, Version 2.3 (MRI-CGCM2.3)—Control climate and climate sensitivity, submitted to *Journal of the Meteorological Society of Japan*, 2005, hereinafter referred to as Yukimoto et al., submitted manuscript, 2005)
MRI-nfa	MRI-CGCM2.3.4nfa	As above without flux adjustments	100	Yukimoto et al. (submitted manuscript, 2005)
UTor	UToronto	NCAR Climate System Model run at University of Toronto (Canada)	100	*Otto-Bliesner and Brady* [2001]
IPSL	IPSL	L'Institut Pierre-Simon Laplace model run at LSCE (France)	100	*Marti et al.* [2005]

[a]Length of run is in years.

models (Figure 1). Features common to several models include a region of lower mean SLP to the west of the UK (CCSM, MRI, HadCM3) and a tendency toward an increased latitudinal gradient in mean SLP (HadCM3, MIROC, FOAM).

[11] Resampling analysis of the 0ky and 6ky BP DJF SLP datasets does not show statistical significance in the 6ky–0ky BP DJF mean SLP difference for any of the models. One concludes from this either that there is no change, or that the change is small compared to modeled inter-annual and inter-decadal variability, in which case longer model runs would be needed to establish significance.

2.2. Modeled NAO

[12] Large-scale NAO patterns and indices are extracted by principal component analysis (PCA) on the DJF (December, January, February) SLP field for the models used in this study. The spatial domain is restricted to 120°W–60°E, 30°N–80°N as in the work by *Stephenson and Pavan* [2003].

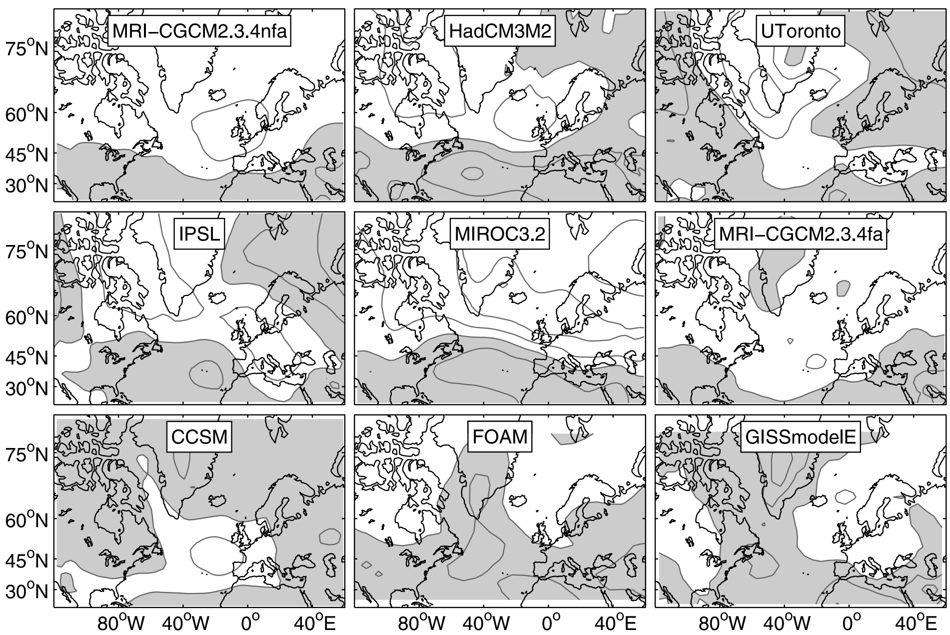

Figure 1. The modelled 6ky BP–0ky BP change in mean DJF SLP. Increases are shaded, contour interval is 100 Pa.

Table 2. Statistical Measures of 6ky BP NAO[a]

Model	PC SD		Percent +ve			Mean Prj[a]	Correlation Coeffs			
	0ky BP	6ky BP	0ky BP	6ky BP	Prj[a]		Mean	EOF	Mean & EOF	NAOI
HadCM3M2	6826	6678	51%	51%	65%	1.53	0.9998	0.9825	0.638	0.92
CCSM	10082	11849	57%	49%	45%	−0.84	0.9986	0.9879	−0.535	0.90
FOAM	3367	2793	57%	52%	59%	1.13	0.9922	0.9889	0.706	-
GISSmodelE	4030	4369	54%	45%	47%	−0.045	0.9922	0.9269	0.102	0.87
MIROC3.2	8987	7416	47%	51%	68%	2.87	0.9896	0.9915	0.792	0.93
MRI-CGCM2.3.4fa	8592	8113	53%	49%	48%	0.016	0.9974	0.9871	−0.028	0.94
MRI-CGCM2.3.4nfa	6669	8937	47%	47%	49%	0.51	0.9961	0.9676	0.258	0.82
UToronto	7228	8315	50%	51%	49%	−0.44	0.9948	0.9914	−0.142	0.86
IPSL	8223	8018	50%	49%	52%	0.044	0.9931	0.9538	0.024	0.84

[a]The first two columns show standard deviation (SD) of the leading principal components (PCs). Columns 3 to 5 show the percentage of positive years (percent +ve) of the leading PC at 0 and 6ky BP, and of the EOF projection (prj, see section 2.3). Column 6 shows the mean of prj, normalised for each model by division by number of grid points. Columns 7 to 10 show the Pearson correlation coefficients between the 0ky and 6ky BP mean winter SLP (col 7) and leading EOF (col 8), between the 6ky BP SLP anomaly and the 0ky BP leading EOF (col 9), and between the 0ky BP NAO index (NAOI) and leading PC (col 10).

[13] The NAO index (NAOI, normalised Iceland-Azores pressure difference) is also calculated. The NAOI is highly correlated to the principal component (PC) time series (see Table 2).

2.2.1. Anomalies in NAO Structure

[14] As found by *Stephenson and Pavan* [2003] the models generally reproduce the NAO structure well, as given by the leading EOF at 0ky BP [*Hurrell et al.*, 2003].

[15] For each model, the 0ky and 6ky BP leading EOFs are very similar. On the basis of resampling analysis, no model shows a significantly different leading EOF at 6ky BP compared to 0ky BP.

[16] The percentage of the total variability explained by the leading EOF increases from 0ky BP to 6ky BP in four models, decreases in four models, and remains unchanged in one model (Figure 2).

2.2.2. NAO Time Series

[17] The leading principal component time series are similar at 6ky and 0ky BP. There is no robust cross-model change in the variance of the PC time series (Table 2). However, four models (CCSM, FOAM, GISS and MRI) show 10–20% less time spent in the NAO positive phase at 6ky BP than 0ky BP. Four models show little or no change, and only MIROC shows an increase in time spent in the positive phase.

2.3. Anomalous 6ky BP Variability

[18] The 'anomalous 6ky BP variability' is defined for each model as the anomaly of 6ky BP DJF SLP with respect to 0ky BP mean DJF SLP. The projection of the 6ky BP anomaly onto the 0ky BP leading EOF (henceforth 'EOF projection') gives a measure of the structural similarity

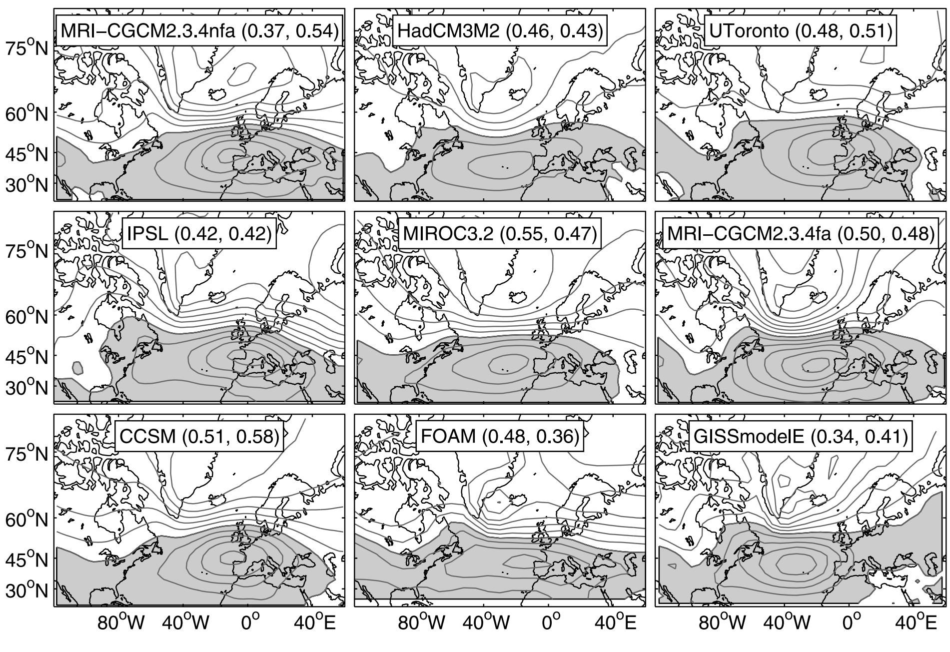

Figure 2. The leading EOF in SLP at 6ky BP for all models. The proportion of the total variability accounted for by the leading EOF at 0ky and 6ky BP respectively is shown in brackets after the model name.

between the 0ky BP NAO and the 6ky BP anomalous variability.

[19] The EOF projection in HadCM3 and MIROC shows 30–40% more time spent in the positive state than in the standard 0ky BP data, and there are correspondingly large increases in the mean EOF projection (Table 2).

[20] The mean EOF projection encodes similar information to the simple correlation coefficient between the 6ky BP anomaly and the NAO structure (i.e. the leading 0ky BP EOF), but, unlike the correlation coefficient, it also takes into account the strength of the anomaly (Table 2).

[21] FOAM, HadCM3 and MIROC all show both a strong correlation between the EOF projection and 6ky BP anomaly, and a large positive mean of the EOF projection, indicating that the mean SLP at 6ky BP for these models was closer to an NAO+ regime.

[22] CCSM shows a response in the opposite direction, with a negative NAO-like change in mean state at 6ky BP. However, the magnitude of both the EOF projection and the correlation coefficient are smaller for CCSM than for FOAM, HadCM3 and MIROC.

[23] The other models show smaller responses in both directions.

3. Discussion

[24] The proxy evidence for a change to a more positive NAO regime at 6ky BP may be interpreted in three ways. There may have been a greater amplitude of NAO variability, or more time spent in the NAO-positive phase compared to today. Both of these cases imply a shift in the mean state, along with changes in variability. Alternatively, there was an NAO-like shift in the mean state, with no change in variability. It is questionable whether this should be referred to as a positive NAO regime. None of the proxies have sufficient time resolution to explicitly capture the variability of the NAO, and so cannot distinguish between these interpretations.

[25] Based on the available model data (100 years in most cases), a significant change in mean DJF SLP at 6ky BP has not been established for any of the models studied here. Nor has a change in the interannual variability.

[26] However, six of the nine models studied do show a positive correlation between the 0ky BP leading EOF and the 6ky BP SLP anomaly. Also, six models show a positive projection of 6ky BP anomalous variability on the leading 0ky BP EOF. This weakly supports the argument for a positive NAO-like shift in the mean state of 6ky BP climate.

[27] Regarding 6ky BP variability, there is no evidence to suggest a shift to a more positive NAO.

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