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Oceanic influence on the North Atlantic Oscillation and associated Northern Hemisphere climate variations: 1959-1993

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Abstract. The North Atlantic Oscillation (NAO) exhibits variations at interannual to multidecadal time scales and is associated with climate variations over eastern North America, the North Atlantic, Europe, and North Africa. Therefore, it is very important to understand causes of these NAO variations and assess their predictability. It has been hypothesized, based on observations, that sea surface temperature (SST) and sea-ice variations in the North Atlantic Ocean influence the NAO. We describe results of an ensemble of sixteen experiments with an atmospheric general circulation model in which we used observed SST and sea-ice boundary conditions globally during 1949-1993. We show that multiyear NAO and associated climate variations can be simulated reasonably accurately if results from a large number of experiments are averaged. We also show that the ambiguous results of previous NAO modeling studies were strongly influenced by the ensemble size, which was much smaller than that in the present study. The implications of these results for understanding and predictability of the NAO are discussed.

1. Introduction

Sir Gilbert Walker defined [*Walker and Bliss*, 1932] oscillations in sea-level atmospheric pressure (SLAP) between Iceland and the Azores as the North Atlantic Oscillation (NAO). More broadly, the NAO is a measure of oscillations in atmospheric mass between sub-polar and sub-tropical latitudes in the North Atlantic region. The NAO is known (see, for example, *Hurrell* (1995), *Kushnir* (1999), and references therein) to play a leading role in orchestrating wintertime weather and climate variations in eastern North America, the North Atlantic, and Europe. In the North Atlantic Ocean, the NAO-associated wind and precipitation anomalies influence temperature, oceanic convection, deep-water formation, and primary production. Therefore, it is very important to understand causes of the NAO variations at interannual and longer time scales, and to assess predictability of the NAO and associated climate variations.

In view of its societal impacts, there have been numerous attempts (see, for example, *Lau* (1997) and references therein) to simulate the NAO variability. Some observational studies have suggested associations between low-frequency variations in the North Atlantic sea surface temperatures (SSTs) and the NAO. Therefore, much of the simulation work has consisted of experiments with numerical models of the atmospheric general circulation, in which observed SSTs were imposed as the lower boundary condition and the models were integrated in time. Whereas weather and climate variability in the actual atmosphere can be "realized" only once, weather and climate variability in models can be realized an arbitrary number of times by repeated integrations from an arbitrary number of slightly different initial conditions, while using the same, time-varying boundary conditions. The random component of the variability can then be reduced by averaging these realizations.

Most of the modeling studies (see, for example, *Kushnir and Held* (1996), *Lau* (1997), and references therein) that attempted to simulate NAO variability as a re-

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sponse to SST variability consisted of ensembles of a few realizations with an atmospheric general circulation model (AGCM) and their results have been inconclusive. Recently, an ensemble of six experiments with the United Kingdom Hadley Center AGCM [*Rodwell et al.*, 1999; hereafter referred to as RRF] showed that multiyear variations in the NAO index from individual AGCM simulations conducted with observed, time-varying, SST and sea-ice boundary conditions correlate poorly with multiyear variations in the observed NAO index during 1947-1997. The multiyear NAO variations averaged over the entire ensemble, however, correlate reasonably well with the observed NAO index. Further experiments with the Hadley Center AGCM suggested that the simulated, ensemble-average NAO variations were caused by SST variations in the midlatitude North Atlantic. The relationship between the accuracy of NAO simulations and the number of realizations, however, is not clear from these studies. The accuracy of associated climate variations is also not clear from these studies.

Independently of the RRF study, we conducted a 16-member ensemble of experiments with the AGCM used in the NASA Seasonal-to-Interannual Prediction Project. Each experiment was of 45 years (1949-1993) duration; these experiments were conducted using identical, observed SST and sea-ice boundary conditions but using initial conditions from 16 different Januarys. Preliminary results on the simulation of multiyear NAO variations and associated climate variations are described here.

2. Simulation of multiyear variations in the NAO

The AGCM has a horizontal grid spacing of 5° longitude and 4° latitude; it has 22 levels in the vertical. Further description of the model and other results from these experiments are given in *Koster et al.* (2000). In these 16 experiments, observed global SSTs and sea-ice fraction from the GISST 2.2 [*Rayner et al.*, 1996] data set for 1949-1993 were imposed as the lower boundary condition of the AGCM. In the analyses reported in this article, we have used model data from 1959 to 1993.

To compare observed NAO variations with those simulated in the 16 AGCM experiments, we calculated

Table 1. Standard deviations (millibars) of sea-level atmospheric pressure over the northern and southern poles of the North Atlantic Oscillation in (1) station and (2) NCEP reanalysis for 1959-1993. The average standard deviation of the 16 AGCM experiments (3) and the standard deviation of the 16-experiment ensemble-average (4) are also shown. The station data are from Iceland and the Azores.

	1	2	3	4
North	5.3	4.2	5.2	2.1
South	3.2	3.0	2.6	1.1
North minus South	8.0	6.6	7.3	2.8

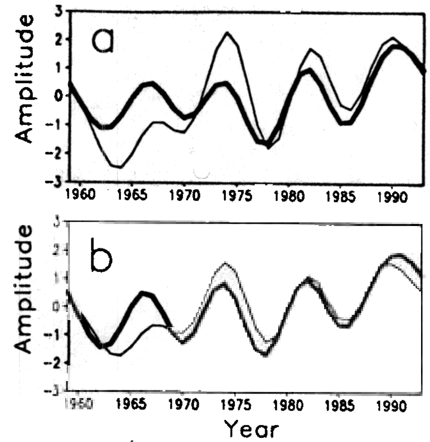

Figure 1. Low-pass filtered, observed (thin line) and ensemble-average, simulated NAO indices (thick line). (a) NAO indices defined as in *Hurrell* (1995), and (b) NAO indices defined as in *Rodwell et al.* (1999). See text for details.

the NAO index from each of the 16 AGCM experiments. Monthly SLAP anomalies, with respect to each experiment's average annual cycle, from December to March were averaged within a northern box (30°W-10°W, 58°N-70°N) over Iceland and a southern box (20°W-5°W, 34°N-46°N) over the Azores for each year from 1959 to 1993. Northern and southern SLAP anomalies from all 16 experiments were then averaged. Such averages are hereafter referred to as the ensemble-average. Following *Hurrell* (1995), the ensemble-average northern and southern SLAP anomalies were then normalized by their respective standard deviations, and the normalized northern SLAP anomalies were subtracted from the normalized southern SLAP anomalies to form the NAO index based on ensemble-average SLAP anomalies. An observed NAO index time series was also calculated from SLAP observations in Iceland and the Azores for 1959-1993. As shown in Table 1, while the average variability of the simulated SLAP anomalies associated with the NAO is reasonably similar to variability of the observed SLAP anomalies over Iceland and the Azores, the ensemble-averaging considerably reduces variability of the average SLAP anomalies. Therefore, the simulated, ensemble-average NAO is considerably weaker than the observed NAO.

To analyze low-frequency (LF) variations in the NAO, we filtered both the observed and simulated NAO index time series with a Fourier filter that passed through periods equal to or longer than approximately seven years. The LF, observed and simulated, NAO index time series are shown in Figure 1a. Multiyear variations in the observed and simulated NAO indices are similar from the late-1970s to the end of 1993. Before the late-1970s, however, the two are substantially different in amplitude but similar in phase. The overall correlation coefficient between the observed and simulated NAO indices in Figure 1a is 0.75. Since the dominant, multiyear timescale in the spectra of the observed and ensemble-average NAO time series during this 35-year

(1959-93) period is approximately 7 years, the LF time series can be assumed to contain five independent realizations of the 7-year oscillation. If we adopt the null hypothesis for the filtered data that the non-zero correlation coefficient between the observed and simulated NAO indices is due to chance, then the threshold correlation coefficient to reject the null hypothesis is 0.68 for 90% confidence and 0.8 for 95% confidence for five degrees of freedom. Therefore, the null hypothesis can be rejected with a reasonably high confidence. Correlation coefficients between multiyear variations in the simulated, ensemble-average NAO index and the observed NAO index (Fig. 1b) is slightly larger (0.81) if RRF's NAO definition is used. All subsequent analyses were performed with conventionally-defined NAO indices.

To explore the response of the simulated NAO and associated climate variations to the imposed boundary conditions, we calculated correlation coefficients between the NAO index, and SLAP and rainfall anomalies in the Northern Hemisphere. Ensemble-average data from the 16 AGCM experiments, SLAP anomalies from the atmospheric reanalysis data set produced by the National Centers for Environmental Prediction, and an observed rainfall data set produced by *Dai et al.* (1997) were used in these calculations. Spatial patterns of correlation coefficients (not shown) between LF components of the observed and ensemble-average model SLAP anomalies, and the corresponding NAO indices are remarkably similar. Both show oscillations in atmospheric mass between the middle and high latitudes, but largely confined to the sector from eastern North America to central Europe and North Africa. Both also show the involvement of the Arctic atmosphere in this oscillation. Spatial patterns of correlation coefficients (not shown) between LF components of the observed and ensemble-average model rainfall anomalies, and the corresponding NAO indices are also remarkably similar, especially over the North Atlantic and Europe.

3. Number of realizations and emergence of oceanic influence on the NAO

Visual and statistical comparisons of the 16 realizations of the simulated NAO showed that the correlation coefficient between the NAO index formed from individual realizations and the observed NAO index ranged from practically zero to almost one. Groups of NAO realizations were then averaged to reduce the random component of variability; each group contained 1 to 16 simulated NAO realizations. These group-average, simulated NAO time series were used to calculate correlation coefficients between the observed and simulated NAO time series. All possible combinations of realizations were included in these calculations. Correlation coefficients were calculated using unfiltered as well as low-pass filtered NAO time series; scatter plots of correlation coefficients as a function of the number of realizations averaged in a group are shown in Figure 2. The average correlation coefficient for each group is also shown in Figure 2.

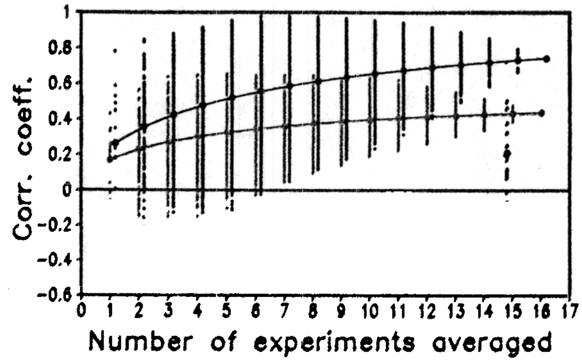

Figure 2. Correlation coefficients between the observed NAO index and a simulated NAO index averaged from various combinations of the 16 AGCM experiments; dots denote correlation coefficients calculated using unfiltered data (blue) and low-pass filtered data (red, displaced to the right), solid lines denote average correlation coefficients. Black dots denote correlation coefficients between each simulated NAO index and the average of the remaining 15 simulated NAO indices, larger black dot denotes the average correlation coefficient. See text for details.

For unfiltered and filtered data, the possible range of correlation coefficients moves towards higher values with increasing group size as progressively larger amounts of random variability are "averaged out". As more realizations are averaged and the number of possible combinations decreases, the range of correlation coefficients starts to decrease until forced to a single-point convergence at group size 16. The increase in the average correlation coefficient is rapid as the number of experiments in the group-average increases from one to approximately six, and then the increase slows down considerably. For the ensemble-average of all 16 realizations, the correlation coefficient between the simulated and the observed NAO indices is 0.43 for unfiltered data and 0.75 for low-pass filtered data. The latter is identical to the correlation coefficient between the observed and simulated NAO indices shown in Figure 1a.

In order to compare LF NAO variations forced by LF variations in the SST and sea-ice boundary conditions with LF NAO variations generated by noise in the AGCM, we calculated correlation coefficients between each of the 16 low-pass filtered, simulated NAO time series and the ensemble-average of the remaining 15 low-pass filtered, simulated NAO time series. These correlation coefficients and their average are also shown in Figure 2. When NAO indices from individual AGCM experiments are thus correlated with the 15-member ensemble-average, the spread in the correlation coefficients is quite large (approximately -0.2 to 0.7) but the average correlation is only 0.21, whereas the correlation coefficient between the observed LF NAO index and the 15-member, ensemble-average, simulated LF NAO index is 0.73. This is a surprising result: the 15-member ensemble-average of the AGCM simulations "explains" approximately 50% of the variance in nature's one "realization", but, on average, only 4% of the variance of its own realizations. The high correlation between the ensemble-average NAO and the observed NAO implies that the AGCM is able to simulate the correct atmospheric response to variations in SST and sea-ice boundary conditions, but detecting this response in these experiments requires removing most of the background noise generated in the AGCM. Also, as Figure 2 shows, the SST-forced signal is much stronger at low frequencies than at high frequencies; therefore, the average correlation coefficients between LF components of the observed and simulated NAO variations are systematically larger.

In previous simulation studies of the NAO with models of the global atmosphere, only a few realizations of the NAO variations were obtained. As Figure 2 shows, correlation coefficients between the observed and simulated LF NAO variations can fall virtually anywhere between -0.3 and almost 1 if a small number of realizations are averaged. There were six experiments in RRF's ensemble, yielding a correlation coefficient between the observed and the ensemble-average LF NAO of 0.74. This is well within the range shown in Figure 2 for an ensemble of six experiments. Another group of six experiments with the AGCM used in RRF could yield a significantly different correlation coefficient.

4. Concluding remarks

Predictability of the NAO has enormous implications for climate predictions over North America, the North Atlantic, and Europe. The results presented here, like those of RRF and a recent study by *Latif et al.* (1999), show that AGCMs can be used to obtain the NAO-related atmospheric circulation patterns forced by multiyear SST variations. The ability to make useful climate predictions in the eastern North America-North Atlantic-Europe sector, therefore, depends on the ability to predict the SST patterns associated with the multiyear NAO variations. Realizing potential predictability also requires an understanding of how these LF NAO variations are forced by SST variations.

A related and very important, unresolved issue is the role of the NAO variability generated by intrinsic atmospheric dynamics. One possible interpretation of our results and those of RRF is that LF SST anomalies associated with the NAO arise from purely oceanic processes and that the atmosphere is passively responding to these SST anomalies. In this case the AGCM experiments we have conducted using imposed SST anomalies are appropriate to assess the "signal-to-noise" ratio. But the fact that, on average, the AGCM's ensemble-average NAO correlates much better with nature than with any of its component realizations (Fig. 2) implies that the AGCM is erring by an order of magnitude in this ratio. Large errors in "signal-to-noise" ratio are found to occur in AGCMs' extratropical response to tropical, interannual SST anomalies (Shukla, personal communication). Neverthless, we believe that it is unlikely that AGCM errors alone can account for the results presented here. A second possibility is that the LF NAO is a thermodynamically-coupled, ocean-atmosphere process over the North Atlantic. Positive feedbacks from the coupling can amplify chaotic variability of the atmosphere [*Barsugli and Battisti*, 1998]. If this is the case, the atmospheric "noise" would be correlated with SST anomalies, particularly at low frequencies, while this noise would be independent from the imposed SSTs in our experiments. This possibility was proposed by *Bretherton and Battisti* (1999) as an explanation of our results and those of RRF. The ensemble-average, anomalous surface heat flux in our study, as also in RRF, however, is such that it would tend to provide a negative feedback to SST anomalies. Further experiments with AGCMs and coupled ocean-atmosphere models should allow us to clarify the relative roles of these mechanisms in producing the NAO's LF variability. Such experiments are in progress.

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