An interpretation of the results from atmospheric general circulation models forced by the time history of the observed sea surface temperature distribution

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Abstract. Recent studies using atmospheric general circulation models forced by the observed time history of global sea surface temperature anomalies have been used to hindcast the temporal history of the North Atlantic Oscillation. They find that the mean of a large ensemble of integrations using slightly different initial atmospheric conditions reproduces the observed variability surprisingly well, especially on time scales longer than a few years. However, they also find that amplitude of the atmospheric variability is considerably reduced and the air-sea heat fluxes are of the reverse sign to those observed. Here, a linear model of midlatitude atmosphere/ocean interaction forced only by high-frequency atmospheric stochastic variability is shown to reproduce all of these findings. This model suggests that despite the hindcast skill, the useful predictability associated with midlatitude SST anomalies may be limited to one or two seasons.

1. Introduction

Recently, *Rodwell et al.*[1999] and *Mehta et al.*[2000] used atmospheric general circulation models (AGCMs) to examine the predictability of a prominent pattern of wintertime Northern Hemisphere extratropical variability, called either the Arctic Oscillation or the North Atlantic Oscillation (NAO). On seasonal and longer time scales, the NAO is responsible for a large fraction of the observed climate anomalies over Eurasia and Northeastern North America [*Hurrell*, 1995]. In both studies, an ensemble of AGCM integrations were identically forced with the historical record of SST and sea ice over approximately the last fifty years, but with slightly different initial atmospheric conditions. For each integration in the ensemble and for the observations, the authors calculate an 'NAO index' of the amplitude of the NAO pattern averaged over each winter season. They investigate how well the SST-forced integrations reproduce the observed year-to-year variations of the NAO index. Some salient features and results of both studies are summarized in Table 1.

In these studies, the NAO index in individual integrations was found to correlate positively with the observed NAO index, especially when both are averaged over periods of several years. More remarkably, the ensemble mean NAO index correlates much better with the observed NAO index than would a typical individual integration. The correlation coefficient of the ensemble mean NAO index with the observations reaches 0.7-0.8 if both time series are smoothed to average out fluctuations with periods of less than 6.5 years. *Rodwell et al.* [1999] also find that air-sea fluxes tend to damp the SST anomalies in their simulations. One might infer that low-frequency variability of the NAO (and wintertime European climate) is in large part driven by SST anomalies that evolve primarily by internal ocean dynamics (e. g. advection [*Sutton and Allen*, 1997]), and therefore might be fairly predictable.

The purpose of this note is to point out that these results can be interpreted quite differently. In fact they are consistent with a linear model of coupled low frequency variability in the midlatitude atmosphere and ocean driven by high-frequency intrinsically uncoupled stochastic variability in the atmosphere. In this model, as in the GCMs, the average of a large ensemble of integrations in which the model atmosphere is forced by the history of SST anomalies from a coupled model run produces a near perfect temporal hindcast of the low frequency atmospheric variability, albeit with reduced amplitude. Furthermore, in these integrations, the model air-sea fluxes on average act to damp the SST anomalies. However, the coupled linear model suggests that these results mislead one about causality within the coupled system. In fact, in this model the air-sea fluxes are precisely what produces the SST anomalies, and the useful predictability of the low frequency midlatitude atmospheric and SST anomalies is limited to six months or less.

2. A linear stochastic coupled model of the midlatitude climate system

The model used here was presented and discussed in *Barsugli and Battisti* [1998]. It is an extension of an ocean-only model put forth by *Hasselman* [1976] and collaborators. It predicts the evolution of a single pattern of extratropical atmospheric variability such as the NAO coupled to a single SST anomaly pattern. It is based on the following observationally supported assumptions: (i) The atmospheric pattern can be excited by internal high-frequency chaotic atmosphere dynamics and would still exist in the absence of SST variability (see, e.g., *Held* [1983]); (ii) the corresponding low-frequency atmospheric circulation anomalies are equivalent-barotropic (surface and mid-tropospheric air temperature anomalies are proportional); and (iii) they interact with SST through patterns of anomalous surface turbulent heat fluxes (see, e.g., [*Cayan*, 1992; *Wallace et al.*, 1990]) – the SST anomalies help maintain the persistence of atmospheric anomalies by reducing the thermal damping of those anomalies by air-sea fluxes [*Barsugli*, 1995; *Bladé*, 1997].

The model is formulated in terms of time-dependent temperature anomalies T_a, cT_a and T_o in the mid-troposphere,

Paper number 1999GL010901.
0094-8276/00/1999GL010901$05.00

Table 1. Simulated NAO variability given prescribed SST in two AGCM studies and the linear model.

Experiment	N^a	Seasonal[b] R^d	Low Freq.[c] R^d	AR[e]
Rodwell et al.	6	0.21 / 0.41	0.43 / 0.74	0.39
Mehta et al.	16	0.17 / 0.43	0.28 / 0.75	0.5
Linear Model	16	0.18 / 0.45	0.45 / 0.80	0.41

[a]The number of AGCM realizations in the ensemble

[b]Seasonal variability is loosely defined as the 3-month winter average for [*Rodwell et al.,* 1999], the one month average for [*Mehta et al.,* 2000] model.

[c]'Low Freq.' refers to time series low-pass filtered to retain periods greater than 6.5 years.

[d]Correlation coefficients are between the simulated and observed NAO index (AGCMs) or atmospheric temperature anomaly (linear model). The first value is the average for one atmospheric realization, and the second value is for the ensemble mean prediction

[e]Ratio between standard deviation of low-pass atmospheric variability in the model to that observed.

atmospheric boundary layer and the ocean mixed layer, respectively. The atmospheric pattern is dynamically forced by white noise forcing N due to the high-frequency chaotic dynamics of midlatitude cyclones and storm tracks and an ad hoc ocean dynamical feedback $(b-1)T_o$. Both T_a and T_o are also forced radiatively and through the turbulent surface heat flux, which is proportional to air-sea temperature difference $cT_a - T_o$. We write the model equations using a nondimensional time t (one time unit corresponds to approximately five days):

$$\frac{\partial T_a}{\partial t} = -aT_a + bT_o + N(t), \quad (1)$$

$$\beta\frac{\partial T_o}{\partial t} = cT_a - dT_o \ . \quad (2)$$

Four nondimensional parameters enter the right hand side; their numerical values (from *Barsugli and Battisti* [1998]) are $a = 1.12$, $b = 0.5$, $c = 1$, $d = 1.08$. The c term incorporates surface turbulent fluxes, the a and d terms also incorporate radiative damping, and the b term combines surface fluxes and dynamical forcing. The ratio of the heat capacity of the ocean mixed layer to the heat capacity of the tropospheric air column, β, is large. We assume a 100 m deep ocean mixed layer, for which $\beta = 40$. Note that in this model, *all* of the variability in the midlatitude ocean is explicitly driven by unpredictable atmospheric variability.

This model of the midlatitude atmosphere-ocean system can be used in the same way that the AGCMs are used to assess the effect of SST anomalies on the atmosphere system. First, the coupled solution to Eq. (1) and (2) is found using a unique realization of the noise N (the chaotic atmospheric dynamics). Since Nature is coupled, this solution is identified as the true (observed) climate record. The 'observed' ocean temperature is then used to force the atmosphere model Eq. (1) in an ensemble of 'prescribed (observed) SST' experiments – each with a different realization of the atmospheric noise (synonymous with different initializations of the AGCM, and therefore different realizations of the chaotic atmospheric dynamics).

The third row of Table 1 compares results from many integrations of the linear model with the two AGCMs. The time series of T_a are analyzed in a similar way as in the AGCMs, by doing 'seasonal' filtering using simple 3-month averaging and by 'low-pass' filtering with a 6.5 year period cutoff. The behavior of the linear model is strikingly similar to the AGCMs, with a very high correlation of the ensemble mean low-pass T_a^E with the coupled low-pass T_a^C.

Using power spectral analysis, it is straightforward to analyze both the linear coupled model and the corresponding prescribed-SST model. Let σ be the nondimensional frequency and let $\hat{T}_o(\sigma)$ be the Fourier transform of the ocean temperature anomaly $T_o(t)$ in a specific realization of the coupled model. From (2), the corresponding atmospheric anomaly is

$$\hat{T}_a^C(\sigma) = (i\beta\sigma + d)\hat{T}_o(\sigma)/c \ . \quad (3)$$

For the j'th individual realization of the prescribed-SST-model, with white-noise forcing $N^j(t)$, the atmospheric frequency response found from (1) is:

$$\hat{T}_a^j(\sigma) = [b\hat{T}_o(\sigma) + \hat{N}^j]/(i\sigma + a) \ . \quad (4)$$

The real part of the coherence of $\hat{T}_a^j(\sigma)$ and $\hat{T}_a^C(\sigma)$ measures the average correlation coefficient over an infinite ensemble of noise realizations $N^j(t)$ of these two time series in a frequency band centered around σ. In Figure 1, this is shown as a dashed curve. We define $z = ad/bc = 2.4$. For low frequencies, we compute this coherence to be

$$\text{Coh}(T_a^C, T_a^j) = (1 + (z-1)^2)^{-1/2} = 0.58, \ \sigma \ll 1/\beta. \quad (5)$$

Thus, if both time series are low-pass filtered to retain only signals of periods much longer than $2\pi\beta = 3.5$ years, individual realizations with the prescribed SST will have an expected correlation coefficient of 0.58 with the coupled run (as seen in Figure 1). For higher frequencies, the real part of the coherence quickly drops, so that if the time series are not low-pass filtered, the correlation coefficient greatly decreases.

Now we consider the mean $T_a^E(t)$ over an infinite ensemble of prescribed-SST solutions. Since the ensemble mean of the noise is zero, (4) implies that

$$\hat{T}_a^E(\sigma) = b\hat{T}_o(\sigma)/(i\sigma + a). \quad (6)$$

This is perfectly coherent with the the atmospheric anomaly from the coupled simulation (given by (3)) at all frequencies. The solid line in Figure 1 shows the band-pass correlation (the real part of the coherence) between $\hat{T}_a^E(\sigma)$ and $\hat{T}_a^C(\sigma)$, which is generally less than one since they are not in phase. The solid line lies above the dashed line at all frequencies; hence the ensemble mean $T_a^E(t)$ is always better correlated with the 'actual' $T_a^C(t)$ than a typical individual prescribed-SST realization would be.

At low frequencies (periods exceeding ten years), $\hat{T}_a^E(\sigma)$ is nearly in phase with $\hat{T}_a^C(\sigma)$, leading to the remarkable near-perfect correlation of low-pass $T_a^E(t)$ with $T_a^C(t)$ shown in Table 1. The explanation suggested by spectral analysis is that $T_a^C(t)$ drives a in-phase low-pass SST response $T_o^C(t)$ which 'records' the coupled model atmospheric variability. The low-pass ensemble response $T_a^E(t)$ of the prescribed-SST model is in phase with low-pass $T_o^C(t)$, 'playing back' the 'recording' of $T_a^C(t)$, but with reduced amplitude. From (3) and (6),

$$\hat{T}_a^E(\sigma) = \hat{T}_a^C(\sigma)/z, \ \ \sigma \ll 1/\beta \ . \quad (7)$$

The low-pass response in the prescribed-SST runs is reduced in amplitude by a factor of $z = 2.4$ compared to the coupled runs, similar to the AGCM simulations (Table 1).

Lastly, we consider the low-frequency variability of the nondimensional downward air-sea heat flux $Q = cT_a - T_o$. For the coupled (observed) case, the frequency response can be found from (3):

$$\hat{Q}^C = (i\beta\sigma + d - 1)\hat{T}_o \quad (8)$$

$$\approx 0.08\hat{T}_o, \quad \sigma \ll (d-1)/\beta. \quad (9)$$

At all frequencies, the downward flux leads the SST, consistent with atmospheric variability driving the ocean. At very low frequencies, the downward flux becomes small and is nearly in phase with the SST anomaly. For the ensemble average of the prescribed-SST realizations, the frequency response can be found from (6):

$$\hat{Q}^E = \left(\frac{bc}{i\sigma + a} - 1\right)\hat{T}_o(\sigma) \quad (10)$$

$$\approx -0.56\hat{T}_o, \quad \sigma \ll 1/\beta. \quad (11)$$

At low frequencies, the downward flux is now out of phase with the SST anomaly, consistent with the prescribed ocean variability driving the atmosphere.

3. Interpreting AGCM experiments with prescribed midlatitude SST

The agreement between the coupled linear stochastic model and the AGCM studies suggests that the former is a viable idealization for much of the variability of the NAO. This hypothesis leads us to the following interpretation of the recent results from the hindcast experiments using the AGCMs forced by the observed history of SST, and of what to expect in this type of hindcast: (i) the observed SST history in the North Atlantic may be primarily driven by a *unique* and unpredictable realization of dynamical induced atmospheric noise; (ii) when the observed history of SST variability is prescribed under an AGCM, the phase of the observed low frequency variability in the atmosphere should be reproduceable with increasing fidelity as the ensemble size increases because the dynamical forcing of each member is uncorrelated (because each member has different initial conditions and the atmospheric dynamics are nonlinear): in essence, ensemble averaging filters out the atmospheric variability that is due to the internal dynamics of the atmosphere, exposing the effect of the unique realization of the noise in nature that has been recorded in the history of the observed SST; (iii) the correlation between the observed and the AGCM ensemble mean hindcast of atmospheric variability must increase as the time scale of the variability increases because of the strong low-frequency coupling between the atmosphere and ocean associated with the surface turbulent energy exchange. Furthermore, our model naturally reproduces two initially puzzling results from the prescribed-SST AGCM runs. It predicts that the ensemble-average AGCM response to the historical SSTs should be about 40% as large as that actually observed. Furthermore, it predicts that the ensemble-averaged surface energy flux in the prescribed-SST runs acts to damp the low-frequency variation of SST, while in Nature the surface energy fluxes are observed to drive the low-frequency variation of SST [*Cayan*, 1992]. These results show that one must use caution in using AGCM studies with prescribed SSTs to interpret the variability of the coupled system.

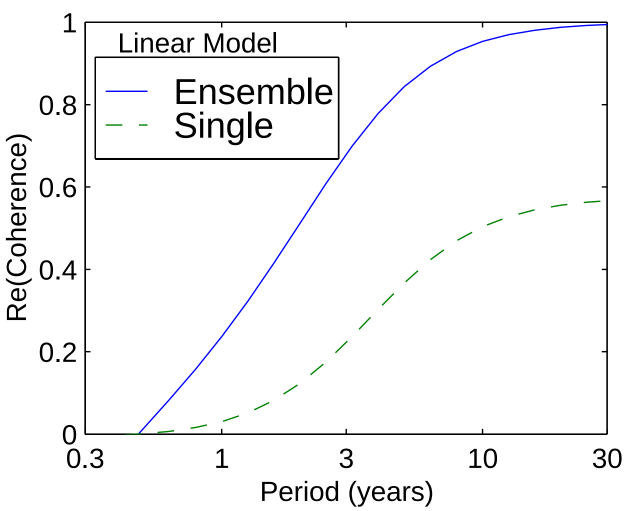

Figure 1. The theoretically computed real part of the coherence (the band-pass correlation coefficient) between the atmospheric temperature anomaly in the linear coupled model and that in the parallel prescribed-SST model. Solid line is for the average atmospheric temperature anomaly over an infinite ensemble of prescribed-SST realizations. Dashed line is the average coherence based on the temperature anomaly for single realizations.

4. Implications for predictability

Finally, we comment on the potential predictability of the midlatitude atmosphere-ocean system as idealized in our model. The initial state of the system is described by T_a and T_o at the initial time t=0. Since the model is linear, the best forecast is derived by averaging over all possible realizations of the noise, which removes the noise forcing from (1). The two resulting linear differential equations can be solved for the optimal forecast $T_a^f(t)$ and $T_o^f(t)$. For large ocean heat capacity β, one can show from (1) and (2) that after a few days

$$T_a^f(t) \approx (bT_o(0)/a)\exp(-t/\tau) \quad . \quad (12)$$

The optimal forecast depends only on the initial SST (all long-term memory resides in the ocean state) and relaxes toward climatology with an e-folding time of $\tau = a\beta/(ad - bc) \approx 6$ months. Despite the excellent hindcast skill of an atmospheric ensemble forced by observed SSTs, less than 15% of the variance in the seasonal atmospheric (NAO) anomaly is predictable six months in advance in our model, even given perfect initial conditions for the midlatitude ocean state. Does the real coupled midlatitude ocean-atmosphere system, with its more complex physics, possess useful predictability beyond this time scale? One possible test is comparison of parallel integrations of a coupled GCM with slightly perturbed initial conditions.

Acknowledgments. We are grateful to M. Rodwell and M. Suarez for providing information used in Table 1. This work was supported by NSF grant DMS-9524770, a grant from the NOAA Office of Global Programs, and the USEPA's National Research Center for Statistics and the Environment through agreement CR825173-01-0 to the University of Washington (but has not been subject to USEPA's review process, does not reflect their views, and does not carry their official endorsement.)

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(Received July 8, 1999; revised November 8, 1999;
accepted December 7, 1999.)