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On the interpretation of AGCMs response to prescribed time-varying SST anomalies

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Abstract. Recently, Bretherton and Battisti (1999) have presented an interesting interpretation of ensemble experiments with atmospheric general circulation models (AGCMs) forced by observed sea surface temperature (SST) whose mean successfully simulates the decadal evolution of the observed North Atlantic Oscillation (NAO) index. Using a linear model of atmosphere/ocean interaction, they plausibly argue that this hind-cast skill, as measured by low-pass correlations between observed and simulated indices, is consistent with the ocean mixed layer merely integrating stochastic surface heat flux forcing governed by the natural variability of the atmosphere. They go on to suggest, however, that predictability associated with middle-latitude SST anomalies is limited to timescales associated with the thermal inertia of the oceanic mixed layer (perhaps a year). Here, we include ocean circulation in a simple coupled ocean-atmosphere model and also consider hypothetical limits in which the coupled system is highly predictable at low frequencies. We find that low pass correlations between observed and simulated NAO indices, obtained from ensembles of SST-forced AGCMs, are insensitive to the predictability of the system. Thus inferences about predictability of the atmosphere-ocean system cannot be made on the basis of this measure of the hindcast skill of atmosphere-only simulations.

1. Introduction

Atmospheric general circulation models (AGCMs) forced by prescribed SST anomalies can be used to help discriminate between natural and 'SST-forced' atmospheric variability: the mean of an ensemble of simulations with differing initial conditions is representative of the forced response to SST, whilst the spread of the ensemble reflects the natural variability of the model. Using AGCMs, several studies have suggested that the low-frequency (decadal) component of the NAO may be driven by SST anomalies [*Rodwell et al.*, 1999], [*Mehta et al.*, 1999] (herafter RM99). Because the slowly evolving and possibly predictable ocean circulation may be involved in modulating SST anomalies on decadal timescales, it has been suggested that a significant fraction of the low-frequency NAO may itself be predictable.

Recently, however, [*Bretherton and Battisti*, 1999] (hereafter BB) have questioned this interpretation of RM99's experiments. Using a simple coupled model of midlatitude air-sea interaction with no predictability of SST beyond a year, they are able to reproduce the high correlation between 'observed' and 'simulated' low-frequency NAO. They go on to argue that predictability of the latter at the decadal timescale is not implied by successful hindcasts and instead suggest that useful predictability is limited to a year or so. Several studies, however, suggest a role for ocean circulation in modulating SST anomalies on decadal timescale, particularly near the Gulf Stream separation point [*Halliwell*, 1998]. Here we extend the model proposed by BB and study the implications of taking into account ocean circulation in a simple model of the midlatitude air-sea interaction, and in the context of RM99's experiments.

2. Stochastic and 'SST-forced' atmospheric variability

We consider an ensemble of AGCM responses to the same time-varying observed SST anomalies and restrict our analysis to the time variations of a particular atmospheric index, the NAO index (surface pressure difference between Iceland and the Azores). BB proposed an elegant framework in which to analyse these experiments, by constructing 'observed' SST and atmospheric index anomalies from an idealized coupled ocean atmosphere model. Forcing the atmospheric component of the coupled model by the 'observed' SST is then the analog of one AGCM experiment forced by observed time varying SST taken from the observational record. Ensemble atmospheric 'response' can be constructed in a way that mimics RM99.

We model the interaction of the NAO with its associated SST anomaly pattern, the so-called SST tripole. For simplicity, we will only consider the interaction of the NAO with the SST dipole between the subpolar and subtropical oceanic gyres, denoted by ΔT (Fig. 1). The model NAO is a surface wind anomaly τ that is linearly decomposed into a stochastic and an SST-forced component,

$$\tau = N - f\Delta T \tag{1}$$

where f denotes the SST dipole feedback on the NAO surface wind. AGCM simulations suggest that f is small and positive (e.g, RM99), implying that $\Delta T < 0$ (cold SST to the north and warm SST to the south) excites a positive NAO (increased westerlies and trade winds). The SST dipole ΔT is assumed to be primarily the result of the stochastic fluctuations of the surface heat fluxes associated with the NAO on seasonal timescales, but may also be modulated by the anomalous ocean circulation heat flux Q_o on longer timescales

$$\frac{d\Delta T}{dt} = -\lambda\Delta T - \alpha N + \underbrace{\text{Adv. by ocean circulation}}_{Q_o} \tag{2}$$

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where λ^{-1} denotes the damping timescale due to air-sea interactions and α scales the stochastic surface wind N into a surface heat flux anomaly. In a positive NAO phase, the jet-stream and the pattern of surface winds are displaced to the North ($\tau > 0$) and cold advection of air from the North and warm and humid air from the Tropics creates cold SST anomalies on the northward flank of the jet and warm SST anomalies on its southern flank [*Cayan*, 1992], so that $\alpha > 0$.

First let us set ocean circulation to zero ($Q_o = 0$). We can reasonably assume that the mixed layer is in equilibrium with this stochastic forcing on timescales of a few years. NAO and ΔT variations thus track each other, with cold subpolar / warm subtropical gyre SST anomalies ($\Delta T < 0$) associated with an intensification and northward shift of the the jet stream (Fig. 1a). Using (2) and (1), one can easily see that at low frequency (neglecting the ΔT tendency)

$$\tau^C = -(f + \frac{\lambda}{\alpha})\Delta T^C \tag{3}$$

where the superscript C is used for the 'coupled' system. What happens, then, if we 'force' the atmospheric component of the coupled model (i.e, eq. (1)) with ΔT^C?. For a single realization of this SST-forced experiment we write $\tau^j = N^j - f\Delta T^C$ where the superscript j stands for the j-th realization. Taking the ensemble average wind-stress anomaly τ^E over all realizations, we have, from the latter equation

$$\tau^E \simeq -f\Delta T^C \tag{4}$$

because the ensemble average of N^j goes to zero for sufficiently large ensemble. Comparing (3) and (4) shows that for positive feedback between ΔT and the NAO ($f > 0$), there is a positive correlation between 'observed' (τ^C) and the ensemble mean simulated (τ^E) NAO index for low-pass timeseries, as found in RM99. It also shows that (4) yields a weaker response than the true coupled model. BB showed that not only the sign found in RM99 but also the magnitude of the correlation can be predicted without considering ocean circulation. If there is no memory in the ocean-atmosphere system beyond that of the thermal inertia of the mixed layer (a year), as tacitly assumed by BB, then indeed the low-frequency SST and atmospheric index anomalies are unpredictable. We show below that such conclusions cannot be made on the basis of low-pass correlations alone. Indeed, by including ocean circulation in the coupled model ($Q_o \neq 0$), we show that similar low-pass correlations are found, even in the unrealistc limit of a strongly coupled predictable ocean-atmosphere system (large Q_o case).

3. A coupled model with active ocean dynamics

The simple coupled model used here is developed in [*Marshall et al.*, 1999] (hereafter M99). Motivated by the particular geometry of the observed surface wind-stress curl associated with the NAO, M99 argues that anomalies in wind driven ocean circulation could carry heat across the mean boundary between the subpolar / subtropical gyres and so modulate ΔT on timescales of several years. The corresponding oceanic heat flux Q_o primarily reflects the strength of the anomalous circulation Ψ - the 'intergyre' gyre - associated with the delayed oceanic response to NAO wind forcing. Simple Sverdrup dynamics suggests a delay of order 8 yr as a result of the propagation of first baroclinic mode Rossby waves across the North Atlantic basin at 45N. Non-dimensionalizing time by this delay, Eqs. (2) and (1) can be expressed as (more details are given in M99)

$$\tau = N - f\Delta T \tag{5}$$

$$\frac{d\Delta T}{dt} = -\lambda\Delta T - \alpha N + g\Psi \tag{6}$$

where Q_o has been written as $g\Psi$, and g is a number measuring the efficiency of the ocean circulation in carrying heat across the mean boundary between the subpolar / subtropical gyres. The parameters f, α and λ are now non-dimensional. Using simple Sverdrup dynamics, M99 showed that $\Psi = \int_{t-1}^{t} \tau dt \simeq -f \int_{t-1}^{t} \Delta T dt \simeq -f\Delta T(t - 1/2)$ where we have neglected the contribution N in (5) and approximated the time integral by a mid point value. The model (6) becomes

$$\frac{d\Delta T}{dt} = -\lambda\Delta T - \alpha N - fg\Delta T(t - 1/2) \tag{7}$$

a modified form of (2). For the purpose of the present note, the reader is asked to regard the delay term in the above as a representation of advective ocean processes that, on long-timescales, play a role in setting SST. Clearly it is a highly symbolic characterization of the processes at work in the

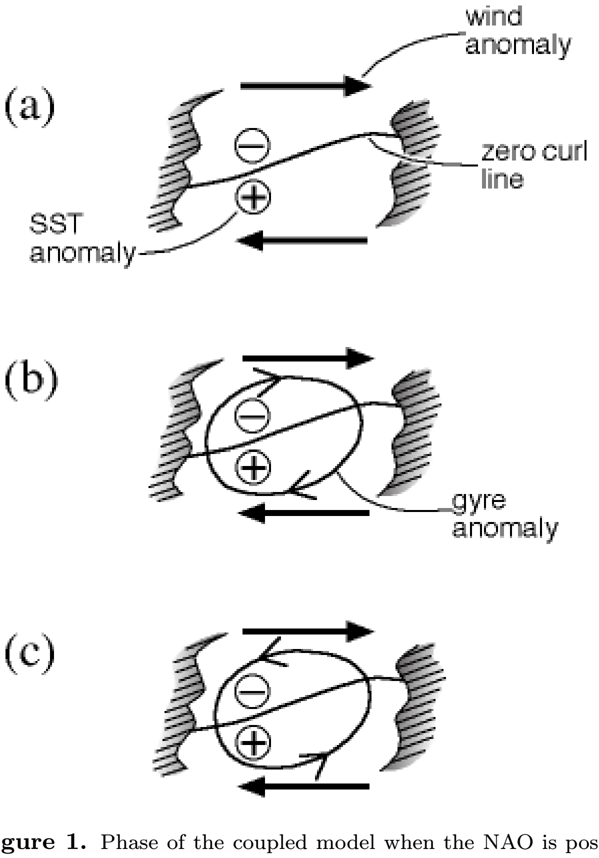

Figure 1. Phase of the coupled model when the NAO is positive. Surface winds (heavy arrows) and SST anomalies (denoted by plus and minus signs) across the line of the climatological zero wind curl line separating the mean ocean gyres are indicated. The anomaly in the wind driven 'intergyre' gyre due to NAO fluctuations is represented by a closed circulation, with anticyclonic circulation implying a northward shift of the Gulf Stream. (a) on short timescales - equivalent to a passive ocean with no dynamics (b) at very low-frequency when ocean circulation damps SST (c) near the decadal period when ocean circulation enhances SST.

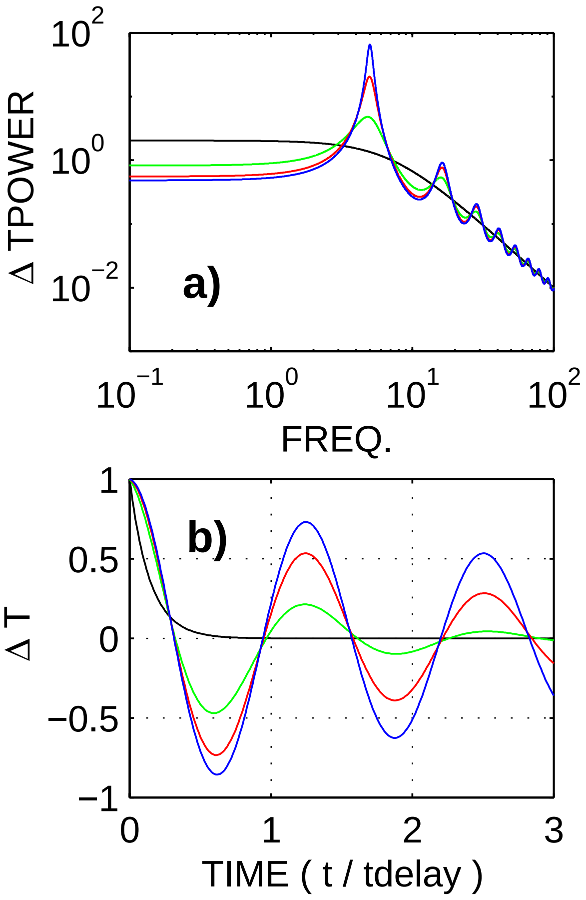

Plate 1. BB and M99's model predictions. (a) ΔT spectrum (b) Free mode of (7). Black is for BB's model whilst green ($q = 2$), red ($q = 5$) and blue ($q = 10$) lines are for M99's model. In both (a) and (b) the amplitude is arbitrary but the frequency and time have been non-dimensionalized by the delay time ($\sim 8yrs$).

real ocean, although, as shown in M99, such a term naturally arises from a consideration of time-dependent Sverdrup dynamics. The magnitude of the delay term depends on f, the feedback of SST on wind, but also on g, which characterizes the inherent efficiency of gyre anomalies to carry heat. In the absence of ocean circulation ($g = 0$) Eq. (7) is very similar to that used by BB (taking the limit where storage of heat in their model atmosphere is neglected). Moreover, if we set $\lambda = 7$, $\alpha = 1.8\lambda$ and $f = 0.4$, then our simple model is in the same parameter regime as chosen by BB. When ocean circulation is included, (7) has the form of a stochastically forced delayed-oscillator equation. Depending on the efficiency of the ocean circulation in carrying heat it supports strongly or weakly damped oscillations, as measured by the quality factor q

$$q = \frac{\omega_o}{\gamma} \qquad (8)$$

where ω_0 and γ denotes respectively the frequency and damping rates of the free solutions $\Delta T \sim e^{-\gamma t/2} e^{i\omega_0 t}$ of (7). The 'resonance' frequency ω_0 is primarily governed by the delay time and is about $2\pi/10\ yr$ for the standard model parameters.

Fig. 1b is a schematic of the model behavior when ΔT and Ψ are in equilibrium with the stochastic forcing, which will be true at timescales longer than the delay time of the oceanic response. An anticyclonic circulation is generated

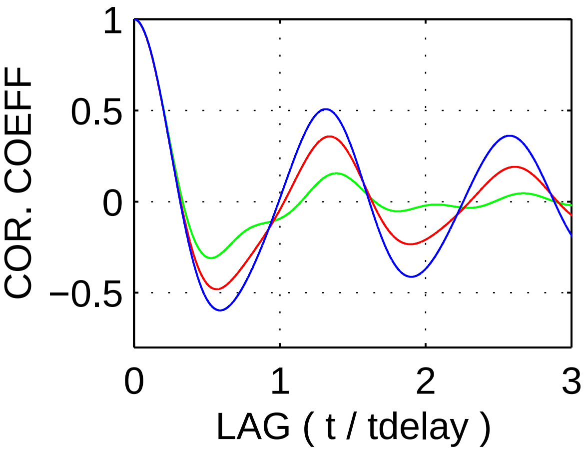

Plate 2. Low-pass autocorrelation function of the model NAO for various q-factors ($q = 2$, green; $q = 5$, red; $q = 10$, blue). Low-pass filtering has been constructed by only including periods greater than 5 yrs when computing the Fourier spectra.

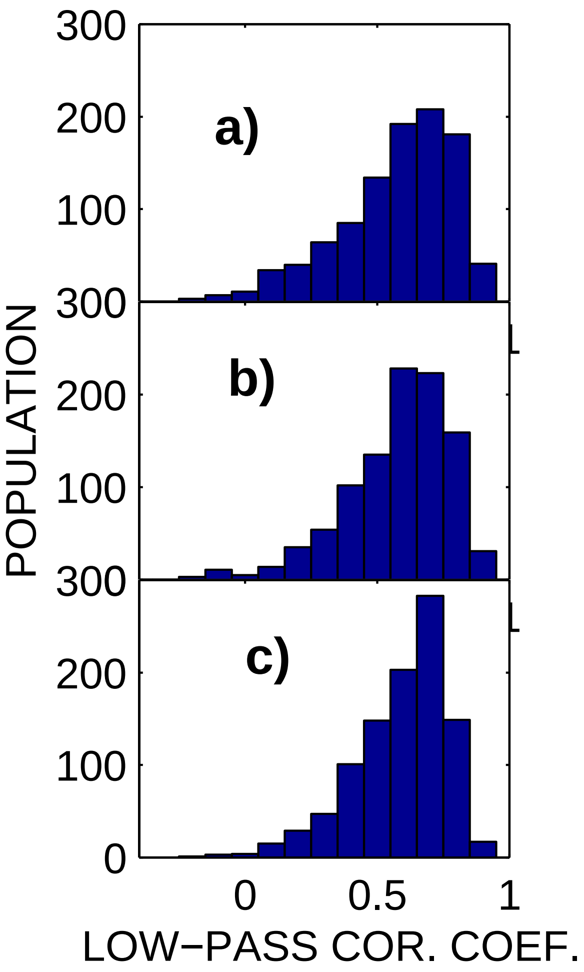

Figure 2. Histograms of low pass correlations between τ^C and τ^E obtained from 1000 simulations of (9), (10) and (11) (a) $g = 0$ (BB's model) and (b) $q = 2$, (c) $q = 10$ (M99's model).

in positive NAO conditions ($f > 0$), which carries heat from warm to cold SST anomalies and thus acts as an additional damping on ΔT. This explains the reduced energy level of the spectrum of ΔT at low-frequency compared to BB, as plotted in Plate 1a. As one approaches ω_0, however, the ocean circulation acts to generate SST anomalies, carrying heat from cold to warm (Fig. 1c), and thus brings extra power to SST compared to the case of no ocean circulation (Plate 1a). Comparison of Fig. 1a with Fig. 1b,c shows that including ocean circulation in BB's model does not modify the phase relationship between ΔT and the NAO. We thus still expect a positive correlation between low-pass 'observed' and 'simulated' atmospheric index, whatever the q-factor is. Note however that the ΔT spectrum plotted in Plate 1a shows a large bump when $q = 5,\ 10$ (black and blue lines), which is associated with a very predictable ocean-atmosphere system. Free mode solutions of (7) show a predictive skill for ΔT on long timescale when ocean circulation is included ($Q_o \neq 0$). Further evidence for significant atmospheric predictability in the large q cases is given in Plate 2, which plots the predicted low-pass autocorrelation function of τ - our proxy for the NAO - for different q-factors. Based on these functions, one can estimate that, respectively, 10 ($q = 2$), 25 ($q = 5$) and 36 % ($q = 10$) of the low-frequency variance of τ can be predicted at a lead time of half the delay time (about 4 yrs) (As discussed elsewhere (Czaja and Marshall, manuscript in preparation), we believe that $q \sim 2$ in the real system). We show below that this predictive skill is not captured by the low-pass correlations used in RM99.

4. Application to the interpretation of AGCM response to prescribed time varying SST anomalies

Following the rationale of BB, we have computed individual realizations τ^j and coupled τ^C index timeseries from a numerical integration of

$$\tau^C = N^C - f\Delta T^C \tag{9}$$

$$\frac{d\Delta T^C}{dt} = -fg\Delta T^C(t-1/2) - \lambda\Delta T^C - \alpha N^C \tag{10}$$

and

$$\tau^j = N^j - f\Delta T^C \tag{11}$$

The ensemble index τ^E is defined as the ensemble mean over R realizations. To make the comparison with BB straightforward we used similar ensemble size ($R = 16$) and similar persistence (five days) and variance for the stochastic component N^C and N^j ($j = 1, ..., 16$). Low-pass correlations are computed from 6-yr running means, applied to the simulated timeseries of 50 yrs (period covered by RM99). Because of the small number of degrees of freedom of the low-pass timeseries, we constructed the ensemble one thousand times.

Fig. 2 shows the histogram of the low-pass correlation coefficient R_{LP} between the simulated ensemble mean and coupled indices (i.e between τ^E and τ^C). We first recover BB's calculations (Fig. 2a), with a maximum probability of R_{LP} between 0.6 and 0.8, which is in good agreement with the 0.75 obtained by RM99. Fig. 2b,c shows the case where ocean circulation is taken into account. As anticipated, we still obtain positive correlations, but with only small differences between the three cases, even in the limit of a very predictable ocean atmosphere system (Fig. 2c, $q = 10$). Compared to BB, however, the signal to noise ratio $f\Delta T/N$ is stronger near resonance but smaller at lower frequency. This is a consequence of ocean circulation enhancing power near the decadal period and damping at lower frequency (see Fig.1b,c). These effects are mixed together by the low-pass filtering. Overall the low-pass correlation R_{LP} is not sensitive to our coupling.

5. Conclusion

In this note we have shown that one cannot draw conclusions about the low frequency predictability of the ocean-atmosphere system on the basis of low-pass correlations between observed and simulated (ensemble-mean) atmospheric indices. Indeed, across a range of model parameters and hence hypothetical predictability of our NAO proxy, we are able to reproduce the correlations obtained from AGCMs forced by observed SST anomalies. First, as in BB, a model without ocean circulation was considered which has a predictability limited by damping to a year (Plate 1b, black line). Then a model including advection of heat by anomalous ocean currents which has a predictability of several years (Plate 1b, green, blue and red lines). We find that low-pass correlations between simulated and observed NAO indices are an insensitive measure of predictability, even in the case where the role of ocean circulation is unrealistically large, inducing a weakly damped coupled mode between the ocean and atmosphere. Clearly the signature of an active role of ocean circulation in the decadal variability of the NAO is not contained in these low pass correlations. Plate 1 suggests, however, very clear signatures in the SST anomalies that can be tested in the observations. This is currently under investigation (Czaja and Marshall, manuscript in preparation).

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