The North Atlantic Oscillation and greenhouse-gas forcing

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[1] **Abstract.** The results of 12 coupled climate models participating in the Coupled Model Intercomparison Project (CMIP2) are compared together with observational data in order to investigate: 1) How the current generation of climate models reproduce the major features of the winter North Atlantic Oscillation (NAO), and 2) How the NAO intensity and variability may change in response to increasing atmospheric CO_2 concentration. Long-term changes in the intensity and spatial position of the NAO nodes (Icelandic Low and Azores High) are investigated, and different definitions of the NAO index and the Arctic Oscillation (AO) are considered. The observed temporal trend in the NAO in recent decades lies beyond the natural variability found in the model control runs. For the majority of the models, there is a significant increase in the NAO trend in the forced runs relative to the control runs, suggesting that the NAO may intensify with further increases in greenhouse-gas concentrations.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is a major mode of atmospheric variability in the Northern Hemisphere. The NAO is a measure of the atmospheric pressure difference between the Icelandic Low (IL) and Azores High (AH) centers of action – stronger than average gives a positive index value (NAO+) and v.v. The NAO is particularly important in winter, exerting a strong control on the Northern Hemisphere extra-tropical climate, e.g., modulating the westerly jet stream and temperature from eastern North America into Eurasia [*Walker et al.,* 1932; *Wallace and Gultze*r, 1981; *Lamb et al.*, 1987; *Hurrell*, 1996]. The NAO can be considered the dominant regional feature of the broader Arctic

Oscillation (AO) [*Thompson and Wallace*, 1998] or Northern Annular Mode (NAM) [*Thompson and Wallace*, 2001] of atmospheric pressure in the Northern Hemisphere, rather than a dynamically separate phenomenon – at least in winter, when they are arguably inseparable [*Deser*, 2000; *Wallace*, 2000].

[3] The NAO has exhibited a positive trend since the 1960s and it has been speculated that this may be linked to global warming, e.g., induced by anthropogenic increases in atmospheric greenhouse gases (GHGs). However, distinguishing natural versus anthropogenic variability in the NAO based on observed sea level pressure (SLP) alone is challenging. There are also uncertainties in the theoretical response of NAO/AO to enhanced greenhouse warming and our ability to model it realistically using numerical climate models [*Delworth and Knutson,* 2000; *Shindell et al.,* 2001; *Frauenfeld and Davis,* 2003; *Gillett et al.*, 2003]. The goal of the paper is to assess how well the current generation of climate models reproduces the general features of the observed winter NAO and to quantify changes in NAO under external forcing. Achievement of this goal requires 1) an assessment of the individual models, 2) an assessment of the ensemble mean of the models, and 3) an investigation of the future climate projections. Here, to investigate the NAO change as a response to increasing GHG forcing, the results of 12 coupled atmosphere–ocean numerical models participating in the Coupled Model Intercomparison Project (CMIP2) are used together with observational data.

2. Data and Methods

[4] We employ monthly-mean SLP fields for the entire Northern Hemisphere from 12 CMIP2 models as specified in Table 1. For documentation and validation of these models

see the CMIP Web site at http://www-pcmdi.llnl.gov/cmip/. We have chosen the models with full-length runs without missing values and include only one model from each modeling center (e.g., only HADCM3, not HadCM2, from the Hadley Centre). For each model, two 80-y experiments are used: 1) a “control” simulation, representing natural variability (CMIP control runs use different constant atmospheric CO_2 concentrations, ranging from 290 to 353 ppm) and 2) a “forced” run perturbed by a 1% per year increase in atmospheric CO_2 concentration starting from the present-day climate state, where CO_2 doubles at about year 80 [*Covey*, 1998]. The CMIP2 idealized scenario with 1% per year. CO_2 increase is only used for model sensitivity tests and is not meant to be representative for present or earlier emissions. However, the radiation forcing corresponding to the CMIP2-protocol cannot be ruled out in the future. In addition, the observed variations in NAO could be caused by natural variations in the climate system. It is presently hard to uniquely state which of the two alternatives are most likely. The model data are available on a variety of grids; to facilitate intercomparison, all the model data are interpolated to a 2.5° × 2.5° regular grid.

[5] Monthly-mean gridded dataset based on observations is also used: NCEP/NCAR re-analysis data from 1948 [*Kalnay et al*., 1996, with updates]. In addition we use time series of station SLP comprising the *Jones et al*. [1997] NAO index. These are Gibraltar (36°N, 5.5°W) and a southwest Iceland time series, based mainly on Reykjavik (64.1°N, 22°W) both extending from 1823 to 2000. The locations are indicated in Figure 1A.

[6] Winter is defined here as November–April (NDJFMA). For the model integrations, SLP anomaly fields were obtained on the basis of the control run's long-term winter mean. The spatial SLP distribution was investigated by applying Principal Component Analysis

(PCA) for both the North Atlantic region (20°N-80°N, 100°W-20°E) and for the area north of 20^{o}N. The latitude–longitude position of the IL center (φ_N, λ_N) was first approximated as the location of the minimum P_{min} of the pressure field $P_{i,j}$ on the latitude-longitude grid (φ_i, λ_j) of the pressure field for latitudes poleward of 55^{0}N. Its exact position was then found as the center of gravity of the pressure field using weighted anomalies. For instance, $\varphi_N = \sum \varphi_i P_{i,j} / \sum P_{i,j}$, where summation is spread over grid nodes where $P_{i,j} < P_{min} + \Delta P$, and ΔP is estimated as 5hPa. The AH center (φ_S,λ_S) is defined in a similar way for latitudes south of 45^{0}N.

[7] Four different definitions of the NAO index are considered: 1) Absolute SLP difference between Gibraltar and Iceland (NAO_1); 2) Absolute SLP difference between the centers of the IL and AH (NAO_2); 3) Difference of SLP averaged over a northern (80°W-30°E, 55°N-80°N) and southern (80°W-30°E, 20°N-55°N) Atlantic region (NAO_3); and 4) First principal component (PC1) time series corresponding to a pressure-field PC pattern (NAO_4) for the North Atlantic region (20°N-80°N, 100°W-20°E). Absolute SLP differences were used for the calculation of NAO index, because standardization could hide errors in the model simulations. For the model data, the NAO_1 index was defined through interpolation from the model grid cells nearest to Gibraltar and Iceland. We also calculated the AO index as PC1 for the area north of 20^{o}N. For each of the four NAO definitions and the AO, temporal trends were then calculated for the observations and models. Clearly, pattern-based indexes provide more information about the main features of SLP distribution than a two-point pressure difference. The statistical significance of the difference between trends for the control and forced run was found for each model, considering maximum difference between trends standardized by the sum of their standard

deviations. Confidence level of the difference between trends was found as an error function of normalized maximum difference between trends.

3. Results

[8] It is found that the models realistically reproduce the IL and AH; e.g., broadly similar patterns in mean winter SLP in both observations and the models (Figure 1A). We find that the NAO pressure patterns are captured as realistically as the NAO-like temperature pattern that *Stephenson and Pavan* [2003] used as an NAO surrogate in their CMIP1 model study. The 12-model control-run mean SLP difference between Gibraltar and Iceland (i.e., *Jones et al*. [1997] NAO index) lies close to observations, with an ensemble-mean difference from the observations ~3hPa and the mean inter-model standard deviation~7hPa (Fig. 1B). The model ensemble-mean locations of the pressure centers are nearly identical to the observations, though with some between-model scatter (Figure 2). The observations indicate that the IL and AH comprise a unified system varying synchronously – their centers simultaneously shift position along a southwest–northeast axis, with a northeastward shift occurring during maximum SLP gradient (i.e., strong NAO^+). Most of the model runs also exhibit this tendency to shift position.

[9] Spatial and temporal differences between the control and forced runs are evident. Spatially, a northeastward shift (Figure 2) in the centers of the IL and AH is found in the forced run compared with the control run for most of the models. This shift is statistically significant at 95% confidence level for the models except CERF, CSIR, MRI and PCM. For most of the forced runs, low pressure at high latitudes spreads over a vaster area with even slight changes of SLP in the IL and AH centers of action.

[10] Temporally, the most interesting result is a difference between trends in the forced and control runs. Figure 3 shows modeled (control and forced) linear trends for the NAO indices (NAO_{1-4}) and the AO index, for each model as well as the ensemble mean of the models. The result shows that for the majority of the models and more or less independent of the index being used, there is a relative increase in the trend between the control and forced integrations [cf. *Scheneider et al*., 2003]. It is noted that the control integrations characteristically have small negative trends for each index, though these are not statistically significant at the 95% confidence level, except BMR, CCSR and PCM. This is an indication of model deficiency and possibly the limited length of the runs. Nevertheless, it should be recalled that the climate experiment in CMIP2 is essentially a “perturbation integration” and therefore the main interest is the *change* in the trend between the control and the forced experiment.

[11] The three pattern-based indices – NAO_3, NAO_4 and the AO – show more consistent model-to-model trends than NAO_1 and NAO_2 and are positive for all forced runs, except for CCSR (NAO_3 and AO), CSIR (NAO_4) and GFDL (NAO_4). Regarding statistical significance, the difference between linear trends in the control and forced runs is more meaningful than the significance of individual trends, as mentioned above. Table 1 indicates that control versus forced trend differences from 8 of the 12 models (BCM, BMR, CCC, CCSR, ECHAM, IAP, MRI and PCM) are statistically significant at $s < 0.05$ (i.e., > 95% confidence level) for at least one index. Three models (CERF, GFDL and UKMO3) have $s < 0.20$, while $s > 0.20$ for the CSIR model.

[12] Further, we calculated successive 30-yr linear trends for NAO_1 from control and perturbed runs, as well as for the NAO_1 calculated from observational data (Figure 4). The

observed NAO_1 trends in recent decades are outside the 95% confidence range of variability simulated during control runs, and this could be interpreted partly as internal variability. The observed NAO_1 index has its largest positive trends during the period 1961-1999 (>6 hPa/30yr) with a maximum (9.8 hPa/30yr) from 1966-1996, in contrast to the control experiments, where no trends were larger than 6.6 hPa/30yr. For the forced runs, maximum trends exceed the observations in three models (13 hPa/30yr (CCSR), 9.4 hPa/30yr (MRI), 8.2 hPa/30yr (GFDL)), while six models range from 4-6 hPa/30yr and three models exhibit trends of ~3 hPa/30yr. These results suggest that some response to GHG forcing could be present in the observed NAO index record, indicating a possible increase of the NAO positive phase.

4. Conclusion

[13] We find that the current generation of climate models reproduces, on average, the main SLP features of the observed winter NAO. The recent trend observed in the NAO lies beyond the natural variability found in the control runs. Furthermore, the forced runs have greater NAO intensity than the control runs, indicating that the NAO may intensify with further increases in atmospheric GHG concentrations. The underlying causes of forced variability in the North Atlantic region are unclear. There are at least two candidate mechanisms to explain the recent trend of the NAO: An extra-tropical response to changes in tropical sea-surface temperature (SST) [*Hoerling et al.*, 2001; *Lin et al*., 2002] and another involving stratospheric changes [*Baldwin and Dunkerton*, 2001]. In either case, the processes linking the NAO to GHG forcing need further elucidation.

Acknowledgments

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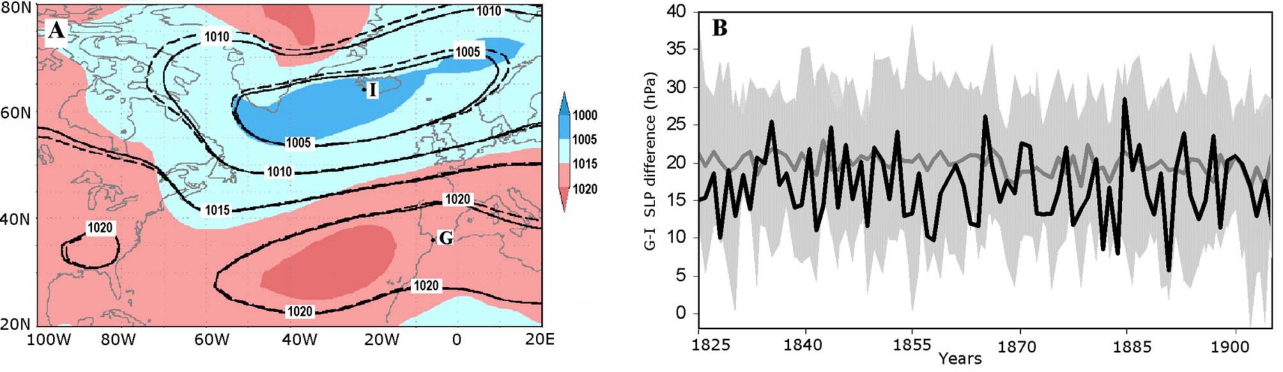
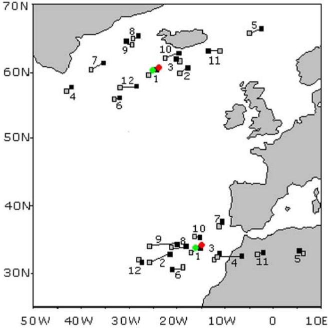
NAO						**MODEL** *						
Index	**BCM**	**BMR**	**CCC**	**CCSR**	**CERF**	**CSIR**	**ECHAM**	**GFDL**	**IAP**	**MRI**	**PCM**	**UKMO3**
NAO1	**<0.01**	0.18	0.13	**0.04**	0.38	0.25	**<0.01**	0.56	**0.03**	0.25	**<0.01**	0.43
NAO2	**0.04**	**0.01**	**<0.01**	0.73	0.16	0.29	**0.01**	0.13	0.43	**<0.01**	**0.02**	0.65
NAO2	**0.04**	**0.01**	**<0.01**	0.73	0.16	0.29	**0.01**	0.13	0.43	**<0.01**	**0.02**	0.65
NAO3	0.08	0.28	**0.01**	0.32	0.43	0.64	0.18	0.49	**0.05**	0.19	0.37	0.32
NAO4	**<0.01**	**0.05**	**<0.01**	0.15	0.58	0.92	**<0.01**	0.65	**0.02**	0.22	**<0.01**	0.17
AO	0.06	0.63	**<0.01**	0.20	0.13	0.52	**0.03**	0.23	**<0.01**	0.29	<0.36	0.24

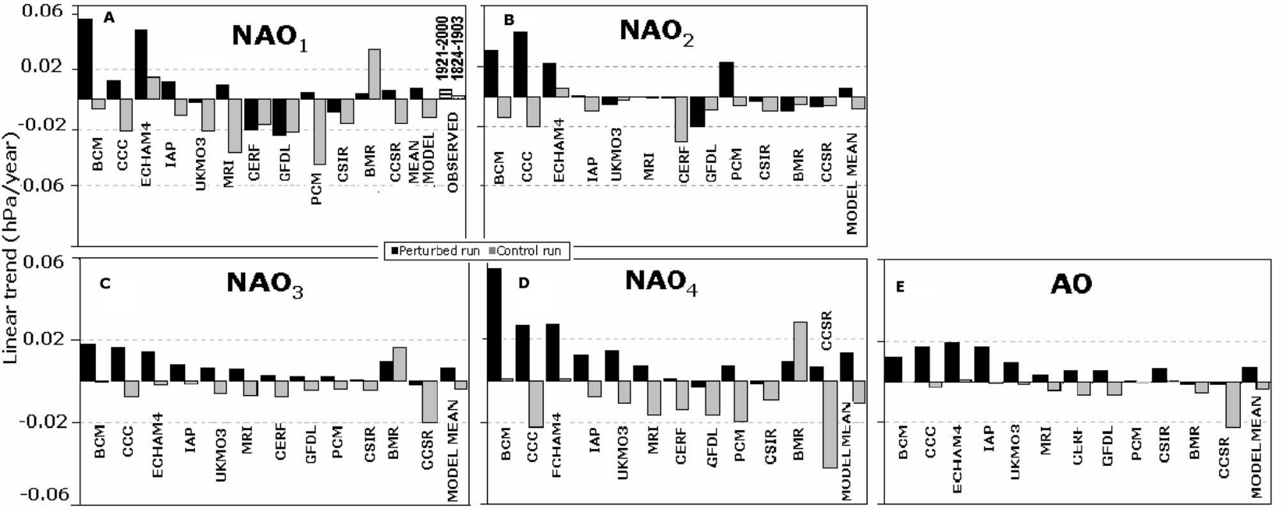
*Model Codes and Countries: BCM-Bergen Climate Model (Norway); BMR-Bureau of Meteorology Research Center (Australia); CCC-Canadian Center for Climate Modelling and Analysis (Canada); CCSR-Center for Climate System Research (Japan); CERF-Centre European de Recherch et de Formation Avanceen en Calcul Scientifique (France) ; CSIR-Commonwealth Scientific and Industrial Research Organization (Australia); ECHAM - DKRZ/MPI (Germany); GFDL-Geophysical Fluid Dynamics Laboratory (USA); IAP-LASG / Institute for Atmospheric Physics (China); MRI-Meteorological Research Institute (Japan); PCM-DOE Parallel Climate Model (USA); UKMO3-United Kingdom Met. Office HadCM3 model (UK)



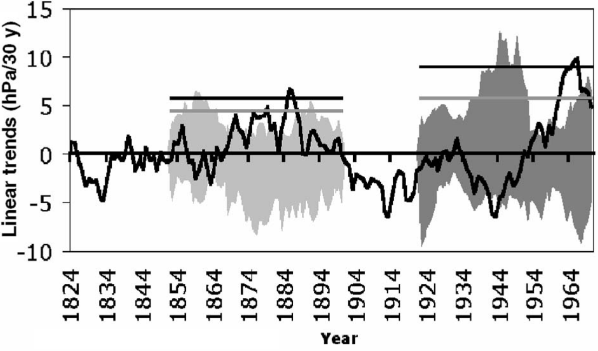
A
80N
60N
40N
20N
100W
80W
60W
40W
20W
0
20E
1010
1005
1015
1020
I
G
1000
B
G-I SLP difference (hPa)
Years
1825
1840
1855
1870
1885
1900
0
5
10
15
20
25
30
35
40



70N
60N
50N
40N
30N
50W
40W
30W
20W
10W
0
10E



Linear trend (hPa/year)
0.06
0.02
-0.02
-0.06
A
NAO1
1921-2000
1824-1903
BCM
CCC
ECHAM4
IAP
UKMO3
MRI
CERF
GFDL
PCM
CSIR
BMR
CCSR
MEAN MODEL
OBSERVED
B
NAO2
MODEL MEAN
Perturbed run
Control run
C
NAO3
D
NAO4
E
AO


15
10
5
0
-5
-10
Linear trends (hPa/30 y)
1824
1834
1844
1854
1864
1874
1884
1894
1904
1914
1924
1934
1944
1954
1964
Year