Climate Change and the North Atlantic Oscillation

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Over recent decades the boreal winter index of the North Atlantic Oscillation (NAO) has exhibited an upward trend, corresponding to lowered surface pressure over the Arctic and increased surface pressure over the subtropical North Atlantic. This trend has been associated with over half the winter surface warming in Eurasia over the past thirty years, as well as strong regional trends in precipitation over Western Europe. Several studies have shown this trend to be inconsistent with simulated natural variability. Most climate models simulate some increase in the winter NAO index in response to increasing concentrations of greenhouse gases, though the modeled changes are generally smaller than those seen in the real atmosphere. The two other principal anthropogenic forcings, sulphate aerosol and stratospheric ozone depletion, are generally found to have little significant effect on the NAO. Natural forcings may have also had an impact on the atmospheric circulation: volcanic aerosols induce the westerly (positive index) phase of the NAO in the 1–2 years following major eruptions, and multi-decadal changes in the NAO have also in part been attributed to changes in solar irradiance. These natural forcings, however, are unlikely to account for a substantial component of the recently observed positive NAO index trend: it is most likely to be the result of increasing greenhouse gas concentrations. Experiments using climate models forced only with changes in tropical sea surface temperatures suggest that at least part of this trend may be due to remote forcing from the tropics. Some authors have argued that greenhouse gas-induced changes in the meridional temperature gradient in the lower stratosphere may be responsible for the upward NAO index trend, but overall the mechanism of response to greenhouse gases remains open to debate.

1. INTRODUCTION

In recent decades the boreal winter North Atlantic Oscillation (NAO) index has increased markedly, with surface pressure in the winter season falling over Iceland by around 7 hPa over the past thirty years. This change has been associated with over half the Eurasian winter surface temperature increase over the same period [*Hurrell,* 1996], and much of the observed trend in precipitation over Western Europe. Thus if we are to make accurate climate predictions, we need to understand the relationship between climate change and the NAO. In this chapter we consider both how external forcing may induce changes in the NAO, and how such NAO changes manifest themselves in other climate variables, such as surface temperature. We start by asking whether the observed winter upward trend in the NAO index is consistent with natural variability. Estimating

The North Atlantic Oscillation:
Climatic Significance and Environmental Impact
Geophysical Monograph 134

10.1029/134GM09

natural variability from the recent observed record is difficult because it is so short and is contaminated by anthropogenic forcing. Instead, estimates of internal variability may be obtained from historical observations [*Jones et al.*, this volume], paleoclimate data [*Cook*, this volume], or from long control simulations of climate models. Aside from an upward trend in the NAO index, we also ask whether the mode of variability is itself changing, for example by a shift in the northern lobe of the NAO pattern [*Ulbrich and Christoph,* 1999].

Having assessed observed changes in the NAO, we also consider how this mode might vary in response to specific external climate forcings by reviewing a wide range of climate model simulations, and we assess the extent to which the simulated changes are consistent with those observed. Over the past century the largest change in tropospheric radiative forcing has been due to changes in anthropogenic greenhouse gases; thus, we first examine evidence of an NAO response to this forcing change. Stratospheric ozone depletion and tropospheric sulphate aerosol both also have significant climate impacts, but the literature on the atmospheric circulation response to these anthropogenic forcings is more limited. Of course changes in the NAO may not only be forced by anthropogenic climate forcings: natural forcings could be important too. Changes in solar irradiance and stratospheric aerosol from explosive volcanism have both been linked to changes in tropospheric circulation, so their impacts on the NAO are also reviewed.

Whilst climate model simulations may allow us to attribute observed changes in the NAO to external forcings, they do not necessarily lead to an improved physical understanding of these changes. Thus, we also ask by which mechanisms these external climate forcings influence the NAO. Though there have been several studies that attempt to answer this question, their conclusions differ.

Various definitions of the NAO index are used in the studies we review. The simplest use differences in sea level pressure (SLP) at two stations [e.g., between Gibraltar and Iceland; see *Jones et al.*, this volume]. Alternatively, hemispheric definitions can be used, derived by projecting SLP onto an Empirical Orthogonal Function (EOF) pattern, for instance of November-April monthly SLP northward of 20°N [*Thompson and Wallace,* 1998]. The latter is often referred to as the Arctic Oscillation index, or Northern Hemisphere Annular Mode index [*Thompson et al.*, this volume]. However, since these all represent essentially the same phenomenon, and to avoid confusing readers, we refer to them as simply the NAO index. When we wish to draw a distinction, we refer to the former as a "station-based" NAO index, and the latter as an "EOF-based" NAO index.

2. OBSERVED CHANGES IN THE NAO

The focus of this chapter is on linkages between the NAO and climate change, here defined as the climate response to external forcings, natural as well as anthropogenic. We are interested in the observed fluctuations of the NAO for three reasons: (i) has the NAO exhibited variations that imply the influence of external forcings?; (ii) are the observed NAO changes consistent with the simulated response to external forcings?; and (iii) are forced or unforced NAO variations masking or enhancing the signal of anthropogenic climate change?

The first question is effectively a "detection" question: can we detect an "unusual" change in the NAO index, where "unusual" might be in reference to the past range of observed variation, or to the range of natural variation generated internally within the climate system (or, more strictly still, generated internally within the atmosphere). Considering the former context, and focusing on the NAO index behavior over the past 30 years, *Thompson et al.* [2000] concluded that the observed positive trend between January and March is significant compared to its own internal variability, assuming that variability is uncorrelated. The upward trend in the monthly NAO index between November and January is also statistically significant compared to a red noise model [*Gillett et al.*, 2001; *Feldstein*, 2002]. Other statistical models may yield different results [*Wunsch*, 1999], though the model used must fit the data if it is to be considered valid [*Trenberth and Hurrell*, 1999].

The current instrumental record is insufficient in length to validate the realism of statistical models of lower frequency NAO behavior [although see *Jones et al.,* this volume]. Extended estimates based on climate proxies of the past variations in the NAO index were compared with recent observed NAO variations by *Jones et al*. [2001], who found that neither the recent, highly positive NAO index values of the 1990s nor the change from the low index values of the 1960s appear to be unique in the context of longer records [see also *Cook*, this volume]. Extended records based on climate proxies are, however, liable to substantial uncertainties [e.g, *Cook*, this volume] and also measure a climate that has been subject to various external forcings. It is worthwhile considering the more restricted context of comparing recent changes with the range of unforced variability, for which we must use unforced climate model simulations to obtain an estimate. Figure 1 shows a comparison of observed NAO winter trends over the past century with those simulated in a control integration of a general circulation model (GCM), using a hemispheric EOF-based NAO index. For almost all trend lengths between 20 and 60 years the observed trend is outside the 5–95% range of simulated internal variability.

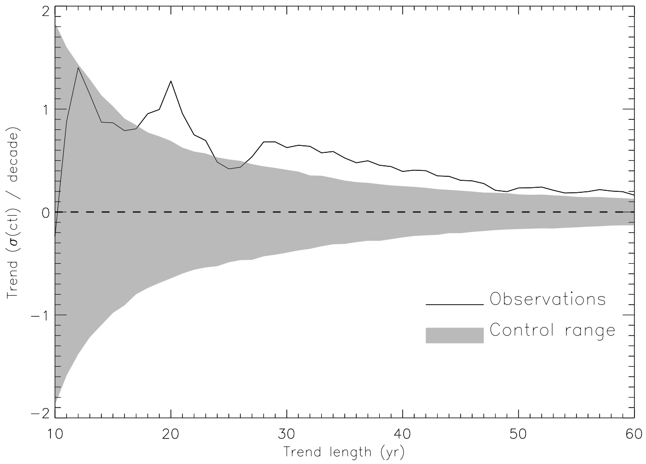

Figure 1. A comparison of the trend in the observed December-February EOF-based NAO index with the corresponding trend in HadCM2 control. The solid line shows the observed trend as a function of the length of time over which it is measured, always ending in 1997. The grey band shows the 5%–95% range of trends in 1091 years of HadCM2 control. Adapted from *Gillett et al.* [2000].

Osborn et al. [1999] demonstrated that observed (positive) 30-yr winter NAO index trends beginning between 1960 and 1967 were outside the 95% range of variability simulated during a 1400-year control run of the HadCM2 coupled climate model. In fact, over these periods observed trends exceeded all simulated 30-yr trends in the HadCM2 control, even those beginning in a period of anomalously low NAO index values. *Osborn* [2002] has extended this study to consider the variability simulated during (shorter) control runs of six other climate models in addition to HadCM2. Figure 2 shows the 95% ranges (from the 2.5 to 97.5 percentiles) obtained when results from these seven simulations are averaged, together with the minimum and maximum of the simulated ranges. These are based on distributions of 30-year winter trends from control simulations, and are compared in Figure 2 with the 30-year trends in the observed NAO index computed in a sliding window. Recent 30-year trends are clearly outside the mean of the simulated natural variability ranges, and those centered around 1981 (e.g., 1966-1995) are also outside the most extreme of the natural variability ranges. The widest ranges are from the two models (CCSR/NIES and NCAR PCM) that simulate interannual variance of the NAO that is more than twice as strong as that observed. The extreme ranges are likely, therefore, to be overestimates.

Our analysis of internally generated climate variability leads us to conclude that increases in the winter NAO index over recent decades are either due in part to some external forcing, or all seven climate simulations are deficient in their levels of interdecadal variability. While the latter possibility cannot be excluded, we note that the models are not in general deficient in their simulated levels of interannual NAO variability, and *Osborn et al*. [1999] point out that the simulated interdecadal NAO variability was similar to that observed prior to the 1950s. Thus it would seem likely that some response to external forcing is present in the observed NAO index record. The evidence from paleoclimate data suggests that this forcing may not be solely of anthropogenic origin [e.g., *Cook*, this volume].

Our understanding of the relationship between the NAO and climate change is complicated by the facts that (i) most external forcings influence the surface temperature field as well as (possibly) the atmospheric circulation and the NAO, and (ii) variations in the NAO influence surface temperature.

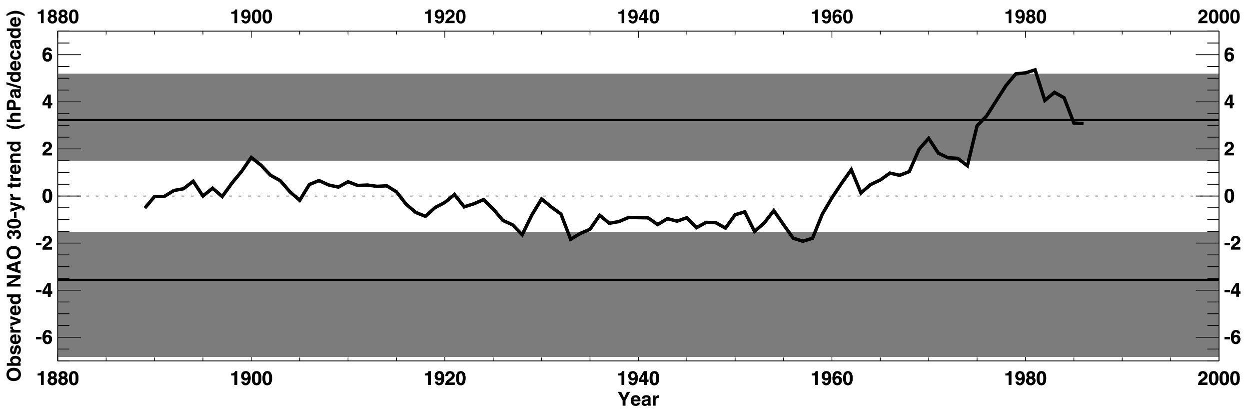

Figure 2. 30-year trend (black line, expressed as hPa/decade) in the observed EOF-based NAO index, computed in a sliding window and plotted against the central year of the window. Grey shading shows the ranges of 2.5 and 97.5 percentiles of 30-year trends computed during seven multi-century control simulations, with the solid horizontal lines indicating the mean 2.5 and 97.5 percentiles computed across the seven models.

The correlation pattern between the winter NAO index and the winter surface temperature field contains regions of both positive and negative influence (Figure 3), but the positive (generally land) regions dominate when averaged over the Northern Hemisphere [*Hurrell,* 1996]. The result is a strong positive correlation between the winter NAO index and the average Northern Hemisphere extratropical winter temperature [see also *Jones et al.*, this volume]. Based on the period 1935-1994, Hurrell [1996] found that the winter NAO variations explain 31% of the interannual variability of the mean extratropical Northern Hemisphere winter surface temperature, and 48% of the recent (1977-1994 average) warming (inclusion of Pacific circulation changes raised this to 71%).

Consequently, it is possible that observed NAO changes (which might be due to natural externally-forced or internally-generated variability) have caused us to overestimate the magnitude of anthropogenically-induced warming. There are, however, three important points to note regarding this statement. First, Northern Hemisphere winter temperatures are but one contributor to the trend in the global, annual mean surface temperature, which has increased 0.6±0.2°C over the past century [*Folland et al.*, 2001]. Second, *Osborn et al.* [1999] note that the strength of the relationship between the NAO and the northern extratropical mean surface temperature has varied through time [see also *Jones et al.*, this volume]. This can be partly explained by changes in station coverage [*Broccoli et al*., 2001] and also by the fact that the analysis period of *Hurrell* [1996] (1935-1994) coincided with the period when the correlation between the NAO and northern extratropical winter surface temperature was strongest [*Jones et al.*, this volume]. Use of a different period for developing the regression equation would have resulted in less of the variability and trend being explained by the NAO. Third, it is likely that part of the recent trend in the winter NAO index has been caused by anthropogenic forcing, in which case the part of the warming trend related to the NAO cannot be considered to be natural.

Thompson et al. [2000] investigated the contribution of the trend in an EOF-based NAO index to Northern Hemisphere warming. This signal is similar to that shown in Figure 3b, with strong warming over much of Eurasia, and explains ~30% of January-March warming over the entire Northern Hemisphere in the past forty years. *Gillett et al*. [2000] note that HadCM2 does not simulate an upward trend in the NAO index in response to a prescribed increase in greenhouse gases. Some authors [e.g., *Shindell et al*., 1999a] have suggested that such a failing may invalidate the results of climate change detection studies using this model [e.g., *Tett et al*., 1999]. However, *Gillett et al*. [2000] show that, using 50 years of surface temperature records, green-

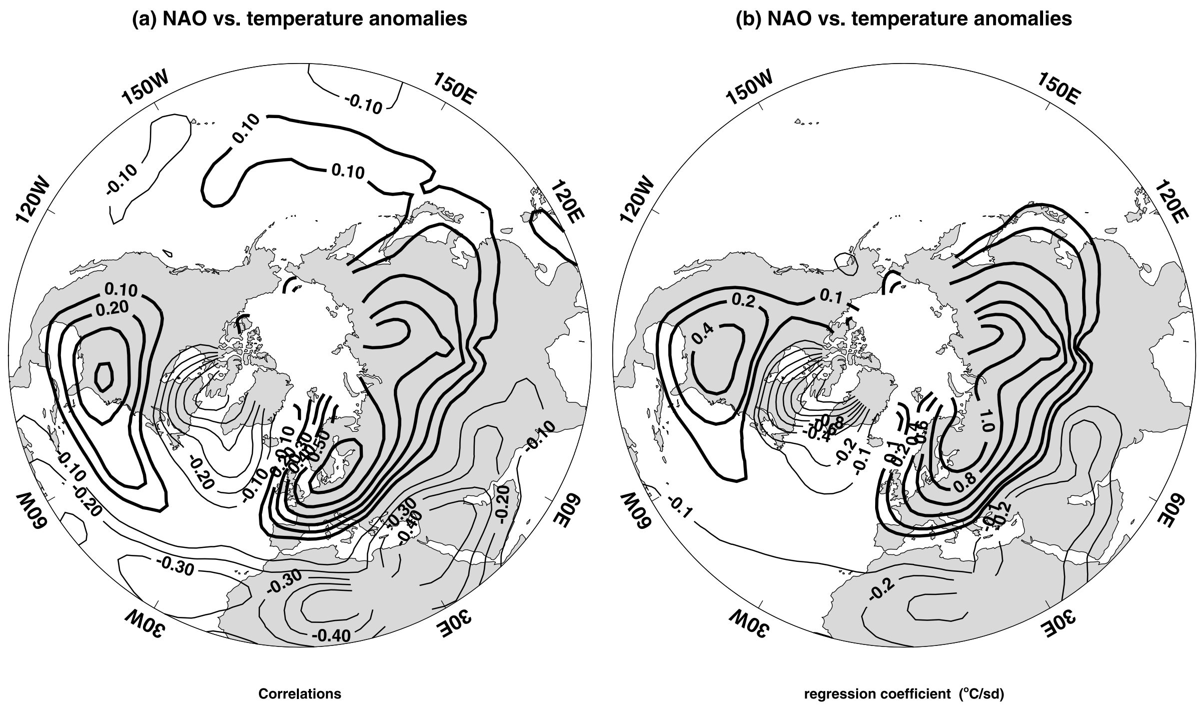

Figure 3. Correlation (a) and regression coefficient (b) of near surface air temperature on the NAO index.

house gas and sulphate aerosol influences may still be separately detected, even when the component of temperature change associated with the trend in the NAO is disregarded. This is likely to be due largely to the temperature changes observed in the tropics and Southern Hemisphere, which are not associated with a change in the NAO.

3. THE RESPONSE OF THE NAO TO FORCING CHANGES

3.1. Greenhouse Gases

Increases in anthropogenic greenhouse gas concentrations represent the largest external forcing on the climate system over the instrumental period of record [*Ramaswamy et al.*, 2001]. Thus, if we are to attempt to identify the cause of the recent increase in the winter NAO index, it is natural that we investigate this influence first.

When the recent upward trend in the NAO index first became apparent in the mid-1990s, several authors speculated that increasing greenhouse gas concentrations were a contributing factor [e.g., *Palmer*, 1993; *Hurrell*, 1995; *Graf et al.*, 1995]. The dominant effect of greenhouse gas increases on the atmosphere is a warming of the troposphere and a cooling of the stratosphere [e.g., *Cubasch et al.*, 2001], but the influence on the NAO is still uncertain. In this section we start by reviewing the response of the NAO to greenhouse gas increases in some coupled general circulation models, and go on to examine the proposed mechanisms by which this response might come about. Note that existing climate models have limited horizontal and vertical resolution that may limit their ability to properly simulate features such as baroclinic disturbances or stratospheric processes, both of which could be important in the NAO response to external forcing [*Thompson et al.*, this volume]. Despite this shortcoming, we devote considerable attention to model-based studies since GCMs are the best tools available to investigate these issues.

3.1.1. Coupled model results.

The first modeling studies to discuss the influence of greenhouse gases on the tropospheric circulation appeared about a decade ago. *Graf et al.* [1995] speculate that greenhouse gases may have contributed to the observed upward trend in the boreal winter NAO index, and they test this hypothesis by forcing a coupled ocean-atmosphere model (ECHAM1) with increased carbon dioxide concentrations and other anthropogenic forcings. However, they found no significant circulation response in their model, though they speculate that this may be due to model failings, such as its lack of modeled chemistry. In contrast, using a later version of the model (ECHAM4), *Ulbrich and Christoph* [1999] found a significant change towards the positive index phase of the NAO (using an EOF-based index), which they noted was linearly proportional to the applied radiative forcing. They also noted a northeastward shift of the northern center of action of the NAO in response to increasing greenhouse gas concentrations. *Osborn et al.* [1999] examined changes in a station-based NAO index in HadCM2 with prescribed increases in greenhouse gases, and found a decrease in the NAO index. However, other studies using this model have since found either no significant change [*Gillett et al.*, 2000] or a weak increase [*Osborn*, 2002] depending on the definition of the NAO index used.

At about the same time, two other studies used an EOF-based index to examine the circulation response to forcing in two different GCMs. *Fyfe et al.* [1999] found a significant increase in the NAO index in response to a combination of greenhouse gas and sulphate aerosol forcing in the Canadian Centre for Climate Modelling and Analysis (CCCma) model. However, although the pattern of SLP trends projected positively onto the hemispheric NAO pattern in their analysis, a station-based NAO index showed no significant increase. *Shindell et al.* [1999a] found that a 9-level model with its upper boundary at 10 hPa showed no NAO response to an increase in greenhouse gases, whilst a second model with 23 levels and an upper boundary at 0.002 hPa showed an increase in the NAO index of an amplitude similar to that observed. This prompted them to argue that greenhouse gases induce a change in the NAO toward its positive index phase through a stratospheric mechanism, though other models without a well-resolved stratosphere have since also been found to produce a similar response.

Thanks in part to the high levels of interest in both climate change and the NAO, circulation changes in response to enhanced greenhouse gases have now been examined in all of the major coupled general circulation models (Table 1). With the exception of HadCM2, the GISS 9-level model, and the NCAR CSM, all these models show at least some increase in the winter NAO index in response to enhanced greenhouse gas concentrations. Note that unlike the real world, these simulations generally include greenhouse gas changes only, prescribed with differing rates of change. However, since anthropogenic greenhouse gases have been the dominant climate forcing over the past century, and since NAO changes are generally found to be linearly dependent on the instantaneous radiative forcing [*Ulbrich and Christoph*, 1999; *Gillett et al.*, 2002a], we would expect the sign, if not the magnitude, of the response to be comparable with observed changes. The recently-published IPCC Third Assessment Report concluded that there was not yet a

Table 1. North Atlantic Oscillation index response to greenhouse gas increases in several general circulation models. Upward arrows indicate an increase in the NAO index, corresponding to a decrease in Arctic SLP, in response to increasing greenhouse gas concentrations (and changes in sulphate aerosol in the case of the CCCma model). A '.' indicates either no significant change, or that the sign of the change has been shown to be dependent on the definition of the NAO index. Note that authors use various different EOF and station-based measures of the NAO, and vary in the rigor of their estimates of the significance of the trend. Adapted from *Gillett et al.* [2002a].

Model	NAO response	Source	Model description
HadCM2	.	1, 2, 3, 4, 12	14
HadCM3	↑	4,12	15
ECHAM3	↑	4, 5	16
ECHAM4	↑	2, 4, 6, 7, 12	6
CCCma	↑	8,12	17
GISS-S	↑	4, 9, 10	18
GISS-T	.	9, 10	9
CSIRO	↑	11,12	19
CCSR	↑	11,12	20
NCAR-CSM	.	7, 12	21
NCAR-PCM	↑	12	22
GFDL	↑	13	23

Sources: 1, *Gillett et al.* [2000]; 2, *Zorita and González-Rouco* [2000]; 3, *Osborn et al.* [1999]; 4, *Gillett et al.* [2002a]; 5, *Paeth et al.* [1999]; 6, *Ulbrich and Christoph* [1999]; 7, *Robertson* [2001]; 8, *Fyfe et al.* [1999]; 9, *Shindell et al.* [1999a]; 10, *Shindell et al.* [2001b]; 11, E. Zorita (pers. comm.); 12, *Osborn* [2002]; 13, *Stone et al.* [2001]; 14, *Johns et al.* [1997]; 15, *Gordon et al.* [2000]; 16, *Voss et al.* [1998]; 17, *Flato et al.* [2000]; 18, *Shindell et al.* [1998]; 19, *Gordon and O'Farrell* [1997]; 20, *Emori et al.* [1999]; 21, *Boville and Gent* [1998]; 22, *Washington et al.* [2000]; 23, *Stouffer and Manabe* [1999]. GISS-S denotes the 23 level GISS model with a model top at 0.002 hPa, and GISS-T the 9 level GISS model with a model top at 10 hPa.

consistent picture of the ability of coupled models to reproduce the observed upward trend in the NAO index [*Cubasch et al.*, 2001], but there is now a growing consensus amongst modeling groups that greenhouse gases induce some increase in the NAO index.

We now turn our attention to the spatial patterns of the simulated SLP trends. Figure 4a [*Osborn*, 2002] shows the average of the first EOF of winter SLP computed separately from the Atlantic sectors of seven coupled GCM control simulations. Most models show broadly realistic patterns of interannual, unforced variability, and this is reflected in the 7-model mean. One consistent difference between the simulated (Figure 4a) and observed (Figure 4b) EOF is the stronger simulated covariance between the North Pacific and the North Atlantic SLP. Such a pattern is only obtained in the observed data by performing an EOF analysis on the hemispheric SLP field [e.g., *Deser,* 2000; *Ambaum et al.,* 2001].

Figure 5 [*Osborn*, 2002] shows the 7-model mean of the trends in boreal winter SLP simulated under increasing greenhouse gas concentrations (a similar scenario was applied to each model), together with an indication of inter-model agreement. Two points are apparent: First, there are large inter-model variations in the patterns simulated. Such trend patterns have been shown to be very sensitive to the details of the model physics. For example *Williams et al.* [2001] found that the relatively zonally symmetric trend pattern simulated by HadCM3 in response to enhanced greenhouse gases was transformed into a response pattern much more like that of HadCM2, with a decrease in pressure over the North Pacific, simply by a small change in the critical relative humidity for cloud formation, and a change in the model's boundary layer scheme. Second, despite these large variations, the models generally show a decrease in pressure over the Arctic region, and some increases at lower latitudes. Such patterns project onto the positive (westerly) phase of the NAO. Thus, if the model EOF patterns (Atlantic-sector only) are used to measure the evolution of the NAO index under enhanced greenhouse forcing, then the winter NAO index shows a positive trend in all seven climate models (Figure 6). Though the magnitude of this trend is highly model-dependent, the consistency in the sign of the change provides some confidence that the circulation response to greenhouse gas forcing is likely to be an enhancement of the westerly circulation in the North Atlantic sector. Note that, if the NAO index is measured by a simple pressure difference between two points (e.g., Gibraltar and Iceland), the spread of modeled responses is greater than if an EOF-based index is used, and some models even show a decrease in such an index [e.g., *Osborn et al.*, 1999].

Often climate model simulations are carried out with different scenarios of increasing greenhouse gas concentrations,

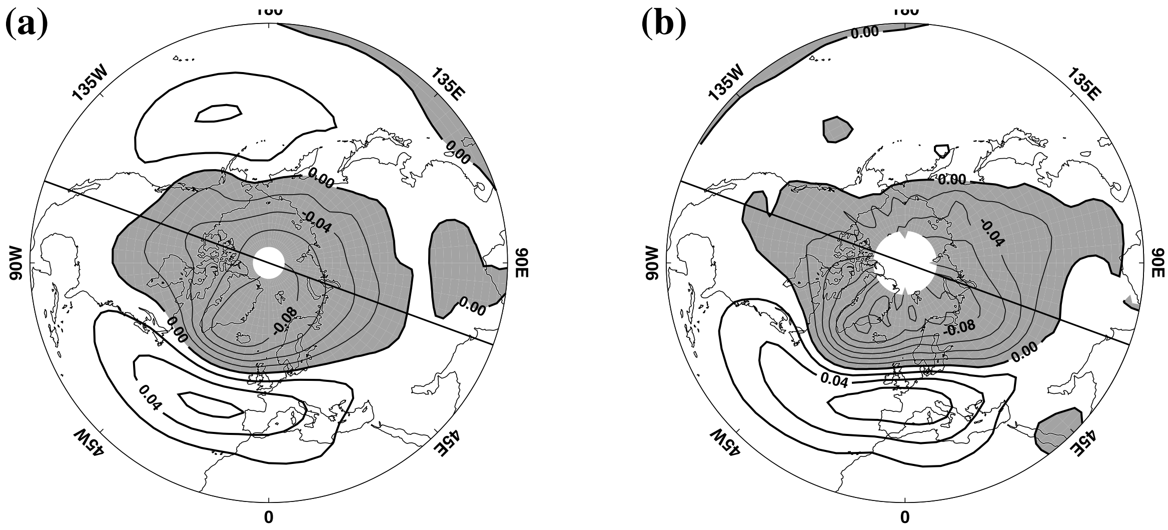

Figure 4. The leading EOF of the winter SLP field computed over the Atlantic sector (below the black line) and then extended to identify covariances across the whole hemisphere: (a) the mean of seven climate model control run EOFs (HadCM2, HadCM3, ECHAM4/OPYC, CCCma, CCSR/NIES, CSIRO and NCAR PCM); (b) the observed EOF.

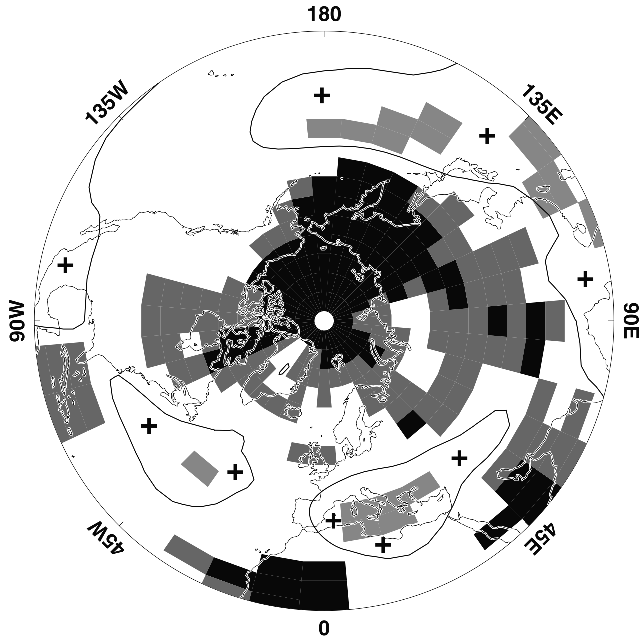

Figure 5. The trend in winter SLP computed from seven climate model simulations under increasing greenhouse gas forcing (1% per annum compounded increase in [CO_2] after 1990) averaged to produce a single mean trend pattern. Only the zero isoline is shown, with '+' to indicate the regions with positive SLP trends (and, therefore, SLP trends are negative elsewhere). Black boxes are drawn where all 7 models exhibit negative trends, dark grey boxes where 6 out of 7 models exhibit negative trends, and pale grey boxes where 6 out of 7 models exhibit positive trends.

and the forcing rarely increases linearly with time. Further, changes in the NAO index are, in some cases, difficult to distinguish from climate noise. How then, are we to quantitatively compare the NAO response in different integrations and different models? *Ulbrich and Christoph* [1999] noted that in a greenhouse gas forced integration of ECHAM4, the NAO index varies linearly with the applied forcing, suggesting that the ratio between the NAO change and the radiative forcing at the tropopause remains constant. *Gillett et al.* [2002] showed that this is also the case in HadCM3 and ECHAM3. This result allows us to make objective comparisons of the sensitivity of the NAO in a range of models by regressing the NAO index against a reconstruction of the radiative forcing. Averaging over different integrations with different time histories of greenhouse gas variations allows us to further reduce uncertainties.

Figure 7 compares the NAO sensitivity in a range of GCMs forced with greenhouse gas changes only, using an EOF-based index [*Gillett et al.*, 2002a]. These sensitivities are essentially the mean regression coefficients of the index with respect to a reconstruction of the radiative forcing at the tropopause. In simple terms they represent how much the NAO index changes per Wm^{-2} of radiative forcing. The associated uncertainty intervals were derived using simulated control variability. Thus if the uncertainty range for a particular model does not include zero, that model has a significant NAO response to greenhouse gas increases. Using a definition of the NAO pattern based on the first EOF of HadCM3 control variability, all the models bar HadCM2 and CCCma show a significant increase in the

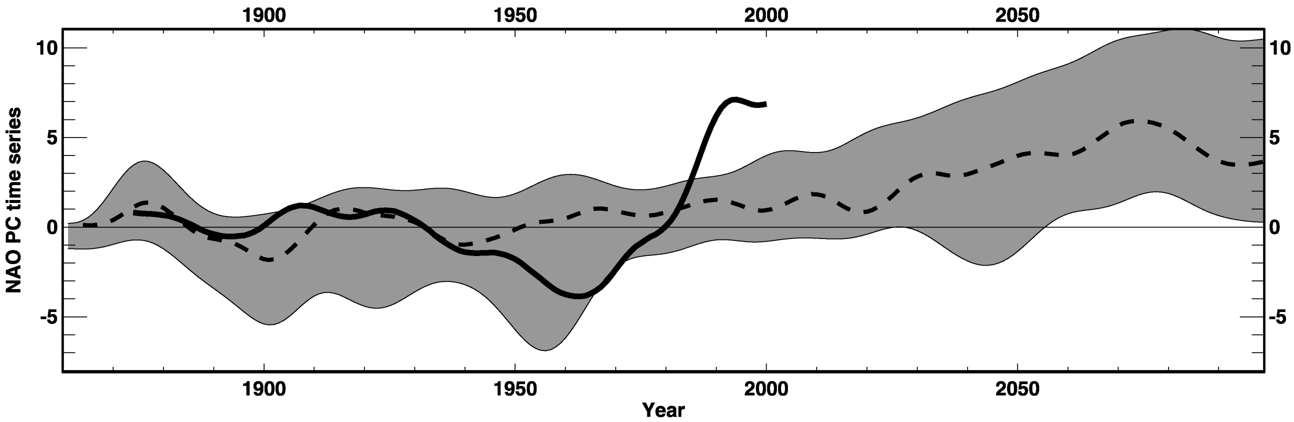

Figure 6. The observed NAO index (solid line) and the average (dashed line) of the NAO indices from seven climate model simulations under increasing greenhouse gas forcing (1% per annum compounded increase in [CO_2] after 1990), together with an envelope containing the individual model simulations (grey shading). All series have been smoothed with a 30-year low-pass filter. The NAO index is the scaled principal component time series associated with each model's leading EOF of the Atlantic-sector SLP field (defined during the control run of each model).

NAO index in response to greenhouse gas increases. Figure 8 shows equivalent sensitivities, but for a station-based NAO index. Again most of the models show a positive NAO index response to the forcing, though in this case more of the uncertainty ranges include zero. Note that the CCCma integration shown here had greenhouse gas forcing only, unlike the ensemble used by *Fyfe et al.* [1999], which also had sulphate aerosol forcing. Applying our analysis to the latter, we too find an NAO index increase, though this result is not significantly different from that for the greenhouse gas only integration.

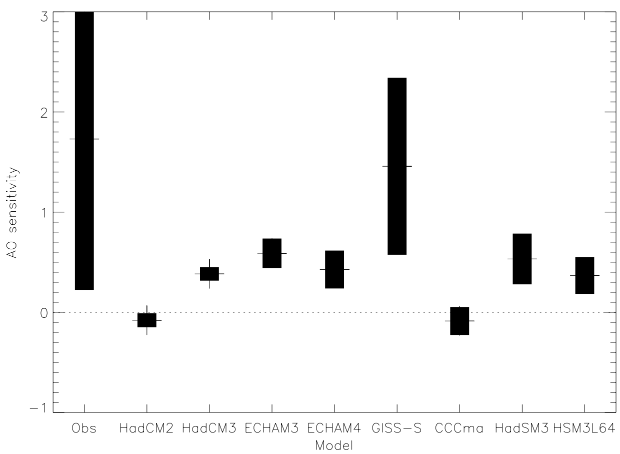

Figure 7. The mean sensitivity of a hemispheric EOF-based NAO index to net radiative forcing at the tropopause due to greenhouse gases in eight GCMs and observations. Black bars show 5-95% uncertainty ranges estimated using control variability. Adapted from *Gillett et al.* [2002a].

Although most of the GCMs included in Figures 7 and 8 simulate a positive NAO sensitivity to greenhouse gas forcing, this is generally less than the sensitivity estimated from observations. The observed sensitivity was calculated with respect to a reconstruction of the radiative forcing at the tropopause due only to greenhouse gases, but similar results are obtained if a reconstruction of total radiative forcing is used. However, the observed sensitivity has a large associated uncertainty, because of the relatively small change in radiative forcing over the length of the observed record, thus we cannot attribute significance to this difference. This apparent underestimate of the observed trend is also seen in time histories of the NAO index shown in Figure 6. Here the

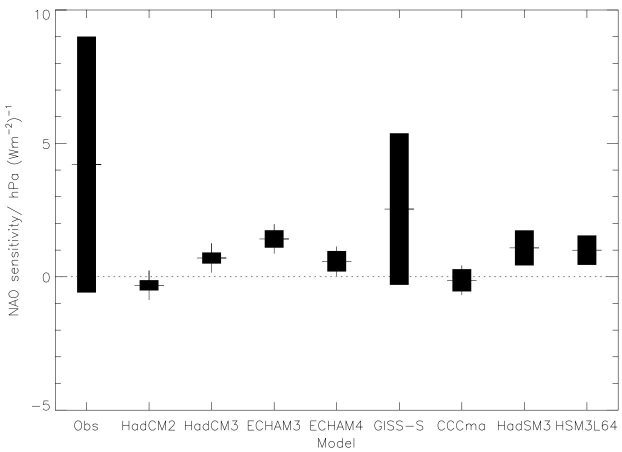

Figure 8. The mean sensitivity of a station-based NAO index to net radiative forcing at the tropopause due to greenhouse gases in eight GCMs and observations. Adapted from *Gillett et al.* [2002a].

observed index is seen to increase outside the range of indices simulated in the forced simulations.

One model that appears to be in closer agreement with observations is the GISS-S stratosphere-resolving model. This model has a much higher upper boundary than most GCMs, with 23 levels extending up to 85km. However, this estimate is based only on the first 60 years of a single greenhouse gas forced integration of the model, prior to the time when *Shindell et al.* [1999a] report that the response saturates. If later years of the integration or additional ensemble members incorporating greenhouse gas and ozone changes are included in the analysis, then the estimate of the NAO sensitivity is considerably reduced [*Gillett et al.*, 2002a]. Furthermore, an enhancement of sensitivity with improved stratospheric resolution is not a feature common to all models. HadSM3 shows no such increase in its NAO sensitivity when its stratospheric resolution is increased and its upper boundary is raised to over 80 km (compare the sensitivities of HadSM3 and HadSM3-L64 in Figure 7) [*Gillett et al.*, 2002b]. Such a test of the sensitivity of the modeled NAO response to stratospheric resolution has not been carried out with any other models to date.

3.1.2. Mechanisms

3.1.2.1. Regime paradigms

Palmer [1993] discusses the role of the North Atlantic Oscillation in climate change, and speculates that increased CO_2 may force it towards its positive phase. However, he contends that this is not because the circulation response to CO_2 looks like the NAO in any direct way. He argues that the system responds in this way primarily because the NAO is a dominant mode of natural variability. Using a variant of the Lorenz model that includes a "forcing" term, he demonstrates that the response of this system is not in the direction of the forcing, but rather close to the dominant mode of natural variability. *Palmer* [1999] and *Corti et al.* [1999] take this argument further by claiming to find observational evidence that Northern Hemisphere circulation changes are manifested through changes in the occupation probabilities of naturally occurring "regimes." These regimes are generally defined as preferentially visited atmospheric states, which are manifested as multiple maxima in histograms of the NAO index or other circulation indices. This viewpoint is, however, contested by *Hsu and Zwiers* [2001] who argue that the regimes identified are not statistically significant, with the possible exception of the Cold Ocean Warm Land (COWL) [*Wallace et al.,* 1995] pattern. *Stone et al.* [2001] also argue against a "regime" view of SLP changes, based on integrations of the GFDL model forced with changing greenhouse gas concentrations. They identify no "regimes" in this model, and they also find a purely linear shift in the distribution of an NAO-like index under increasing greenhouse gas concentrations. This result is also reflected in that of *Gillett et al.* [2002a], who find that the NAO index increases linearly with radiative forcing in HadCM3 and does not exhibit multiple regimes.

However, even in the absence of quasi-stationary regimes, if physical processes act to amplify the natural variability of a particular pattern, then they may also amplify any component of the greenhouse gas response which projects onto that pattern. *Graf et al.* [1995] argue that climate change forces changes in naturally occurring modes, which they identify through physical arguments. They argue that the low latitude greenhouse effect and other anthropogenic forcing produce changes in a coupled troposphere-stratosphere baroclinic mode.

An alternate paradigm would suggest that the physical mechanisms underlying the natural mode of variability and the response to anthropogenic forcing are distinct, and it is perhaps only a consequence of the Earth's approximate zonal symmetry that the pattern of SLP trends is similar to the pattern of natural variability. Until we obtain a better understanding of the physical mechanisms underlying both the variability and the trends in SLP, it may be impossible to determine which view more closely reflects the real world.

3.1.2.2. Sea surface temperature modulated changes

Several authors have suggested that sea surface temperatures (SSTs) may be critical in modulating the NAO, either in the North Atlantic [*Rodwell et al.*, 1999] or in the tropical Indian and Pacific oceans [*Hoerling et al.*, 2001; see also *zaja et al.*, this volume]. *Rodwell et al.* [1999] prescribe the observed, time-varying history of global SSTs in an ensemble of simulations with an atmospheric GCM, and they are able to explain around half of the observed boreal winter trend in the NAO index. They further argue that SST variations in the North Atlantic are of greater relevance. *Mehta et al.* [2000] and *Latif et al.* [2000] obtained similar results with different models. However, other authors have argued that this result could also come about from an ocean that essentially responds passively to stochastic atmospheric forcing [*Bretherton and Battisti*, 2000; *Czaja et al.*, this volume]. *Bretherton and Battisti* [2000] used a model that consists of two time-dependent equations describing a stochastically forced atmosphere and a mixed-layer ocean. It is first integrated in a coupled configuration with a single realization of atmospheric stochastic noise: this is taken to represent the "observed" record. Ocean temperatures from this integration of the model are then prescribed in an ensemble of integrations with an atmosphere-only configuration, and the resulting ensemble mean atmospheric temperatures were found to be highly correlated with the original "observed" temperatures. They thus demonstrated that a model of this type could have significant hindcast skill in an ensemble mean, even though the ocean was only responding passively to atmospheric forcing.

More recently *Hoerling et al.* [2001] argued that the upward trend in the boreal winter NAO index is linked to a warming of tropical SSTs, particularly over the Indian and Pacific oceans. By prescribing observed SSTs since 1950 over the tropics, and fixed seasonally varying climatological SSTs elsewhere, they were able to explain roughly half the magnitude of observed mid-tropospheric height trends in the Northern Hemisphere. This was similar to the trend explained when global observed SSTs were specified. Although NAO anomalies could certainly force changes in tropical Atlantic SSTs, they would be less likely to influence tropical SSTs in the Indian and Pacific oceans. Thus simulated changes that project onto the NAO pattern may really be a response to SST forcing in this experiment, and the objections raised by *Bretherton and Battisti* [2000] to the *Rodwell et al.* [1999] experiment may not apply. *Hoerling et al.* [2001] ascribe this response to changes in tropical rainfall, latent heating, and hence changes in the driving of the extratropical circulation. Note that these studies do not necessarily indicate that the ocean itself plays a strong physical role in determining NAO variability. Prescribed SSTs in a model closely constrain the temperature of the whole tropospheric column, thus it may be that warming tropical SSTs are just a reflection of greenhouse gas forcing in the atmosphere, and it is this atmospheric change that is more directly responsible for the upward trend in the NAO index. These results do, however, suggest that greenhouse gas forcing could modulate the NAO merely through changes in the tropical circulation.

3.1.2.3. Meridional temperature gradient changes in the upper troposphere - lower stratosphere

The first order effect of greenhouse gas forcing is a warming of the troposphere, and a cooling of the stratosphere. In particular, models predict an enhanced warming of the tropical upper troposphere: this is the signature we expect of a moist adiabat. On the basis of radiative calculations and some models, we expect the stratospheric polar vortex to cool in response to enhanced greenhouse gas concentrations. Since the tropopause tilts downwards from the tropics to the pole, these effects would together combine to increase the meridional temperature gradient in the upper troposphere – lower stratosphere region. Many models show such a temperature response to enhanced greenhouse gases [*Cubasch et al.*, 2001]. This in turn might be expected to enhance the vertical shear of zonal wind in the mid-latitude tropopause region, and strengthen the stratospheric vortex.

Shindell et al. [1999a] and others have argued that this strengthening of the vortex may be augmented by a planetary wave feedback, whereby the changed zonal wind profile in the mid-latitude tropopause region acts to deflect planetary-scale Rossby waves equatorwards. These waves are responsible for driving the meridional circulation of the stratosphere, hence also the descent in the region of the pole, which induces a dynamical warming. An equatorward deflection of the waves would thus weaken the stratospheric meridional circulation and reduce dynamical heating of the pole, leading to a further cooling of the vortex: a positive feedback.

On average, circulation anomalies on short timescales have been observed to appear first at around the 10-hPa level, and at the surface around three weeks later [*Baldwin and Dunkerton*, 1999]. This apparent downward propagation has been shown to be significant compared to a noise model [*Gillett et al.*, 2001], though the physical mechanism underlying downward propagation through the troposphere is not well understood [*Thompson et al.,* this volume]. Some authors thus argue that a change toward a stronger zonal circulation in the stratosphere could cause an enhancement of the zonal circulation at the surface, and hence a change toward the positive index phase of the NAO [*Shindell et al.*, 1999a; *Hartmann et al.*, 2002; *Thompson et al.,* this volume].

There are, however, some aspects of this mechanism that are not in agreement with other modeling studies. First, some stratosphere-resolving models predict that planetary wave changes in response to enhanced greenhouse gas concentrations will act against radiative changes and lead to a weakening of the Arctic winter vortex [e.g., *Rind et al.*, 1990; *Schnadt et al.*, 2002; *Gillett et al.*, 2002b]. Second, at least one model shows an increase in the NAO index even though its stratospheric vortex weakens [*Gillett et al.,* 2002b], suggesting that a tropospheric mechanism might be responsible for the NAO trend. More work is clearly needed to resolve these issues.

3.2. Tropospheric Aerosols

The direct and indirect effects of tropospheric sulphate aerosol together make up the second largest radiative forcing after greenhouse gases on the climate over the last century [*Ramaswamy et al.*, 2001]. Sulphate aerosol has a direct radiative effect through the scattering and absorption of solar and infrared radiation, and an indirect effect through induced changes in cloud properties. Sulphate aerosol has had a large cooling effect on surface temperatures, likely counteracting much of the greenhouse warming over the past century [*Tett et al.*, 1999]. Thus one might expect that this forcing agent has also had an influence on the NAO. Several authors have examined trends in the NAO index in integrations of climate models incorporating the effects of changes in anthropogenic sulphate aerosol [*Fyfe et al.*, 1999; *Osborn et al.*, 1999; *Gillett et al.*, 2000]. However, *Fyfe et al.* [1999] and *Gillett et al.* [2000] look only at runs incorporating both greenhouse gas increases and sulphate aerosol increases, thus the influence of the sulphate aerosol cannot be separately identified. *Osborn et al.* [1999] compare changes in the NAO index in ensembles of HadCM2 integrations with both greenhouse gas and sulphate aerosol increases, and with greenhouse gas increases only. They note no significant differences between the NAO responses.

HadCM2 was recently integrated with sulphate aerosol changes only (M. Wehner, personal communications), allowing the response to this forcing to be better separated from the response to greenhouse gases. Based on a four-member ensemble over the past 140 years, we found that winter SLP changes were generally not significant in the northern extratropics, but showed a small decrease over parts of the tropics and southern middle latitudes, and an increase over Southeast Asia, a strong aerosol source region. The simulated SLP response to sulphate aerosol forcing was derived for two more GCMs (CCCma and HadCM3) by differencing SLP changes in ensembles forced with both greenhouse gas and sulphate aerosol changes, and ensembles forced with greenhouse gas changes only. Both models showed few regions of significant SLP response. In recent work, *Chung et al.* [2002] prescribed changes in radiative heating due to aerosol changes over the Indian Ocean region, as measured by the INDOEX experiment, in the NCAR Community Climate Model (CCM3). They found a large dynamical response to this forcing over the tropics, with a northward shift of the intertropical convergence zone, and changes to the subtropical jetstream. Preliminary results also suggest that increases in the South Asian haze may have contributed to the upward trend in the boreal winter NAO index, though the response appears to be very sensitive to the geographical extent of the forcing in the model (Chung, personal communication). Thus, overall, most studies show that anthropogenic sulphate aerosol is unlikely to have had a large influence on the NAO, although the work on the topic must be viewed as preliminary.

3.3. Stratospheric Ozone Depletion

The substantial reduction of lower stratospheric ozone content over the last two decades has received considerable attention in view of its possible contribution to climate change [e.g., *Bengtsson et al.*, 1999; *Forster*, 1999; *Randel and Wu*, 1999; *Langematz,* 2000]. Model simulations and observational evidence show that ozone depletion clearly leads to reduced stratospheric temperatures over both poles mainly in late winter and spring, when sunlight comes back to the polar night area [e.g., *Ramaswamy et al.*, 1996; *Graf et al.*, 1998]. Since a colder polar stratosphere leads to a stronger and more stable polar vortex, which may be linked to a positive index phase of the NAO [*Perlwitz and Graf,* 1995; *Hartmann et al.*, 2002], some model studies have examined the contribution of Arctic ozone depletion to the increase of the winter NAO index [*Graf et al.*, 1998; *Volodin and Galin*, 1999; *Shindell et al.*, 2001b]. While *Volodin and Galin* [1999] claimed that tropospheric circulation and temperature anomalies in the years 1989-94 relative to 1977-88 can be explained by the reduction in Arctic ozone, *Graf et al.* [1998] and *Shindell et al.* [2001b] suggest that ozone depletion plays only a minor role for the months with the strongest NAO index trends, when compared with the effect of the increasing greenhouse gas concentrations. In accordance with *Hartmann et al.* [2000], both authors find that ozone reduction acts in the same direction as greenhouse gases, i.e. strengthening the positive index phase of the NAO, but only at an amplitude which is not sufficient to explain observations. *Gillett et al.* [submitted] found that, in the Southern Hemisphere, stratospheric ozone depletion induced a significant change in the Southern Hemisphere Annular Mode [see *Thompson et al.*, this volume] in HadSM3 in austral summer, a result also obtained by *Sexton* [2001]. However, this change was not reflected in the Northern Hemisphere, where circulation changes due to the smaller changes in ozone concentrations were not found to be statistically significant.

3.4. Volcanic Activity

There are only a few studies directly linking the NAO with volcanic eruptions. The interest in this relationship mainly arose from the need to explain the winter warming observed over Northern Hemisphere continents after strong eruptions. The SO_2 injected into the stratosphere during such volcanic events is oxidized within a few weeks to sulphuric acid, which, due to its very low saturation pressure, is rapidly condensed into submicron droplets that interact with solar and terrestrial radiation. The direct radiative effect of these particles leads to surface cooling and warming in the stratosphere lasting up to 3 years. This was clearly demonstrated with radiative-convective models [*Hansen et al.*, 1978], with Energy Balance models [e.g., *Schneider and Mass*, 1975] and also with early GCM studies [*Hunt,* 1977; *Hansen et al.*, 1988; *Rind et al.*, 1992]. In a comprehensive study into the radiative effects of the Mt. Pinatubo eruption, *Stenchikov et al.* [1998] showed that the main forcing of the atmosphere is due to effects in the visible and near-infrared part of the solar spectrum. Here the volcanic aerosol absorbs incoming solar radiation that leads to a deficit at the surface of the order of several Wm^{-2}. Infrared effects at the surface are at least one order of magnitude smaller. However, in the stratosphere the absorption of longwave radiation from below adds to stratospheric warming by as much as absorption of shorter wavelengths.

It was first suggested by *Groisman* [1985] and in earlier Russian literature [see references in *Groisman*, 1985] that over central Russia and North America warm winters occurred after strong volcanic eruptions. Such positive temperature anomalies were also found in a GCM study by *Graf et al.* [1992], who simulated a high latitude eruption by forcing the ECHAM1 model with a mid to high latitude reduction in solar radiation only. In a later "perpetual January" simulation, *Graf et al.* [1993] also included the effect of absorption of longwave radiation and showed, for an idealized stratospheric aerosol anomaly of the Pinatubo eruption (1991), that mid-tropospheric circulation anomalies and surface temperature patterns generated by the model are in very good agreement with observations. *Robock and Mao* [1992] presented a systematic analysis of the global temperature anomalies after all violent eruptions since Krakatoa (1883). They found, after removal of El Niño effects, similar patterns after all 12 eruptions included in their study.

Kodera [1994], *Graf et al.* [1994] and *Kelly et al.* [1996] demonstrated that observed mid-troposphere geopotential height anomalies after eruptions since the 1950s resemble the mid-tropospheric signature of the positive index phase of the NAO in the boreal winter. *Perlwitz and Graf* [1995] and *Kodera et al.* [1996] suggested that this pattern is the positive phase of the leading mode of the coupled tropospheric-stratospheric circulation, which occurs when the stratospheric polar vortex in winter is very strong. The associated temperature pattern at the surface corresponds to that observed after volcanic eruptions by *Robock and Mao* [1992]. *Graf et al.* [1994] suggested that volcanic eruptions exaggerate the positive phase of a naturally occurring variability mode similar to the NAO.

Graf et al. [1993] first proposed a mechanism for the exaggeration of the positive index phase of the NAO by volcanic stratospheric aerosol. They suggested that the absorption of near-infrared solar and longwave terrestrial radiation by the volcanic aerosol leads to strong heating in the stratosphere at low latitudes. Since, over the winter pole, solar radiation is absent and long-wave irradiance from the surface is smaller than at low latitudes, the meridional temperature gradient in the stratosphere is strengthened, which makes the polar vortex of the winter hemisphere stronger and less susceptible to vertically propagating planetary waves. Hence a stronger zonal wind is induced, which further deflects planetary waves equatorwards: a positive feedback. The effect is much stronger in the Northern Hemisphere, since in the Southern Hemisphere the mean state of the polar vortex is already close to radiative equilibrium.

This interpretation was shared by *Kodera et al.* [1996], *Shindell et al.* [1999b] and others. However, the model simulations by *Graf et al.* [1992], which neglected the stratospheric warming effects and only accounted for the reduction in shortwave radiation, showed similar effects in tropospheric circulation and near surface temperature. Hence, the differential heating in the stratosphere is probably not the only possible factor that may induce the positive phase of NAO and a strong polar vortex. *Stenchikov et al.* [submitted] performed a specific experiment series to study this. They studied the response of the NAO, using an EOF-based index, to aerosols and observed ozone changes in the stratosphere after the June 15, 1991 Mount Pinatubo eruption using the SKYHI GCM. An enhanced positive phase of the NAO is reproduced in the model when forced with aerosols. Experiments with albedo changes, but without aerosol absorption and its associated stratospheric heating, show as strong an NAO response as with the total aerosol forcing. *Stenchikov et al.* [submitted] suggested that aerosol stratospheric warming in the tropical lower stratosphere is not the dominant NAO-forcing mechanism. Stratospheric aerosols can also induce tropospheric cooling, which is strongest in low latitudes especially in winter. This could then influence the NAO directly through a tropospheric mechanism, or via the stratosphere through a reduction in the tropospheric meridional temperature gradient, which may lead to a decrease of the mean zonal energy and amplitudes of planetary waves in the troposphere. The corresponding decrease in wave driving in the lower stratosphere may then cause a strengthening of the polar vortex.

3.5. Solar Forcing

Many studies have examined links between 11-yr solar cycle variability and the tropospheric climate, though observed links are generally stronger in the stratosphere. Changes in irradiance are generally largest in the ultra-violet, thus they may be expected to have particularly strong impacts on ozone and stratospheric temperatures. *Kodera* [1995] identified a correlation between the strength of the polar vortex in the Northern Hemisphere winter stratosphere and the 11-year solar cycle, a stronger vortex being associated with higher solar irradiance. *Labitzke and van Loon* [2000] also identified a strengthening of the winter vortex in periods of high solar irradiance.

Several authors have also attempted to examine the impact of solar cycle variability on the atmospheric circulation using GCMs. In a model with prescribed changes in solar irradiance and corresponding stratospheric ozone changes, but limited stratospheric resolution and prescribed sea surface temperatures, *Haigh* [1996] found a slight increase in the strength of the westerlies through most of the Northern Hemisphere extratropical troposphere when solar irradiance was increased. She also found a corresponding decrease in SLP over the Arctic, and an increase further south. In a second study incorporating spectrally resolved changes in solar irradiance and solar-induced changes in the distribution of stratospheric ozone, *Haigh* [1999] found a similar pattern of SLP response, with a decrease over the Arctic, and an increase over the northern mid-latitudes.

Recently, *Shindell et al.* [2001a] argued that model sea surface temperatures must be allowed to adjust in order to properly simulate the tropospheric response to changed solar forcing. By comparing output from two equilibrium integrations of the GISS GCM coupled to a mixed layer ocean model with reconstructed spectrally-resolved solar forcing representative of 1680 and 1780 (Figure 9), they concluded that the main regional climate changes associated with the Maunder Minimum (a period of decreased solar irradiance in the late seventeenth century) were due to a solar-induced shift towards the negative phase of the NAO. They demonstrated that the pattern of temperature response they simulated is similar to that derived by regressing 20-yr lagged paleo-temperature measurements onto a reconstruction of solar forcing. They associated this change with solar-induced changes in tropical sea surface temperatures, and argue that this is why their earlier studies using fixed sea surface temperatures showed no such response [*Shindell et al.*, 1999b; *Shindell et al.*, 2001b].

Thus, overall we conclude that there is considerable evidence that enhanced solar forcing strengthens the winter stratospheric vortex, perhaps because of enhanced heating in the tropical stratosphere due to the associated ozone increases. There is also weaker evidence linking changes in solar irradiance to changes in the NAO, particularly on multidecadal timescales. However, reconstructions of solar irradiance [e.g., *Lean et al.*, 1995] do not show a large change over the past forty years. Thus, even if solar forcing has caused multi-decadal NAO variations in the past, it is unlikely to account for the recent upward trend in the NAO index.

4. SUMMARY

Boreal winter indices of the NAO have shown a positive trend over the last forty years [e.g., *Hurrell et al.,* this volume]. While paleoclimate reconstructions of the NAO index indicate that the recently observed upward trend is rare, but possibly not unique over the past 600 years [*Cook*, this volume], significance testing against a red noise model [*Thompson et al.*, 2000; *Gillett et al.*, 2001], or comparisons with model control variability [*Osborn et al.*, 1999; *Gillett et al.*, 2000] indicate that the trend is outside the range of internal variability. If the trend in the NAO index is not due to internal variability, what then is it due to?

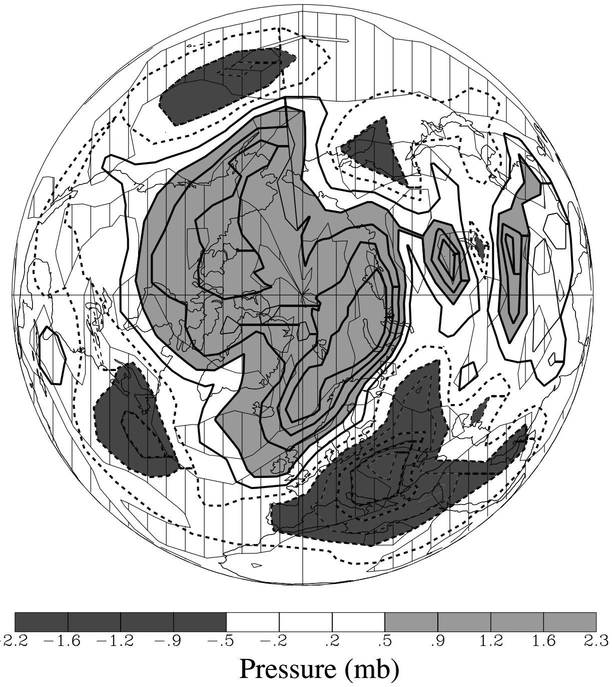

Figure 9. The difference in SLP between equilibrium simulations with spectrally-resolved solar irradiance reconstructed for 1680 and 1780 (higher SLP over the Arctic in 1680). The simulations were performed with the GISS model. Reprinted with permission from *Shindell et al.* [2001a]. Copyright 2001, American Association for the Advancement of Science.

The impacts of various anthropogenic and natural forcing agents on the NAO have been examined in the literature, in particular greenhouse gases, stratospheric ozone, tropospheric sulphate aerosol, volcanic aerosol, and solar irradiance changes. There is considerable disagreement about the relative roles of all these forcings, but most authors agree that greenhouse gases are likely to be at least partly responsible for the long-term trend in the boreal winter NAO index. The influence of prescribed increases in greenhouse gases on the NAO has been examined in all the major climate models. With some exceptions, an increase in the winter NAO index is generally found as greenhouse gas forcing is increased. Some authors argue that the change in the NAO is not limited to a simple increase in its index, but that the locations of the centers of action of the pattern move [*Ulbrich and Christoph*, 1999]. *Gillett et al.* [2002a] regress the NAO index against radiative forcing at the tropopause, and conclude that the observed sensitivity is somewhat larger than that simulated by several GCMs (HadCM3, ECHAM3, ECHAM4), although this difference is not statistically significant. The GISS stratosphere-resolving model reproduces a trend with a magnitude much closer to that observed, but another stratosphere-resolving model with higher horizontal and vertical resolution (HadSM3-L64) does not. Thus, overall, we might conclude that the observed NAO trend is somewhat larger than one might expect based on models forced with greenhouse gas increases. Thus it may be that the NAO index in the real atmosphere is more sensitive to greenhouse gas changes than in models, or it may be that the anthropogenically-induced trend in the observations has been enhanced by natural variability over the past forty years.

Note that most of the studies reviewed in this chapter consider the effects of one forcing agent only, whereas in reality multiple forcing agents have affected the atmosphere simultaneously. It is of course possible that the responses to these forcings combine nonlinearly. However, an ensemble of integrations of HadCM3 with all the main anthropogenic and natural forcings did not reproduce an NAO index trend comparable to that observed [*Stott et al.*, 2000]. Thus, at least in HadCM3, a nonlinear combination of responses does not explain the discrepancy between the simulated and observed NAO trend.

Several mechanisms have been proposed to explain the observed increase in the winter NAO index. Some authors [e.g., *Palmer*, 1999] argue that a system's response to external forcing will always resemble its leading mode of variability. This idea relies on the fact that the processes that enhance a mode of natural variability are likely also to enhance any component of a forced response which projects onto that mode. Thus, the argument suggests that the response of the Northern Hemisphere circulation to anthropogenic forcing is likely to resemble its leading mode of natural variability, the NAO. If this is the case, then it is important first to understand the mechanisms underlying the natural variability of the mode [*Czaja et al.,* this volume; *Thompson et al.*, this volume]. An alternative paradigm would suggest that the mechanisms underlying the natural variability and the forcing response are independent, and that it is a coincidence that the associated SLP patterns are similar.

Shindell et al. [1999a] argue that the upward trend in the NAO index has been forced by changes in the stratospheric circulation. Greenhouse gases warm the tropical upper troposphere and cool the polar stratosphere radiatively at the same height, leading to an enhancement of the equator-to-pole temperature gradient in the tropopause region, strengthening zonal winds in the lower stratosphere and the polar vortex. They also suggest that this effect is augmented by a planetary wave feedback. Although the exact mechanism is not clear, this enhancement of the stratospheric circulation is then presumed to lead to an increase in the strength of the tropospheric westerlies. While a strengthening of both surface and stratospheric westerlies has been observed, some model simulations of the response to increasing concentrations of greenhouse gases show an enhancement of the tropospheric westerlies, but a weakening of the Arctic stratospheric vortex [*Gillett et al.*, 2002b]. This suggests that at least in some models the stratospheric and tropospheric changes may be independent, and the processes responsible for the NAO change may have their origins outside the stratosphere.

One remaining influence to which NAO changes have been attributed is the warming of tropical SSTs. *Hoerling et al.* [2001] were able to reproduce an upward trend in the winter NAO index in a GCM by prescribing observed changes in tropical SSTs. Observed interdecadal variations were also reproduced, though the amplitude of the 12-member ensemble mean changes was only about half of that observed. They ascribe most of the NAO change to warming in the Pacific and Indian Oceans. Since SSTs are closely coupled to temperatures throughout the tropospheric column, it may be that the ocean has simply "recorded" the influence of increasing greenhouse gases, and the temperature of the tropical troposphere could have more directly forced the observed NAO changes.

Overall we conclude that there is considerable evidence that remote forcing from the tropics has played a role in inducing the upward trend in the NAO index. While the state of the stratosphere may influence the surface circulation on sub-annual timescales [*Thompson et al.*, this volume], it remains to be determined whether it has played a significant role in inducing long-term trends in surface climate. We feel that changes in the NAO have been convincingly shown not to be associated with changes in the occupation probabilities of distinct "regimes", but the importance of the physical mechanisms underlying the natural variability of the NAO in determining its response to external forcing remains to be determined. Thus considerable work remains to be done before we fully understand the physical origins of the observed upward trend in the boreal winter NAO index.

Thompson et al. [2000] ascribe 50% of January-March warming over Eurasia over the past thirty years to the trend in the NAO index, and even larger fractions of the trends in precipitation in some regions, particularly the increase in precipitation over Northwest Europe, and the decrease over Southern Europe. *Thompson and Wallace* [2001] also show that the NAO is linked to the occurrence of extremes in a range of surface climate variables around the Northern

Hemisphere, and that its upward trend has contributed to a decrease in the severity of winters over most of this region. Thus, if the NAO index continues to increase in response to enhanced greenhouse gases, it is likely to have significant implications for Northern Hemisphere winter climate. If current climate models adequately resolve the response to anthropogenic forcing of this mode of variability, then these effects will already be incorporated into projections of future climate change. However, if as some authors suggest [e.g., *Shindell et al.*, 1999a], the response of this mode to external forcing is not well-simulated by most GCMs, then predictions of regional Northern Hemisphere climate change are likely to be unreliable. Thus, if we are to make accurate predictions of regional climate change, it is important to ensure that the NAO and its response to external forcings are adequately represented in the models we use.

Acknowledgments. We thank Peter Stott (U.K. Met Office) for the provision of HadCM2 and HadCM3 data, and Dáithí Stone for his comments on the manuscript. We are also grateful for the useful comments and suggestions of four anonymous reviewers. NPG was funded in Oxford by a CASE studentship from the U.K. NERC and Met Office, and in Victoria by NSERC and CFCAS under the Canadian CLIVAR program. TJO was funded by the U.K. NERC (GR3/12107).

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