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# Can a State of the Art Atmospheric General Circulation Model Reproduce Recent NAO Related Variability at the Air-Sea Interface?

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**Abstract.** Recent studies claim that useful predictability of the North Atlantic Oscillation (NAO) up to several years in advance may be possible using atmospheric models in which the sea surface temperature (SST) is specified from observations. Achieving this goal requires that such models adequately capture the observed variation in the NAO at *interannual* as well as interdecadal timescales. We investigate whether this is the case by comparing interannual variability in the HadAM3 atmospheric model with observations in the SOC air-sea flux dataset for 1980-1995. We find that the model NAO time variation does not correspond to that observed, thus claims of multiannual predictability need to be viewed with caution. In addition, analysis of the observations reveals that NAO related SST anomalies do not exert a significant heat flux feedback on the atmosphere at seasonal to interannual timescales.

## Introduction

Atmospheric general circulation models (AGCMs) in which the observed sea surface temperature (SST) is specified as a lower boundary condition have been used in several recent analyses of the role of the ocean in driving the North Atlantic Oscillation (NAO) [*Rodwell et al.*, 1999; *Mehta et al.*, 2000; *Robertson et al.*, 2000]. Such models have some skill at reproducing observed decadal trends in the NAO index, leading to the suggestion that useful predictions of European winter climate up to several years in advance may be possible [*Rodwell et al.*, 1999]. However, in order to make such predictions it is important that models are able to reproduce the observed *interannual* as well as interdecadal variation in the NAO. We address this issue by comparing interannual variability in the Hadley Centre Atmospheric Model version 3 (HadAM3), forced with observed SST, with observations in the Southampton Oceanography Centre (SOC) air-sea flux dataset for 1980-1995. We will show that the recent time variation of the NAO in HadAM3 does not correspond to that observed and thus suggest that claims of useful predictability of European winter climate with this type of model need to be viewed with caution. Further, given recent studies which suggest that the NAO is not strongly governed by SST [*Sutton et al.*, 2001], we have explored the observed time decay of NAO related SST anomalies and their possible heat flux feedback to the atmosphere.

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## Observational Data and Model Output

The SOC dataset consists of monthly mean surface meteorological variable and air-sea flux fields on a global $1^\circ \times 1^\circ$ grid for 1980 - 1995 derived using bulk formulae [*Josey et al.*, 1999] from approximately 30 million ungridded weather reports in the Comprehensive Ocean-Atmosphere Dataset 1a [*Woodruff et al.*, 1993]. The model output is from HadAM3 which has a $3.75^\circ \times 2.5^\circ$ horizontal grid and 19 vertical levels [*Pope et al.*, 2000]; *Rodwell et al.* [1999] employed a similar version of this model. We analyse an ensemble average, for 1980 - 1995, of a six member set of runs starting in 1870 in which the Global sea-Ice and Sea Surface Temperature 3.0 dataset (GISST3.0, an update of *Rayner et al.* [1996]) was used to prescribe the SST; note, observations of meteorological variables are not assimilated in the model. Each member was initialised with atmospheric conditions from different earlier model runs. We also briefly discuss results from a 1000 year run of HadCM3, a coupled ocean-atmosphere model [*Collins et al.*, 2001] which uses HadAM3 as its atmospheric component. Monthly anomaly time series of the surface variables have been calculated for both SOC and HadAM3, where by anomaly we mean the difference of an individual monthly value from the climatological monthly average for 1980-1995. NAO index values have been determined as the difference in the normalised average sea level pressure (SLP) anomaly between boxes centred on the Azores High ($32^\circ W - 9^\circ E, 34^\circ - 41^\circ N$) and Iceland Low ($24^\circ W - 9^\circ E, 61^\circ - 66^\circ N$). The *Hurrell* [1995] NAO index (Hurrell hereafter) has also been used to verify the SOC values. Although our analysis is for a short period, in which the long term trend of the NAO was positive, this interval is known to contain sufficient short term NAO variability to enable the effects of the oscillation to be captured [*Hurrell*, 1995].

## Results

### Time Evolution of the NAO Index

Time series of the HadAM3 and SOC winter (December-March) NAO indices are shown on Fig.1 with Hurrell. The HadAM3 series is not correlated with either observational index, $r^2 = 0.01(0.05)$ for SOC( Hurrell), i.e. the model does not reproduce the observed interannual variations in the NAO. The SOC and Hurrell series are strongly correlated ($r^2 = 0.97$), verifying the SOC ship based index as a reliable measure of the NAO. Time series of the Southern Oscillation Index (SOI), calculated according to *Zhang et al.* [1997], also shown indicate that the model is able to capture the observed variability over the Tropical Pacific. The SOI and NAO series are correlated in HadAM3 ($r^2 = 0.31$, sig-

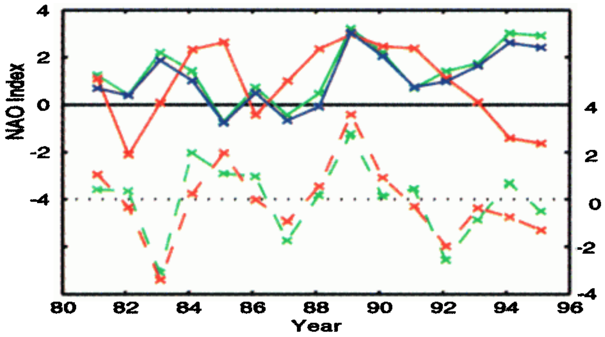


**Figure 1.** Time series of the winter NAO index (solid lines) for HadAM3 (red), SOC (green) and Hurrell (blue) for 1980-1995. Also shown are time series of the SOI (dashed lines) for HadAM3 (red) and SOC (green). The HadAM3 and SOC NAO indices have been offset by the mean value, 1.1, of the Hurrell index for 1980-95.

nificant at 95%) but not SOC ($r^2 = 0.01$). Hence, the poor model representation of the NAO appears to be partly due to an unrealistically strong link between atmospheric variability over the Tropical Pacific and the North Atlantic. In contrast, analysis of HadCM3 indicates that the connection becomes significantly weaker when HadAM3 is coupled to an ocean model. The NAO-SOI correlation for a sample of twenty 15 year intervals taken from 300 years of HadCM3 output is insignificant, $r^2 = 0.08 \pm 0.02$. The implication is that processes affecting Tropical Pacific teleconnections to higher latitudes differ between the atmosphere-only and coupled models.

The SOC SLP dataset has been averaged onto the model grid and correlated with the HadAM3 individual winter month SLP anomalies, Fig.2, to examine regional variations in their level of agreement. The strongest correlations occur in the Tropics where SST variations are known to strongly influence the atmosphere. In the North Atlantic and North Pacific mid-high latitudes, agreement is poor although pressure variations in the Eastern half of each basin are better represented than in the West. The lack of correlation in the Southern Ocean is likely due to uncertainties in the observational dataset resulting from undersampling in this region.

## NAO Composited Surface Forcing

HadAM3 and SOC have been composited on NAO extrema to determine whether the model NAO related air-sea interactions are spatially similar to those observed despite the differences in time evolution. Composite anomalies have been formed by averaging over separately selected individual winter months with NAO index > 1.5 (< -1.5) for NAO+ (-) states. These criteria result in different months for HadAM3 and SOC; the selected months and the NAO index for each are provided as an electronic supplement Table[1]. Composite difference plots of SLP, net heat flux (Qnet, defined to be positive for ocean heat gain) and SST are shown in Fig. 3. Note the model SST composite is the mean GISST3.0 field for the months when HadAM3 is in an NAO extreme state. Both SOC and HadAM3 show the meridional dipole in SLP between the Azores and Iceland characteristic of the NAO, although the model pressure gradient is somewhat weaker than observed. The dominant feature in each Qnet composite is a dipole with heat loss enhanced in the Labrador and Irminger Seas and reduced over the Gulf Stream. Reduced heat loss also occurs in the Greenland/Iceland/Norwegian (GIN) Seas. The anomalous Qnet in the Labrador/GIN Seas is consistent with observations of stronger/weaker rates of deep water formation in these regions during NAO+ relative to NAO- states [*Dickson et al.*, 1996]. The SOC SST composite is consistent with a passive ocean response to the Qnet anomaly i.e. cool(warm) SST anomalies correspond to stronger(weaker) heat loss. The model composite is similar to the SOC field at mid-high latitudes but does not contain the dipole between the US and African coasts. Thus, HadAM3 contains NAO extrema despite having an SST pattern composited on these extrema which does not fully correspond to that observed.

Composites of the heat flux components and surface meteorological variables (not shown) reveal that both the SOC and HadAM3 NAO Qnet patterns are dominated by latent heat anomalies of up to 70 $\mathrm{W\,m^{-2}}$. Anomalously strong latent heat loss occurs south of Greenland in response to drier air and stronger winds, while anomalously weak heat loss over the Gulf Stream is due to moister air and weaker winds. *Cayan* [1992] found that latent heat anomalies at the same locations were the dominant term in Qnet variations at multidecadal timescales. This suggests that the mechanism responsible for the dominant mode of air-sea heat exchange may be the same at interannual and interdecadal timescales in the mid-high latitude North Atlantic.

In summary, the HadAM3 NAO Qnet composite is spatially similar to SOC but the model NAO index time vari-

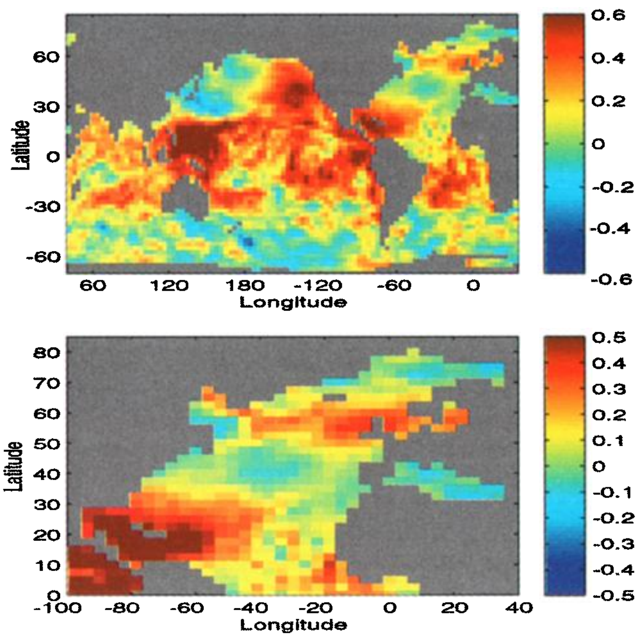


**Figure 2.** a.) Global variation of the correlation coefficient ($r$) between HadAM3 and SOC winter month SLP anomaly time series for coincident grid cells. Values of $r$ greater in magnitude than 0.21 are significant at the 95% level. b.) Detail of a.) for the North Atlantic.

[1]Supporting material is available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

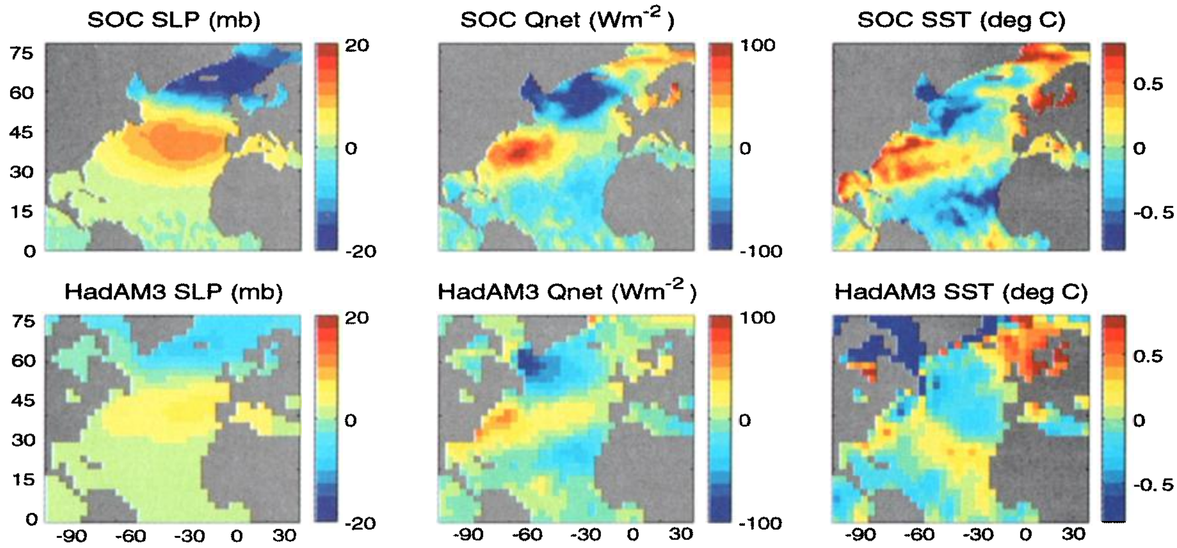


**Figure 3.** NAO+ – NAO- composites for SOC and HadAM3 SLP, Qnet and SST. The composites were generated by selecting winter months with NAO index magnitude > 1.5 within the period 1980-1995.

ation does not agree with that observed. As the only time dependent information supplied to the model is SST, the implication is that either SST does not play a major role in the time evolution of the NAO at interannual timescales, or that the SST forced atmospheric model considered here does not capture the processes which establish this role. We have separately verified that the GISST3.0 and SOC SST datasets are similar in their seasonal cycle and interannual variability. Thus it is unlikely that the disagreement between the model and observed time evolution of the NAO is due to a misrepresentation of SST variability in HadAM3.

## SST Anomaly Decay and Potential Feedback

The evolution of the observed SST pattern following extreme positive states of the NAO has been examined via a lagged analysis of the SOC dataset. SST and Qnet composites have been calculated at monthly intervals up to 12 months after those in the set of winter months with NAO index > 1.5, those for lags of 1-3 months are shown in Fig. 4. The lag 0 SST field (not shown) has a similar pattern to the NAO+ - NAO- composite in Fig.3. At lags of 1 and 2 months the main elements of the lag 0 pattern persist. Subsequently these features weaken on a timescale that increases with latitude, the cold anomaly to the south of Greenland is still significant after 5 months. The Qnet composites have been checked to see whether the SST anomalies are coincident with changes in the heat flux. No significant pattern is seen, suggesting either that the atmosphere has adjusted to maintain the air-sea temperature and humidity differences, or that the signal is dominated by Qnet anomalies associated with unrelated atmospheric variability at these timescales.

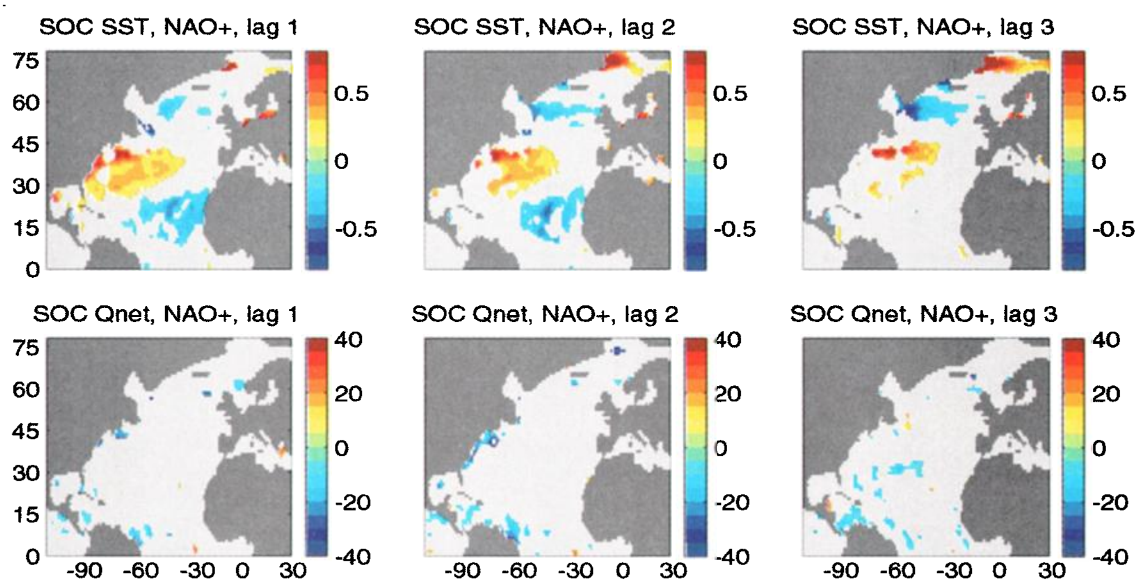


**Figure 4.** SOC SST and Qnet composite anomalies at lags of 1-3 months relative to the subset of extreme NAO+ winter months, units as Fig. 3. Only anomalies significant at the 95% level are shown, lag intervals are in months.

## Summary and Discussion

Several recent studies have investigated NAO variability using AGCMs in which the SST is prescribed [*Rodwell et al.*, 1999; *Mehta et al.*, 2000; *Robertson et al.*, 2000]. How the results of such studies should be interpreted from a theoretical perspective is the subject of continuing debate [*Czaja and Marshall*, 2000]. We have investigated from an observational perspective whether a particular atmospheric model (HadAM3) adequately captures the recent observed variation in the NAO at interannual timescales using the SOC flux dataset. The time variation of the NAO in HadAM3 does not correspond to SOC for 1980 – 1995. In contrast, the model NAO related spatial patterns of Qnet are similar to those observed. The lack of temporal coherence appears to be due in part to an unrealistically strong model connection between the North Atlantic and the Tropical Pacific. The dynamical processes responsible for this connection are the subject of an ongoing comparison with output from a coupled model. In addition, we have found from the observations alone that NAO related SST anomalies do not exert a significant heat flux feedback on the atmosphere at seasonal to interannual timescales. To conclude, our main result is that a state of the art SST forced AGCM is unable to reproduce the observed recent interannual variability of the NAO. Hence, claims that useful predictions of the North Atlantic winter climate may be achievable with such models up to several years in advance, given knowledge of the SST, need to be viewed with caution.

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