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Oceanic Control of Decadal North Atlantic Sea Level Pressure Variability in Winter

Mojib Latif, Klaus Arpe, and Erich Roeckner

Max-Planck-Institut für Meteorologie, Hamburg, Germany

Abstract.
The predictability of winter-time North Atlantic sea level pressure (SLP) variability has been investigated by means of an ensemble of integrations with an atmospheric general circulation model (AGCM) forced by observed sea surface temperatures (SSTs) for the period 1951-1994. The results imply that the SLP variations on timescales of several years to decades may be predictable, provided the SST anomalies themselves used to drive the AGCM can be predicted. The model, however, suffers from systematic errors, and the simulated centers of action are shifted relative to those observed.

Introduction

The most prominent mode of atmospheric variability over the North Atlantic Ocean is the North Atlantic Oscillation (NAO, see *Hurrell* [1995] and references therein). The NAO affects the climates over North America and Europe and over parts of Africa (see *Lamb and Peppler* [1987], *Lamb and Peppler* [1991] and *Visbeck et al.* [1998] and references therein). The NAO is also felt by the North Atlantic Ocean through changes in the surface fluxes of momentum, heat and fresh water (see *Dickson et al.* [1996] and *Curry et al.* [1998]). The NAO exhibits strong year-to-year variability, but it has undergone also strong low-frequency changes during the last decades (Fig. 1).

Different hypotheses have been put forward to explain the low-frequency changes in the NAO. Internal atmospheric dynamics have been proposed by *James and James* [1989]. Different versions of *Hasselmann's* [1976] "stochastic climate model" have been used also to explain the origin of the decadal variability. *Delworth et al.* [1993], for instance, argue that the interdecadal variability in their model is consistent with the stochastic climate model scenario and describe the mode in their model as a stochastically forced ocean-only mode. *Saravanan and McWilliams* [1997] and *Sutton and Allen* [1997] highlight the role of spatially coherent stochastic forcing by the atmosphere which can lead to distinct time scales in the ocean in the presence of strong mean currents. *Frankignoul et al.* [1997] emphasize the role of stochastically forced Rossby waves in the ocean. Coupled ocean-atmosphere modes have been described by *Delworth et al.* [1997], *Grötzner et al.* [1998] and *Timmermann et al.* [1998]. Here, we are basically interested in the question whether the ocean is a pure "slave" which responds passively to the atmosphere, or whether changes in the ocean feed back onto the atmosphere.

In order to study this question we performed ensemble integrations with an AGCM that was forced by observed SSTs. Similar integrations have been performed by *Rodwell et al.* [1999] and *Mehta et al.* [1999] who found that the observed low-frequency changes in the NAO were quite reproducable when the SSTs were prescribed from observations. Such atmosphere model integrations provide some indications of the "potential" predictability of the NAO, because it is not clear a priori that the SSTs themselves are predictable.

Model, data and statistical methods

We used the ECHAM-4 AGCM described by *Roeckner et al.* [1996] to conduct an ensemble of integrations with observed monthly SSTs and sea ice distributions for the period 1951-1994. The model has been run at T42 (2.8°x2.8°) resolution and with 19 vertical levels. Four realisations were performed with different initial conditions but identical boundary forcing. The SSTs and sea ice distributions have been obtained from the GISST2.2 dataset of the British Meteorological Office (UKMO). Only the ensemble mean response which is a (crude) measure of the forced response is shown here. We restrict ourselves to the winter season and concentrate on the SLP variability.

For verification, we used the traditional winter-NAO index as defined by *Hurrell* [1995]. The model NAO index was computed by using the nearest grid points. Both the observed and model NAO indices were computed from the months December through March (DJFM). We compared our simulation additionally to the SLP anomaly fields derived from the NCEP reanalyses [*Kalnay et al.*, 1996] which were available for the period 1958-1998.

The model response and the NCEP reanalyses have been compared for the common period 1958-1994 by applying Canonical Correlation Analysis (CCA). CCA is a multi-variate statistical method which finds those patterns in two datasets that are most highly correlated

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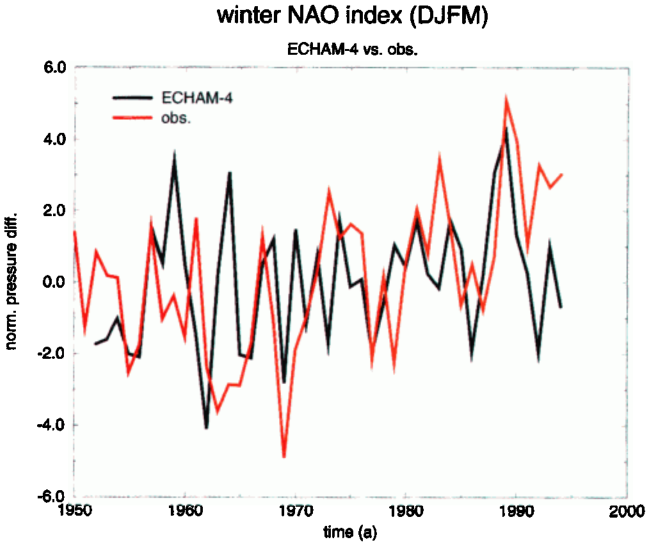


Figure 1. Observed winter (DJFM) NAO index as defined by *Hurrell* [1995] (red curve) and the ensemble mean winter NAO index simulated by the ECHAM-4 model (black curve). The NAO indices have been computed as the differences of the normalised pressure anomalies at Lisbon (Portugal) and Stykkisholmur (Iceland).

with each other in terms of their principal components (see e. g. *Barnett and Preisendorfer* [1987] and references therein). The CCA time series of the leading CCA mode were used to compute SST anomaly correlation patterns to study the relationship of the SLP variability to the anomalous SST.

Results

We compared first the simulated with the observed NAO index (Fig. 1). The model simulates the observed low-frequency variations reasonably well, especially after 1965. The correlation between the two time series amounts to 0.32 (which is significant on the 95% level) and to 0.43 if the period after 1965 is considered. The model fails to reproduce the year-to-year variability, which indicates that the high-frequency variations are mainly due to probably unpredictable internal atmospheric variability. The model underestimates strongly the secular variability, especially the drop in the NAO observed during 1950-1970, a result consistent with the model study of *Mehta et al.* [1999]. The reasons for the better simulation during the most recent period are unclear. Differences in the forcing SSTs used by *Rodwell et al.* [1999] and those used by *Mehta et al.* [1999] and in our study may explain part of the problem. One should keep in mind, however, that the observed evolution of the NAO is only one "single realisation", and one should not expect a perfect agreement, since the noise level of the atmosphere in midlatitudes is relatively large. Another possible reason for the model's failure could be related to systematic model errors. Such systematic errors may lead, for instance, to shifts in the variability centers.

In order to address this topic in more detail, we performed CCA between the winter (DJF) model SLP anomaly fields and those derived from the NCEP reanalyses. The leading CCA mode accounting for about 25% of the variance in each of the two datasets is closely related to the NAO. This can be inferred from the comparison of the two CCA time series with the NAO index (Fig. 2). The correlation between the two CCA time series amounts to 0.63 and that of the model CCA time series with the observed NAO index to 0.58. The year-to-year fluctuations are not well reproduced by the model, while the lower-frequency changes agree quite well. Thus, the CCA supports the picture that low-frequency SLP variations over the North Atlantic are largely controlled by changes in SST.

The two CCA patterns (Fig. 3) show clearly that the centers of action in the model and in reality are shifted relative to each other. Although both CCA patterns are dominated by a north-south dipole, the high-pressure center in the model is located too far to the west compared to the NCEP reanalyses. Furthermore, the model exhibits strongest changes in the high-pressure center, while the reanalyses show strongest changes further to the north in the region of the Icelandic low. Thus, the model response suffers from serious systematic errors. The major result, however, is that the model exhibits a consistent response to anomalous SST and sea ice distributions at low-frequencies, implying a great deal of potential predictability at decadal timescales.

Finally, we investigated the relationship of the SLP variability (associated with the leading CCA mode) to

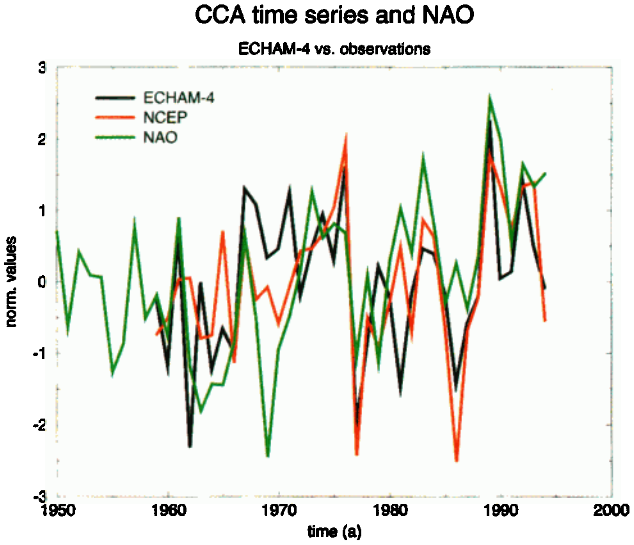
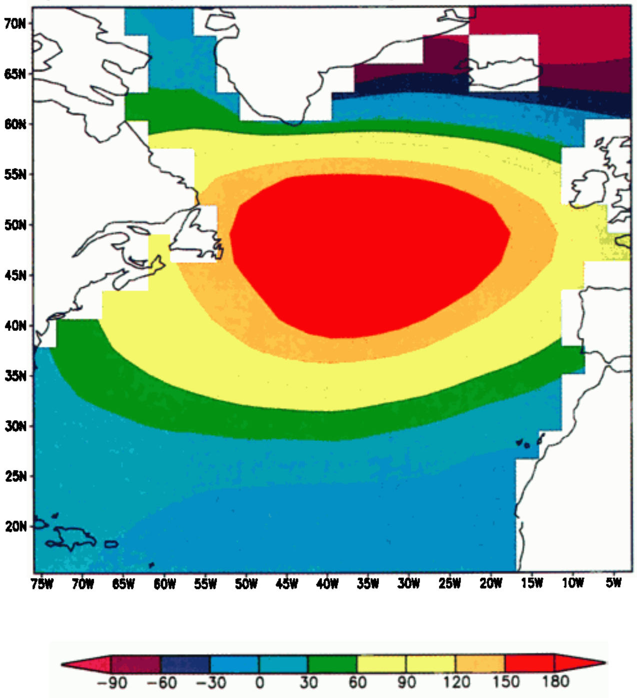


Figure 2. Time series of the leading CCA mode between the ensemble mean SLP anomalies of the model simulation and those derived from the NCEP reanalyses. The correlation between the two CCA time series amounts to 0.63. The CCA has been performed using winter (DJF) values and by retaining the five leading EOF modes explaining more than 90% of the variance in each dataset. The observed NAO index (shown in Fig. 1) is reproduced for comparison (green curve). The observed NAO has been scaled by a factor of two for better comparison with the CCA time series.

a) ECHAM pattern of leading CCA mode, 25 %



b) NCEP pattern of leading CCA mode, 26 %

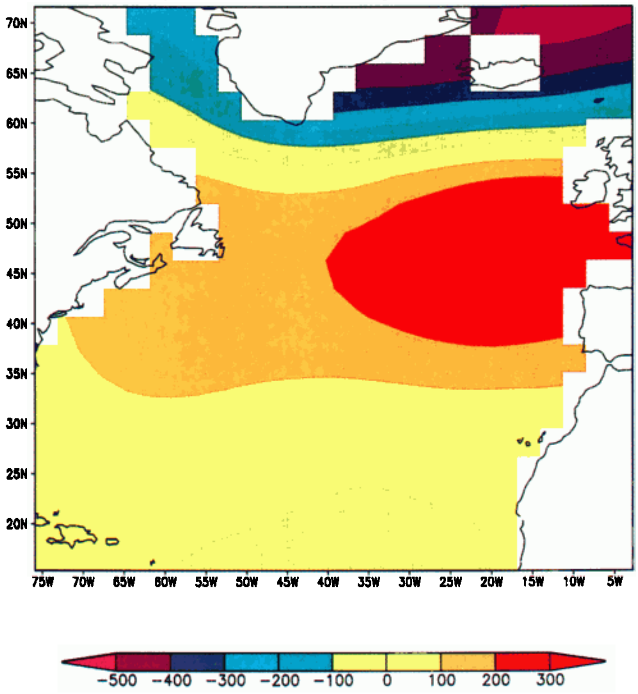


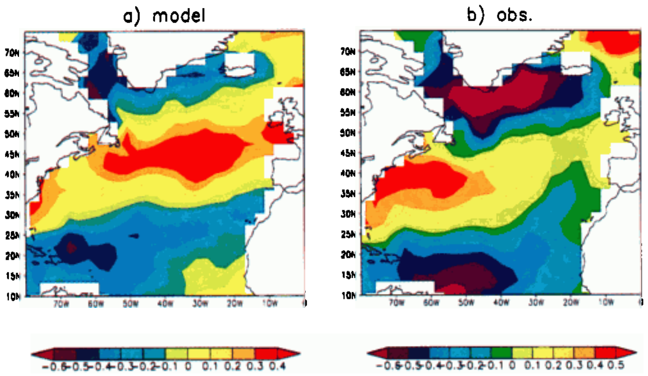
Figure 3. SLP anomaly patterns [Pa] of the leading CCA mode. a) Model pattern explaining 25% of the total variance and b) pattern of the NCEP reanalysis explaining 26% of the total variance.

the anomalous SST by computing correlation patterns using the CCA time series. As expected, the two SST anomaly patterns obtained from the model and the NCEP (CCA) time series are very similar to each other. We show therefore only the pattern obtained from the model time series (Fig. 4a). The SST anomaly pattern shows the well known three bands in the North Atlantic, with negative anomalies in high latitudes, positive SST anomalies in midlatitudes and negative anomalies in the subtropics. We note, however, that the SST anomalies are somewhat shifted relative those connected to the (observed) NAO (Fig. 4b). This indicates that the response characteristics of our model may be somewhat different to those of the real atmosphere.

Remote forcing from the Pacific may be also important. Relatively high correlations are found in both the equatorial Pacific and the North Pacific (not shown). Additional experiments performed with Pacific SST anomalies observed during the El Niño winter 1997/1998 support the picture of a significant remote response of the atmosphere over the North Atlantic to Pacific SST anomalies [*Grötzner et al.*, 1999]. Thus, our model integrations suggest that the SLP variability over the North Atlantic is not only governed by North Atlantic SST anomalies but also by Pacific SST anomalies, a result that is consistent with the findings of *Venzke et al.* [1999].

Summary and discussion

We have performed ensemble integrations with the ECHAM-4 AGCM forced by observed SST and sea ice distributions for the period 1951-1994 to study the potential predictability of North Atlantic SLP variability. Our results confirm earlier conclusions (*Rodwell et al.*, 1999; *Mehta et al.*, 1999) that SLP variations on decadal timescales may be predictable to the extent the SSTs themselves are predictable. The model, however, suffers from some systematic errors, which lead to errors in the spatial structure of the response. At this stage it is unclear which model errrors cause the errors in the response.


a) model

b) obs.

Figure 4. SST anomaly correlation patterns to a) the model time series of the leading CCA mode and b) the observed NAO index.

Different questions arise from this study. First, are the anomalous boundary conditions predictable? A few studies indicate that SST anomalies are indeed predictable at decadal timescales (e. g. *Griffies and Bryan* [1997] and *Sutton and Allen* [1997]). Another important question is the role of air-sea coupling. One could take in principal three different views. First, one may argue (e. g. *Bretherton and Battisti* [1998]) that the ocean is basically a slave to the atmosphere. Second, the atmosphere responds to the low-frequency changes in the SST, but the SST variability is still consistent with the simple stochastic climate model scenario, according to which the ocean integrates the high-frequency weather fluctuations. Thirdly, one may argue that the air-sea coupling is instrumental in causing specific modes of climate variability such as the El Niño/Southern Oscillation (ENSO) phenomenon (e. g. *Latif and Barnett* [1994], see also *Latif* [1998] for a more detailed discussion). At this stage of research, we are not in the position to distinguish between the three scenarios. Our results, however, indicate that the ocean is not purely slaved to the atmosphere. Finally, the relative roles of Pacific and Atlantic SST anomalies in driving the low-frequency SLP variability over the North Atlantic need to be investigated.

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M. Latif, K. Arpe, and E. Roeckner, Max-Planck-Institut für Meteorologie, Bundesstr. 55, D-20146 Hamburg, Germany, (email: latif@dkrz.de; arpe@dkrz.de, roeckner@dkrz.de)

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