GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 12, PAGES 1755-1758, JUNE 15, 2000

Disagreement between predictions of the future behavior of the Arctic Oscillation as simulated in two different climate models: Implications for global warming

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Abstract. Two global climate models (HadCM2 and ECHAM) forced with the same greenhouse-gas scenario (IS92a) are found to disagree in their simulated long-term trends of the intensity of the Arctic Oscillation (AO), an atmospheric circulation pattern of the Northern Hemisphere. The simulated AO trends are strongly dependent on the model and on the initial conditions of the simulations. The simulated winter temperature increase averaged over the Northern hemisphere is very similar in both models. However, the effect of the different AO trends on temperature causes clear differences in the predicted regional warming, which are reduced if the effects of the AO is linearly discounted. The uncertainty in the predictions of circulation changes has impacts on the estimation of regional temperature changes.

Introduction

The Arctic Oscillation (AO) is one of the main variability patterns of the atmospheric circulation in the Northern Hemisphere in wintertime. It is an hemispheric version of the North Atlantic Oscillation (NAO) [*Lamb and Peppler,* 1987; *Kushnir and Wallace,* 1989]. These circulation structures are known to be strongly linked to climate anomalies over the Northern Hemisphere [*Hurrell,* 1995]. In the last decades, the AO has become more intense and it has been suggested that this has been the cause of part of the recently observed North Hemispheric surface warming [*Wallace et al.,* 1995; *Mann and Park,* 1996; *Hurrell,* 1996]. Recently, it has been shown that the AO can be sensitive to greenhouse-gas forcing [*Shindell et al.,* 1999; *Fyfe et al.,* 1999], but the results so far disagree on the role of the stratosphere: whereas the Goddard Space Center climate model produces an AO trend only with versions with a realistic stratosphere [*Shindell et al.,* 1999], the Canadian Climate Center climate model without stratosphere predicts, under greenhouse-gas forcing a clear positive trend [*Fyfe et al.,* 1999].

The AO trend is relevant, since it is recognized that winter regional climate variability in the extratropics is driven to a great extent by advection by the atmospheric circulation [*Hurrell,* 1996; *Thompson and Wallace,* 1998]. For instance, a stronger than normal AO brings mild oceanic air masses into the Eurasian continent, producing warmer winters. Therefore, future trends of this atmospheric circulation pattern may strongly affect regional climate change predictions.

Here, we analyze several greenhouse-gas simulations with two global climate models without stratosphere and find that both models disagree in their predicted AO trends. One of the models, the HadCM2 model of the Hadley Centre for Climate Prediction and Research, simulates AO trends that are dependent on the initial conditions of the simulation; the other model, the ECHAM model developed at the Max-Planck-Institut of Meteorology, predicts positive AO trends. It is argued that part of the disagreement in the temperature predictions at regional scales by different climate models may stem from discrepancies in the predicted intensity of large-scale atmospheric patterns.

Results

Our analysis is based on the output of control and scenario simulations by two coupled models. The scenario simulations were subject to very similar radiative forcing according to the Intergovernmental Panel on Climate Change (IPCC) [*IPCC,* 1996]: historical atmospheric concentrations of greenhouse gas from 1860 until 1989 and an annual increase of about 1 % until year 2100, similar to the IS92a scenario. One of the models is the HadCM2 climate model of the Hadley Centre for Climate Prediction and Research [*Johns et al.,* 1997]. An ensemble of four simulations with different initial conditions were analyzed. The other one is the ECHAM4 model developed at the Max-Planck-Institut of Meteorology [*Roeckner et al.,* 1998]. Since no ensemble is available for this model, another simulation with an earlier version of the ECHAM model, ECHAM3 [*Voss et al.,* 1998] has been also analyzed. The horizontal resolution of the models is quite similar: the HadCM2 model uses a regular grid, with a resolution of 2.5° (meridional) x 3.75° (zonal); the ECHAM4 is a spectral model with an equivalent spatial resolution of about 2.81°x 2.81°. Both models use 19 atmospheric levels, with the last one located at 10 mb (ECHAM)

Paper number 1999GL010979.
0094-8276/00/1999GL010979$05.00

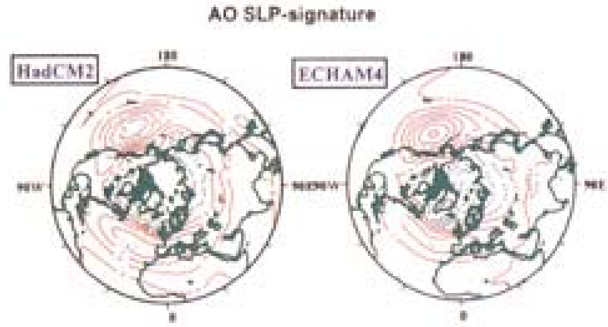

Figure 1. Leading Empirical Orthogonal Function of the winter mean (DJF) SLP in the HadCM2 and ECHAM4 control simulations. The variance explained is (28 %) in both models. The spatial correlation between both patterns is 0.72; between the modeled patterns and the equivalent pattern from observations is 0.68 (HadCM2) and 0.79 (ECHAM4). The data were filtered by a 3-year running-mean. Solid (red) and dashed (black) contours indicate positive and negative values, respectively. The contour interval is 0.5 hPascal.

and 5 mb (HadCM2). Thus, the stratosphere is only very roughly represented in these models. They agree remarkably well with each other, and with the observations, in reproducing the mean surface circulation in the boreal winter (not shown) and its most important pattern of variability (Fig. 1). The leading Empirical Orthogonal Function (EOF) of the simulated winter sea-level pressure (SLP) in the control simulations consists of three centers of action of alternating signs centered over the mid-Atlantic, the North Pole, and the North Pacific, respectively. The corresponding observed pattern is very similar [*Kutzbach,* 1970; *Hurrell and van Loon,* 1997; *Thompson and Wallace,* 1998; *Fyfe et al.,* 1999; *Shindell et al.,* 1999], the largest differences arising in the North Pacific where models simulate stronger anomalies. The spatial correlations between the simulated SLP patterns is 0.72; between the simulated and the observed are 0.68 (HadCM2) and 0.79 (ECHAM4), respectively. The simulated patterns explain about 28 % of the variability in each simulation.

The intensity of the AO (the AO index) can be calculated by projecting the simulated SLP anomalies onto the modeled AO pattern. The anomalies of near-surface air-temperature associated with the AO are given by the regression pattern between the AO index and temperature at each grid point (Fig. 2). Both regression patterns are similar to each other (spatial correlation r=0.55) and to the pattern obtained from observations in the same way (r=0.55 for HadCM2 and r=0.68 for ECHAM4), showing positive values over Northern Eurasia and Eastern North America and negative values over Greenland. This is the winter temperature signal of the AO [*Thompson and Wallace,* 1998; *Fyfe et al.,* 1999; *Shindell et al.,* 1999], and can be explained by anomalous advection of air masses. For instance, a positive AO index induces a stronger mid-Atlantic air-flow over western Europe, subtropical flow over South-eastern USA and Pacific subpolar air-flow over Western Canada, leading to warmer temperatures in both former cases and cooler in the latter region.

The agreement between models and observations shows that in the control run both models satisfactorily simulate the large-scale behavior of the low-level circulation and the air-temperature anomalies associated with them. The predicted AO index can be also calculated by projecting the SLP fields from each scenario simu-

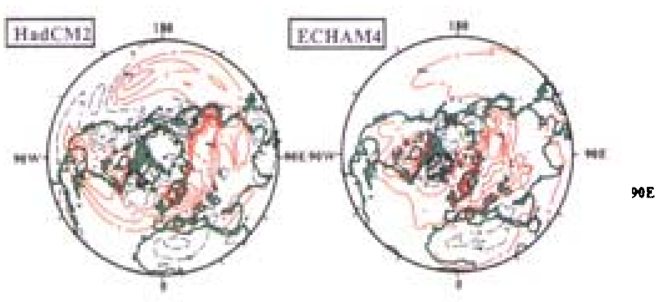

Figure 2. Regression patterns between the simulated AO indices onto the winter near-surface air-temperatures in the HadCM2 and ECHAM4 simulations. The spatial correlation between both patterns is 0.55; between the modeled patterns and the equivalent pattern from observations is 0.56 (HadCM2) and 0.68 (ECHAM4). Units are K. Solid (red) and dashed (black) contour indicate positive and negative values, respectively. The contour interval is 1 K.

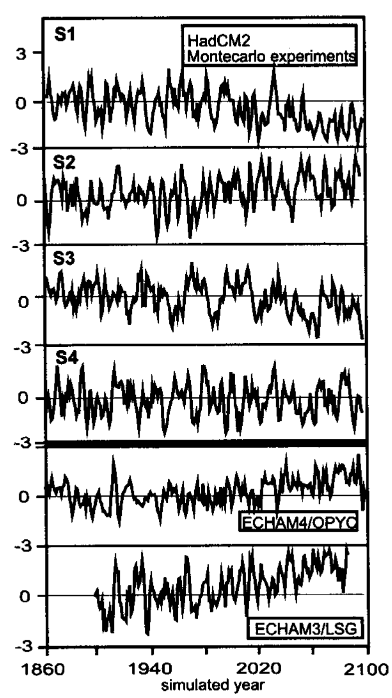

Figure 3. The AO indices simulated by an ensemble of HadCM2 runs (S1 to S4) and two versions of the ECHAM model under the same greenhouse-gas scenario: observed greenhouse-gas concentrations until 1990 and about 1 % annual increase thereafter.

lation onto the AO pattern. The resulting time series for the four HadCM2 ensemble simulations (only differing in the initial conditions) and the ECHAM4 and ECHAM3 simulations (Fig. 3) clearly reveal a disagreement: the trends predicted by the HadCM2 model may have either sign, whereas both ECHAM models predict a clear positive trend. This means that the AO in the ECHAM models seems to be sensitive to the external greenhouse forcing, whereas in the HadCM2 model the internal model variability is more important.

The origin of this discrepancy is unknown, and might be linked to hypothesized causes of low-frequency variability of the North Atlantic Oscillation: the tropical Atlantic [*Rajagopalan et al.,* 1998], mid-latitude North Atlantic sea-surface temperatures [*Rodwell et al.,* 1999] or interaction with high-frequency eddies [*Hurrell and van Loon,* 1997].

It has been also reported that the origin of the AO tendencies may lie in the model representation of the stratosphere [*Shindell et al.,* 1999]. The results presented here indicate that a detailed representation of the stratosphere is not needed to produce AO trends, as also found by Fyfe *et al.* [1999]. Furthermore, these results indicate that long-term trends in the AO may not be necessarily due to greenhouse gas forcing, but also possibly to internal model dynamics.

The different AO trends should also have an impact on the simulated regional air-temperature change. A negative AO trend like that of the S1 and S3 simulations with the HadCM2 model, should weaken the decreasing temperatures increases over Eurasia and Southeastern USA and reinforce temperatures increases over Greenland and Western Canada; positive trends, such those in the ECHAM model, should show opposite tendencies. This hypothesis would be supported if the climate change signal simulated by such diverging simulations converge when the temperature impacts of the AO trends are subtracted. This hypothesis will be tested in the S1 HadCM2 and the ECHAM4 simulations, which show the most diverging AO trends (Fig. 3). The simulated total air-temperature change between the periods 2091-2100 and 1961-1990 in both simulations show (Fig 4) discrepancies of about 5 K in Northern Siberia, Western Canada and the Labrador Peninsula and the overall spatial correlation between both climate change signals is low (r=.30). The linear effect of the simulated AO on the temperature change, denoted as ΔT_{AO}, can be estimated by:

$$\Delta T_{AO}(\vec{x}) = \Delta\alpha_{AO} P(\vec{x}), \qquad (1)$$

where $\Delta\alpha_{AO}$ is the change of the AO index (mean difference between 2091-2100 and 1961-1990 means) and P_{AO} is the AO pattern. Once the AO influence is subtracted from the absolute temperature change at each grid point the simulated temperature signals in both simulations increase in similarity (Fig. 4) (spatial correlation r=.60).

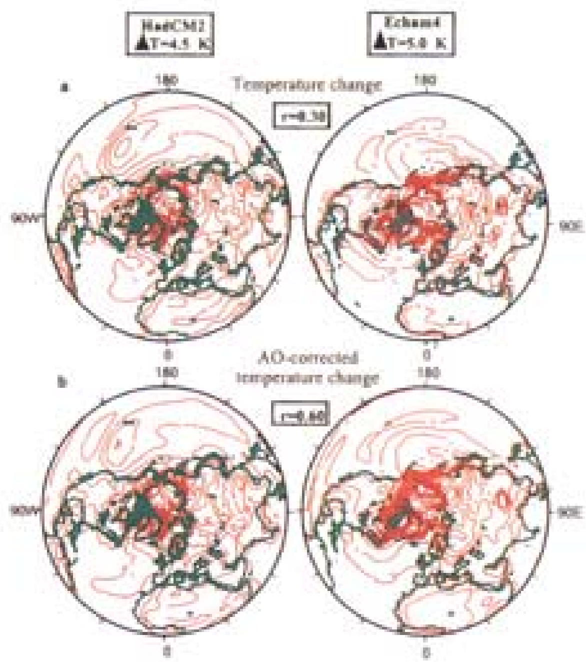

Figure 4. Changes in the winter air-temperature between the 2091-2100 and 1961-1990 means in the HadCM2-S1 and the ECHAM4 simulations, in absolute and AO-corrected values. The hemispheric-mean temperature change is indicated. r denotes the spatial correlation between the patterns. Contour interval is 1 K.

The second consequence concerns the effect of the AO on the hemispheric-mean temperature. It has been proposed that due to the large heat capacity of the ocean, the advection of cold air masses over the winter warmer oceans during the positive phase of the AO can induce hemispherically averaged net heat-transfer anomalies from the ocean to the atmosphere, and vice versa for negative index periods [*Wallace et al.,* 1995]. Accordingly, the predicted AO trends should also have an effect on the simulated hemispheric mean temperature change. This effect is not observed in the present scenario simulations, since the simulated mean temperature change is very similar in both runs ($\Delta T_{HadCM2-S1} = 4.5\ K, \Delta T_{ECHAM4} = 5.0\ K$). Also, the spatial means of the temperature regression patterns (Fig. 2) are very close to zero.

Summary

The HadCM2 and ECHAM models exhibit realistic AO patterns which may show future trends of either sign when forced by the same greenhouse-gas forcing. These different trends may have a strong impact on the predicted temperature change signal. The results of these climate simulations indicate that the predictions of the intensities of the main patterns of atmospheric circulation, even at planetary scales, are either not yet reliable or they depend strongly on internal model variability.

A second conclusion concerns the methodologies for regional climate change predictions [*Wilby and Wigley,* 1997]. These are currently performed by using statistical or regional dynamical models driven by large-scale boundary conditions simulated by global climate models. The present study indicate that the regional predictions may be strongly dependent on the global model.

Acknowledgments. We thank M. Montoya and D. Bray for their helpful comments. F. G.-R. was supported by a fellowship of Foundation Ramón Areces (Spain). The data were obtained from the IPCC Data Distribution Center.

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(Received August 3, 1999; revised March 7, 2000; accepted March 29, 2000.)