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Prospects for decadal prediction of the North Atlantic Oscillation (NAO)

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[1] For certain, but realizable, states of the thermohaline and wind driven circulation of the North Atlantic Ocean, we demonstrate the possibility of making statements regarding the likely range of values to be taken by the annual average of the NAO-index on time scales out to a decade. Given that the North Atlantic is currently in such a predictable state, a simple surrogate model yields a prediction that the NAO index is more likely to be positive than negative for the next couple of years, followed by several years in which the NAO index is more likely to be negative. *INDEX TERMS:* 4215 Oceanography: Climate and interannual variability (3309); 4263 Oceanography: Ocean prediction; 4504 Oceanography: Air/sea interactions (0312); 4255 Oceanography: Numerical modeling

1. Introduction

[2] The NAO accounts for 30% of the variance in winter mean surface air temperature over the northern hemisphere [*Hurrell*, 1996] and has a major influence on winter weather in Europe [*Kushnir*, 1999; *Greatbatch*, 2000]. Several authors [*Rodwell et al.*, 1999; *Mehta et al.*, 2000] have shown that atmospheric general circulation models (AGCM's), forced by the historical record of sea surface temperature (SST) and sea-ice, can reproduce, in an ensemble mean sense, the observed NAO index (NAOI). Knowledge of the future evolution of SST therefore permits useful long-term forecasts of the atmosphere. The important caveat is that the SST must itself be predictable. *Bretherton and Battisti* [2000] consider a very simple coupled model (BB) in which SST is the integrated response to forcing by atmospheric (white) noise. After a couple of months, the SST is as unpredictable as the (white) weather noise driving it, with the consequence that the NAOI in the BB model is also unpredictable. Nevertheless, in ensembles of atmosphere-only experiments with specified SST, the BB model reproduces the results of the complex AGCM's. We exploit this finding and couple the atmospheric component of the BB model to a realistic model of the Atlantic Ocean. We demonstrate that information about the dynamical state of the ocean can sometimes extend the predictability of SST, and hence potentially of the NAOI, on time scales out to a decade, confirming previous speculations [*Griffies and Bryan*, 1996; *McCartney*, 1997].

[3] The BB model is similar to the stochastic climate model [*Hasselmann*, 1976], and is formulated as a simple heat balance for the lower atmosphere (T_a) and the upper, mixed layer of the ocean (T_o). The unpredictable atmospheric weather is specified as a stochastic variable (N) with a Gaussian distribution characterized by mean zero and variance one (white noise); i.e.

$$\dot{T}_a = bT_o - aT_a + N, \ \ \beta\dot{T}_o = cT_a - dT_o$$

To relate the BB model to the more complex SST-forced AGCM experiments, *Bretherton and Battisti* [2000] interpret their atmospheric variable T_a as the NAOI and the oceanic variable T_o as a certain SST-index for the North Atlantic. Following the argument by *Marshall et al.* [2001], this SST-index can be regarded as the north-south SST gradient that underlies the atmospheric jet stream, with the potential to influence the atmosphere, and hence the NAOI, by modifying the local baroclinicity.

[4] In this study, we have replaced the ocean component of BB with a realistic model (OGCM) of the Atlantic Ocean [*Eden and Jung*, 2001; *Eden and Willebrand*, 2001]. The model is able to reproduce important aspects of the observed decadal and interdecadal changes in circulation and water masses when driven by surface fluxes only. To obtain T_o (required for the atmospheric component of BB), we project SST anomalies produced by the OGCM on to a fixed SST (feedback) pattern, corresponding to the north-south SST gradient. The pattern is derived from a regression of observed SST [*Smith et al.*, 1996] against the NAOI. We take this projection to be proportional to T_o, use the atmospheric component of BB to compute T_a, associate T_a with the NAOI, and then force the OGCM with NAO-related surface heat flux and wind stress anomalies (i.e. the same as in *Eden and Jung* [2001]). Scaling parameters are needed to convert the SST projection to T_o, and T_a to the NAOI. The scaling ensures that the variance of the NAOI and the SST projection implied by the original BB model are the same, respectively, as the variance of the observed NAOI, and the SST projection from a previous hindcast simulation with the OGCM [*Eden and Willebrand*, 2001]. Note that we are not implying any causality by using the SST feedback pattern. Rather, the aim is to reduce the ocean-atmosphere interaction to a single degree of freedom. More details about the coupling can be found in *Eden et al.* [2001], in preparation.

2. Results

[5] Figure 1a shows T_o from a 170-year-long coupled experiment (Exp. COUPLED), together with T_o from an integration of the original BB model. Both experiments are driven by the same realization of the weather noise. Note that the variance of T_o in COUPLED and the original BB model are comparable in size, confirming a posteriori our scaling for T_o. However, T_o from COUPLED obviously shows a more quasi-periodic behavior compared to T_o from the BB model. We conclude that including a more realistic ocean leads to different behavior from that of the BB model, but what is the reason? We have made use of an experiment in which the OGCM is forced by a positive NAO that is suddenly switched on and kept constant for several years, without any feedback to the atmosphere (Exp. HIGHNAO). Figure 1b shows T_o from HIGHNAO, compared with an equivalent experiment using the BB model. While T_o for the BB model shows an increase and a saturation after about 10 years, T_o in HIGHNAO resembles the behavior of a damped oscillator, with a rapid increase (positive feedback to the NAO) and a decrease after about 5 years (negative feedback to the NAO). It is this damped oscillation which extends the potential predictability of the SST and the NAO to decadal time scales.

[6] The damped oscillation is caused by the dynamical response of the ocean and the associated northward heat transport [*Eden and*

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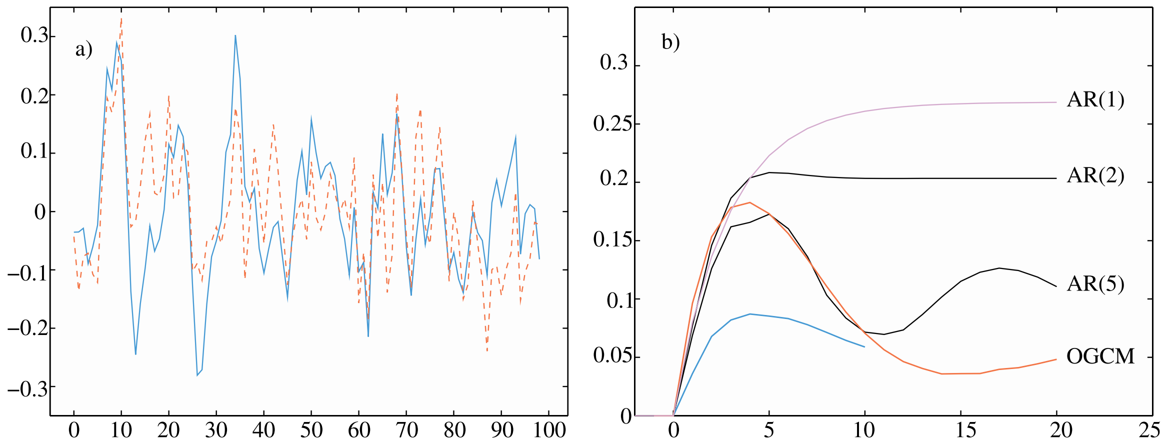
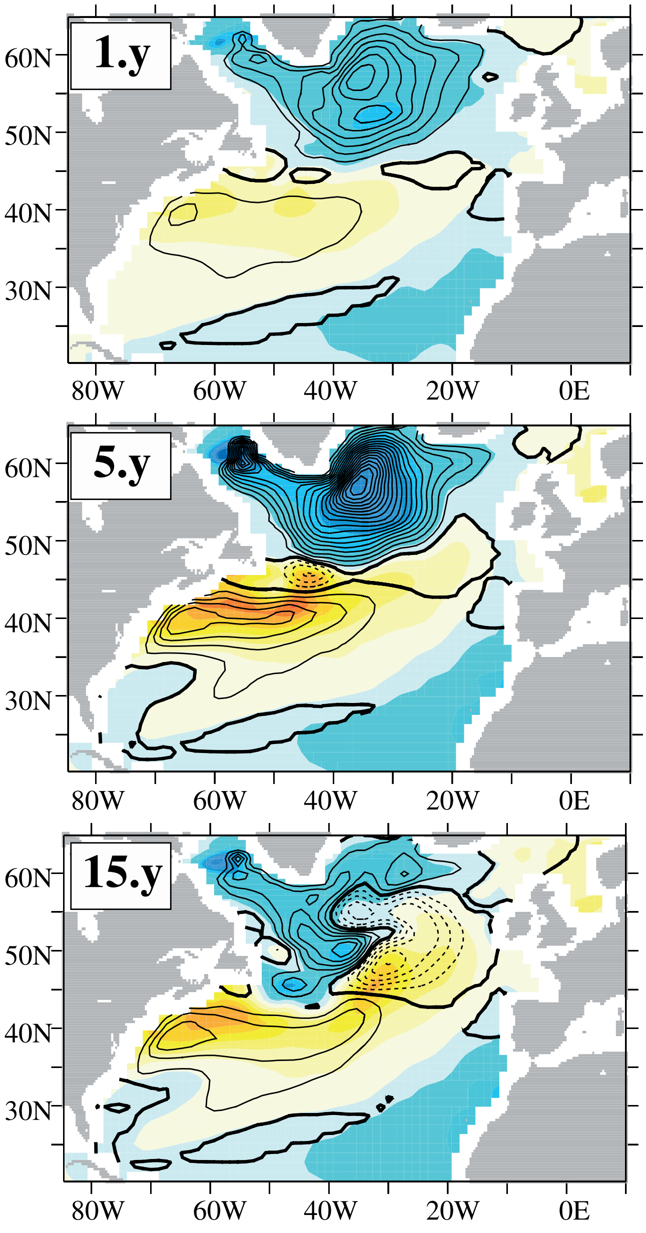


Figure 1. (a) Annual means of T_o from COUPLED (blue line) and of T_o from an integration of the BB model, using the same realization of the white noise *N*. (b) Response of T_o to the switch on of a steady, positive NAO: HIGHNAO (thick red line); as HIGHNAO but using NAO wind stress only (thick blue line); the BB model (magenta line); an AR2 fit to T_o from COUPLED and the AR5 fit (thin black lines). In each experiment, NAOI = 0 before year 0, after which NAOI = 1.



Willebrand, 2001]. Figure 2 shows some yearly averages of the SST anomalies in HIGHNAO, together with the projection on to the prescribed SST feedback pattern. For the first year, negative SST anomalies develop in the subpolar North Atlantic, while south of about 45°N, positive anomalies show up. Both regions yield positive contributions to the projection on to the SST feedback pattern. Up to the fifth year, the SST anomalies get stronger, resulting in higher loadings of the projection and higher values of T_o. This enhancement is not only due to the local surface heat flux anomalies. Figure 1b shows T_o for an experiment using only the wind stress anomalies associated with the NAO forcing. T_o reaches half the amplitude achieved in HIGHNAO, showing that the dynamical response to the wind stress change contributes about half of the initial increase in T_o. After 5 to 15 years the dynamical adjustment involves a intensified thermohaline circulation (transporting more heat northward) which results in reduced negative subpolar SST anomalies and even positive SST anomalies on the eastern flank of the subpolar front. The overall effect is a reduction in T_o after about 15 years.

3. Implications for Predictability

[7] Ensemble predictions for T_o and T_a with the OGCM would be computationally very expensive, hence we use a surrogate model instead. Since T_o from the BB model is essentially an AR1 (auto regressive order 1) process, which cannot show the oscillatory behavior, we have estimated the AR(n) parameters for T_o from COUPLED, to see if higher order AR models are better analogies for the OGCM behavior. The response of the estimated AR1, AR2 and AR5 models in a set-up corresponding to HIGHNAO is shown in Figure 1b. Since the AR5 model shows a similar oscillatory behavior as the OGCM, while all lower order fits fail to simulate this response, and since standard methods (AIC [*Akaike*, 1973], BIC [*Swartz*, 1978]) judge the AR5 model as the best fit, we

Figure 2. (opposite) Annual means for years 1, 5 and 15 of changes in SST in exp. HIGHNAO (shaded) relative to the spin up, and their "local product" with the SST feedback pattern (contoured). (The sea surface integral of the "local product" gives the projection of the SST on to the SST feedback pattern, i.e. T_o.) The color shading is from -1.6 *K* to 1.6 *K*, contour isolines have arbitrary units but constant spacing. The SST and the projection have been smoothed with a 2-dim. 3-point-Hanning window.

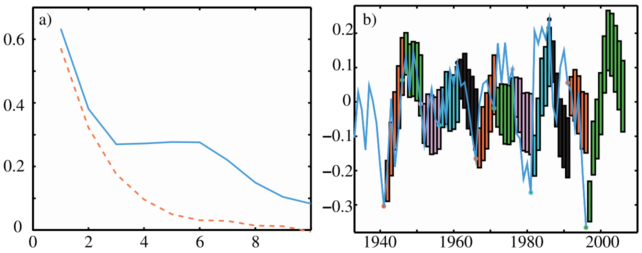
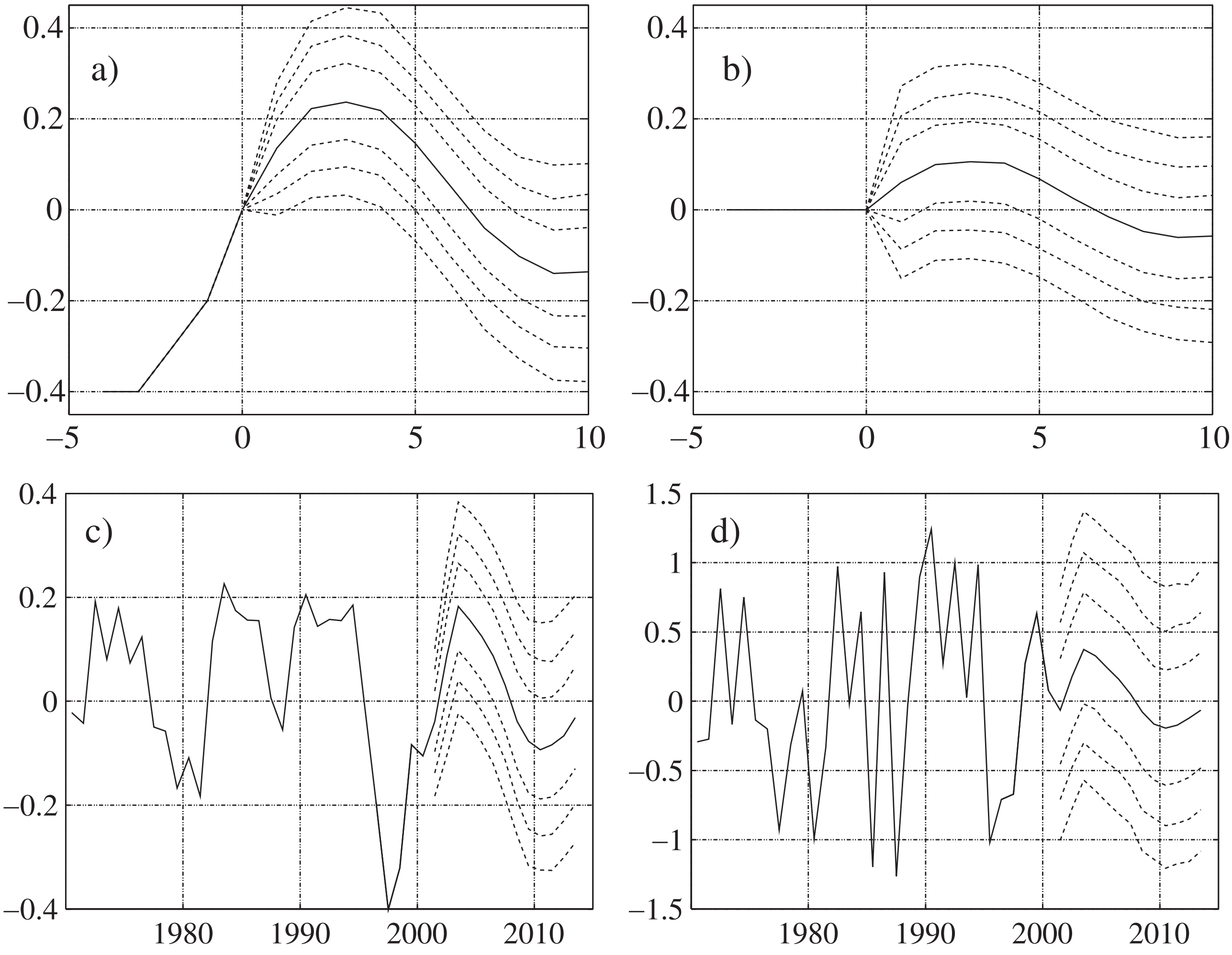


Figure 3. (a) Estimated correlation skill score for T_o of the AR5 model (solid blue line) and the AR1 model (dashed line) using all possible initial conditions for T_o. (b) Forecasts with the AR5 model compared to the "observed" T_o (solid blue line). The latter was obtained by projecting the detrended SST anomalies from the GISST [*Rayner et al.*, 1996] dataset on to the SST (feedback) pattern used to compute T_o in the model. The starting year of each ensemble of forecasts (5000 members) is denoted with a dot in different color coding. The figure shows bars for the bounds of the annual mean T_o in which 50% of the ensemble members are located. Each member of a particular ensemble of forecasts shares the previous 5 years of the observed T_o as initial condition, they differ from each other afterwards by the weather noise (N) only.

choose the AR5 model as the appropriate analogue to the OGCM. Note that the theoretical spectrum for T_o of the AR5 model shows a peak at about 12 years, similar to spectral estimates of T_o (not shown) from exp. COUPLED.

[8] Figure 3a shows correlation skill scores of forecasts of T_o with the AR5 model together with skill scores for the AR1 model (essentially the original BB model). While for the first year the skill scores are similar for both models (about 0.6), the skill rapidly decreases for the AR1 model in the subsequent years to become no better than climatology ($T_o = 0$) or a random forecast, while for the AR5 model there is a plateau of values of about 0.3 for years 4 to 7. Obviously, the damped oscillatory behavior of the AR5 model is responsible for this enhanced skill, but with, however, rather low values. To further test the ability of the AR5 model to forecast the real North Atlantic, we have constructed T_o from observations and use this time series as initial conditions for subsequent 5-year forecasts of T_o, shown in Figure 3b (note that the observations are independent data, since we have not used them for the fit of the AR5 model). As expected, the forecasts are not always correct, but for certain initial conditions, e.g. when the rate of change or the excursion of the harmonic oscillator analogue is maximal (as for the first forecast), the forecasts seem to be better.

[9] To study this behavior in detail, Figures 4a and 4b shows an ensemble of predictions for T_o and T_a for the AR5 model initialized with roughly a quarter cycle of a typical oscillation of the AR5 model. For this special initial condition the AR5 model forecasts a positive T_a (NAOI) with a likelihood of about 75% persistently for the first 5 years. Note that the AR1 model performs no better than the climatological forecast ($T_a = 0$) in this situation. It should, nevertheless, be noted that for different ocean initial conditions, the surprisingly good prediction of the AR5 model will deteriorate. For example, if there is no excursion from zero in the initial conditions for the AR5 model, the forecast



will be identical to that from the AR1 model and the climatological forecast. It is only knowledge about an exceptionally exited dynamical state of the North Atlantic (e.g. Figure 2) that yields an useful forecast (compared to e.g. a climatological forecast). Averaged over all possible initial conditions the correlation skill score for T_a from the AR5 model is therefore rather poor, only about 0.1 for the first year decreasing to a plateau with values of only 0.05. But this low skill score masks the potential of the AR5 model since for certain dynamical oceanic states (determined by the initial conditions) it might be possible to gain useful forecasts of the NAO on decadal time scales.

4. Concluding Remarks

[10] We have made several assumptions in this simple coupled model. First, we have assumed a feedback ($b > 0$) of mid-latitude SST anomalies on the NAO. Putting $b > 0$ is supported by the hindcast AGCM experiments, but note that the actual magnitude of b determines the quality of the forecast for the NAOI. We follow *Bretherton and Battisti* [2000] and use $b = 0.5$ under the caveat that this choice may lead to an overly optimistic view of the prospect for prediction. Second, we have reduced the ocean-atmosphere interaction to a single, a priori given, SST pattern, from which we derive T_o. It is, of course, possible that other SST patterns also have a role to play. Third, we have excluded any influences on the NAO other than mid-latitude SST anomalies.

[11] Under the caveat of these possible oversimplifications, it seems that the precondition for a useful forecast of the NAOI is currently close to ideal. Figures 4c and 4d show time series for T_o and the NAOI from observations, together with an ensemble prediction for these variables using the last 5 years of T_o as initial conditions for the AR5 model. We find a greater likelihood for a positive NAOI (74% at maximum) up to year 2007, followed by a period in which a negative NAOI is more likely, with an uncertainty of the forecast comparable to Figure 4b.

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Figure 4. (opposite) (a) and (b): Ensemble (5000 members) predictions of annual means of T_o (a) and T_a (b) with the AR5 model for a particular initial condition. The figure shows the ensemble mean (solid lines), and the bounds within which 90%, 75% and 50% of the ensemble members are located (dashed lines). We are using nearly a quarter cycle of an oscillation, ending with zero, as the initial condition for T_o. Each integration of the ensemble prediction differs from the other by the weather noise (N) only. (c) and (d): Ensemble (5000 members) predictions of observed (annual mean) (c) T_o and (d) NAOI using the AR5 model. Each ensemble member shares the same initial conditions, taken as the last five years of T_o, but differs in the weather noise. T_o (up to year 2001) was obtained by projecting the detrended SST anomalies from the NCEP/NCAR reanalysis dataset [*Kalnay et al.*, 1996] on to the SST (feedback) pattern (here we use the NCEP/NCAR data rather than the GISST data since the former extends nearly to the present). The NAOI are annual means of the (detrended) difference of normalized monthly mean sea level pressure between Ponta Delgada, Azores and Stykkisholmur, Iceland.