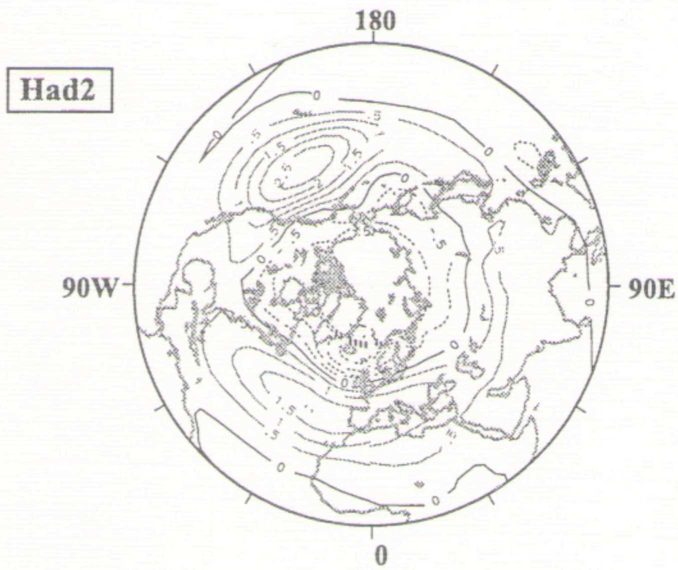
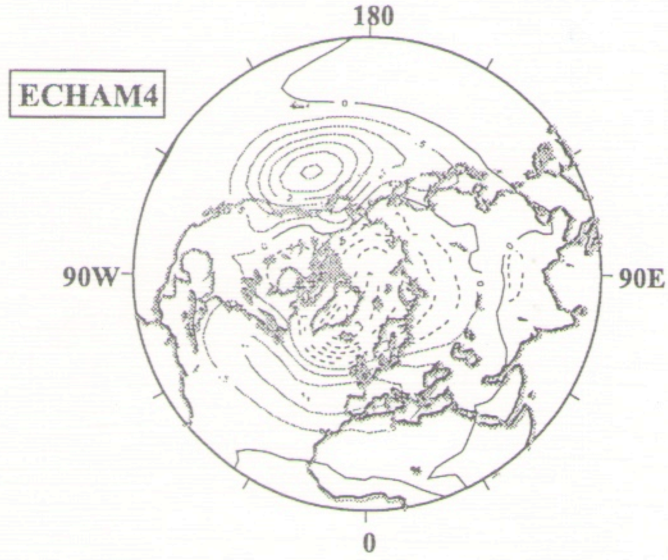
GKSS
FORSCHUNGSZENTRUM

Future trends in the North Atlantic Oscillation simulated by two climate models





Authors:

F. Gonzales-Rouco
E. Zorita

GKSS 99/E/59

GKSS 99/E/59

Future trends in the North Atlantic Oscillation simulated by two climate models

Authors:

F. Gonzales-Rouco

E. Zorita

(Institute of Hydrophysics)

GKSS-Forschungszentrum Geesthacht GmbH • Geesthacht • 1999

Corresponding author's address:

Eduardo Zorita
Institute of Hydrophysics
GKSS Research Centre
PO Box 11 60
D-21494 Geesthacht, Germany

email: zorita@gkss.de

Die externen Berichte der GKSS werden kostenlos abgegeben.
The delivery of the external GKSS reports is free of charge.

Anforderungen/Requests:

GKSS-Forschungszentrum Geesthacht GmbH
Bibliothek/Library
Postfach 11 60
D-21494 Geesthacht
Germany
Fax.: (49) 04152/871717

GKSS-Forschungszentrum Geesthacht GmbH · Telefon (04152)87-0
Max-Planck-Straße · D-21502 Geesthacht/Postfach 11 60 · D-21494 Geesthacht

ISNN 0344-9629

GKSS 99/E/59

Future trends in the North Atlantic Oscillation simulated by two climate models

F. Gonzalez-Rouco, E. Zorita

13 pages with 4 figures

Abstract

The changes in the intensity of the North Atlantic Oscillation (NAO) in two simulations with different climate models (ECHAM4-OPYC and Had2) forced by the same scenario of greenhouse gas concentrations in the atmosphere has been investigated. It has been found that the simulated long-term trends are opposite. The consequences of this discrepancy for the simulation of regional temperature changes have been estimated with a simple linear relationship between the NAO intensity and the near-surface air temperature change. If the effects of the NAO on air-temperature are substracted from the simulated temperature change, the climate change patterns simulated by both models become more similar. The consequences for proxy data-assimilation in paleoclimate simulations and the estimation of regional climate change are briefly discussed.

Zukünftige Trends der Nordatlantischen Oszillation simuliert mit zwei Klimamodellen

Zusammenfassung

Die Änderungen der Intensität der Nordatlantischen Oszillation (NAO) in zwei Klimamodell-simulationen mit unterschiedlichen Klimamodellen (ECHAM4 und Had2), die mit dem gleichen zukünftigen Treibhausgasszenario angetrieben wurden, wurde untersucht. Die modellierten langfristigen Trends in beiden Simulationen haben umgekehrte Vorzeichen. Die Auswirkungen solcher Unstimmigkeiten für die Simulation regionaler Temperaturänderungen wurden mit Hilfe eines einfachen linearen Zusammenhangs zwischen der NAO und der bodennahen Lufttemperatur abgeschätzt. Zieht man diese Auswirkung der NAO von der simulierten Temperaturänderung ab, so werden die räumlichen Strukturen der Klimaänderung in beiden Simulationen ähnlicher. Die Konsequenzen für die Assimilation paläoklimatologischer Datensätze und für die Abschätzung regionaler Klimaänderungen werden ansatzweise diskutiert.

Manuscript received / Manuskripteingang in der Redaktion: 27. Oktober 1999

1 Introduction

The reconstruction of the climates of the last several thousand years is an important contribution to estimating the natural variabity of the climate system. This estimation is central to the question of deciding if the climate change observed in the last century lies within the normal variations of the climate or hides already the signal of the influence of greenhouse gases of anthropogenic origin. In the project "Climate variations in historical times" (HGF Strategiefonds) several simulations with global climate models are being performed for that purpose.

In one of these simulations the external forcing factors estimated for the last millenia (intrinsic solar variability, changes of the earth orbital parameters, atmospheric concentrations of greenhouse gases, concentrations of stratospheric aerosols of volcanic origin, etc) are prescribed to drive a global climate model. However, due to the stochastic nature of the climate system this simulation will only provide one of the possible trajectories that the climate system may have followed, consistent with the given external forcing. It would be, however, desirable to drive the climate model close to the trajectory that the climate actually followed in its evolution from the past into the present. This goal will be pursueded in another type of simulation, in which paleoclimatic proxy data, such as tree-ring density, stable isotope ratios in corals and ice-cores, laminated lake sediments and others will be incorporated into the model.

This incorporation will be performed by using variations of standard data-assimilation techniques. In our case, the paleoclimatic proxy data (already translated when necessary to climate variables such as temperature or precipitation) will not be directly assimilated into the model, since they may be affected by large uncertainties and inconsistencies with one another. In this project another strategy will be implemented. Statistical models linking local climate variables with large-scale climate features, like hemispheric circulation patterns or large-scale temperature distributions, will be designed based on instrumental records of this century. These statistical models will be then used to infer the large-scale climate structures that were probably the forcing factors of the local paleoclimatic data. Finally, the climate model will be gently driven to follow a trajectory as close as possible to the inferred intensity of the large-scale structures.

Within this context one important question is if these large-scale structures respond in a model-independent way to the external forcing and if the data-assimilation scheme can under certain circumstances correct possible errors intrinsic to the models. In this report we describe the behaviour of one leading structure of the Northern Hemisphere atmospheric circulation, namely the North Atlantic Oscillation, in two different climate models forced with the same external forcing, in this case the same future scenario of atmospheric greenhouse gas concentrations. Since the behaviour of the NAO is different in each model, it has been found that a simple *a posteriori* correction scheme can increase the consistency of the simulations, indicating that the paleoclimate simulations will indeed benefit from data-assimilation schemes.

2 The North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is one of the main patterns of the winter atmospheric circulation in the Northern Hemisphere[1,2]. Its intensity is roughly given by the sea-level pressure difference between the quasi-permanent subtropical Atlantic High and the Icelandic Low. The NAO is known to be strongly linked to temperature and precipitation anomalies over the Northern Hemisphere[3]. In the last decades the NAO has become more intense and it has been suggested that much of the recently observed North hemispheric surface warming may have been due to this enhanced NAO[4−6]. However, the question is still open as to whether the NAO is sensitive to greenhouse-gas forcing. Here we analyze simulations with two global climate models and find that under the same future greenhouse-gas scenario the models do predict clear trends in the NAO intensity, but with opposite signs. Although the globally averaged temperature increase is very similar in both models, the effect of the opposite NAO trends on winter temperature causes clear differences in the predicted regional warming. These differences are significantly reduced if the effects of the simulated NAO on air-temperature are subtracted. Although model predictions of large-scale patterns are thought to be reliable, these results show that important defiencies still exist, which have an impact on the estimation of regional climate changes.

It is recognized that the winter regional temperature variability in the extratropics is driven to a great extent by advection induced by large-scale atmospheric circulation patterns, whereas in summertime radiation plays a more important role[6,7]. The NAO and its associated westerly winds is a clear example: in the periods when the it is more intense than normal, mild oceanic air masses are advected into the Eurasian continent, giving rise to anomalously warm winter temperatures.

One of the main goals of our project "Climate variations in historical times" (HGF-Strategiefonds) is to reconstruct the global climate of the last several thousand years. This wil be achieved in part by a large-scale stmospheric circulation patterns into the global climate simulation Since regional winter temperatures in the current climate are strongly affected by the intensity of the leading large-scale atmospheric patterns, we argue that part of the disagreement in the predictions at regional scales by various climate models also stems from discrepancies in the predicted intensity of large-scale atmospheric patterns. Therefore a better of the atmospheric dynamics may strongly contribute towards a higher agreement between global climate models.

3 The North Atlantic Oscillation in two climate change simulations

Our analysis is based on the output of the control and scenario simulations of two state-of-the-art coupled atmosphere-ocean models. The scenario simulations were subject to the same radiative forcing according to the Intergovernmental Panel on Climate Change (IPCC)[8]: historical atmospheric concentrations of greenhouse gas from 1860 until 1989 and an annual increase of about 1% until year 2100. One of the models is the Had2 climate model of the Hadley Centre for Climate Prediction and Research[9] and the other one is the ECHAM4-OPYC3 (hereafter ECHAM) developed at the Max-Planck-Institut of Metereology[10]. One important difference between the models is the way in which the dynamical equations representing the atmospheric horizontal motions are solved. The Had2 model uses a regular grid, with a resolution of 2.5° (meridional) x 3.75° (zonal), over the globe to discretize the equations, whereas the ECHAM is a spectral model using a spherical harmonic decomposition to solve the linear part of the equations (in this simulation with an equivalent spatial resolution of about 2.81°x 2.81°). The vertical resolution is very similar in the two models, and both use 19 atmospheric levels with the last one located at 10 mb (ECHAM model) and 5 mb (Had2 model). The models differ also in other aspects concerning the semi-empirical representation of the unresolved processes, but both models agree remarkably well with each other, and with the observations, in reproducing the mean surface atmospheric circulation in the boreal winter (not shown) and its most important pattern of coherent variability around this mean state. This is shown in Fig. 1 by displaying the first Empirical Orthogonal Function (EOF)[11] of the winter sea-level pressure (SLP) using the output of the control simulations (constant greenhouse gas concentration), indicating that these patterns consist in both models of three centers of action of alternating signs centered over the mid-Atlantic, the North Pole, and the North Pacific, respectively. These patterns are very similar to the observed NAO pattern[12,13]. The correlations with the leading EOF of the observed SLP are 0.68 (Had2) and 0.79 (ECHAM) and with each other it is 0.72. The part of variability described by the corresponding pattern in each data set is about 28%. Due to this similarity we will denote the patterns in Fig 1 as the simulated NAO by each model.

The intensity of the NAO is described by an associated time series (the NAO index) that can be calculated by projecting the mean SLP anomalies in each winter onto the NAO pattern. In order to estimate the association between the NAO and the near-surface air-temperature, the regression pattern between the NAO index and the air temperature at each grid point in the control simulations has been calculated (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 Had2 and r=0.68 for ECHAM), showing positive values over Northern Eurasia and Eastern North America and negative values over

Greenland. This is the well-known winter temperature signal of the NAO[3], and can be explained by anomalous advection of air masses. For instance, a positive NAO index induces a stronger mid-Atlantic air-flow over western Europe, subtropical flow over Southeastern 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 runs both models are satisfactorily simulating the coherent large-scale behavior of the low-level atmospheric circulation and

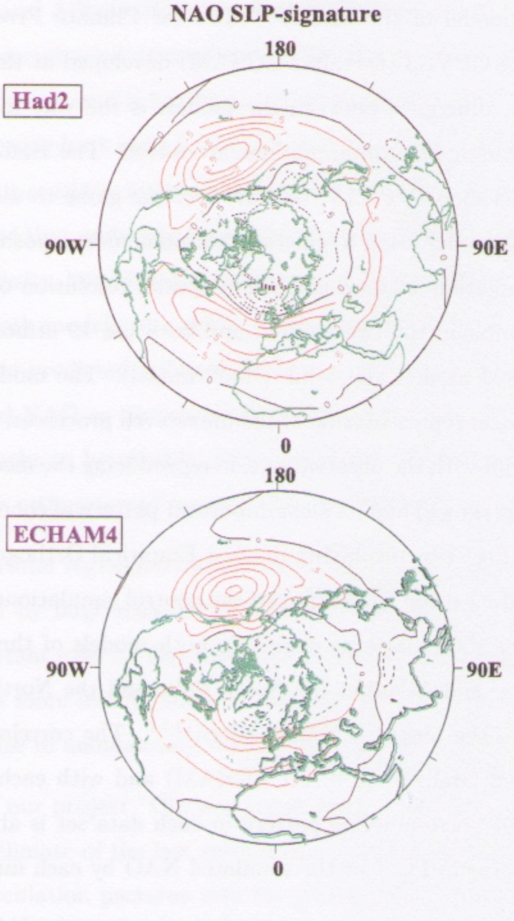


Figure 1: Leading Empirical Orthogonal Function of the winter mean (December through February) sea-level pressure in the Had2 and ECHAM4 control simulations. These patterns are the eigenvectors of the covariance matrix of each data set that explain the largest portion of variance (28 % in both models) The spatial correlation between both patterns is 0.72; between the modeled patterns and the equivalent pattern from observations is 0.68 (Had2) and 0.79 (ECHAM). The data were filtered by a 3-year running-mean to focus on the low-frequency behavior. Solid (red) and dashed (black) contours indicate positive and negative values, respectively. The contour interval is 0.5 hPascal.

the air-temperature anomalies associated with them, so that NAO trends in the scenario simulations should have implications for air-temperature regional predictions. The predicted NAO index in both models can be also calculated by projecting the scenario-simulated SLP fields onto the winter NAO pattern. The resulting time series (Fig. 3) clearly reveal that the Had2 model predicts a weakening of the NAO, whereas the ECHAM4 model predicts the opposite result.

The origin of this discrepancy is unknown, and might be linked to hypothesized causes of the NAO

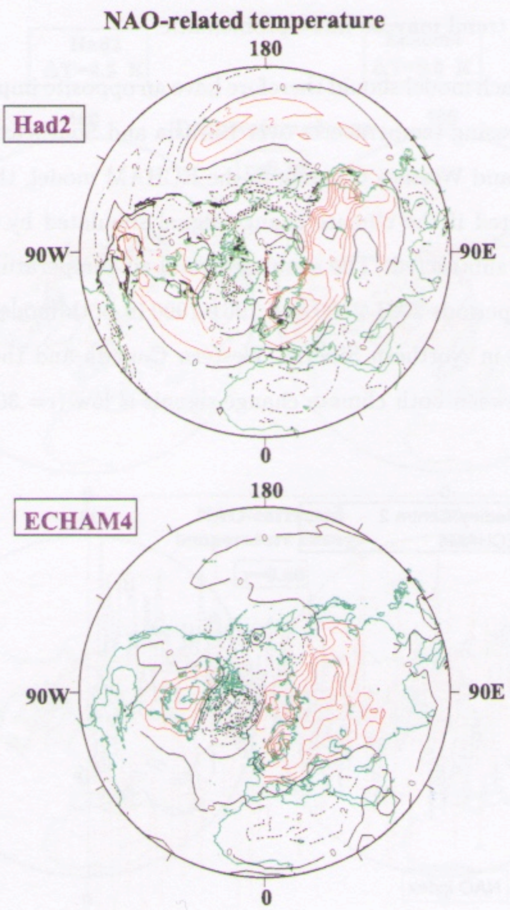


Figure 2: Regression patterns between the simulated NAO indices (intensities of the patterns in Fig. 1) onto the near-surface air-temperatures in winter simulated by the Had2 and ECHAM4 models, corresponding to an NAO index anomaly of one standard deviation. The spatial correlation between both patterns is 0.55; between the modeled patterns and the equivalent pattern from observations is 0.56 (Had2) and 0.68 (ECHAM). Units are K. Solid (red) and dashed (black) contour indicate positive and negative values, respectively. The contour interval is 1 K.

low-frequency variability: the tropical Atlantic[14], mid-latitude North Atlantic sea-surface temperatures[15] or interaction with high-frequency eddies[13]. It has been also recently reported that the origin of the NAO tendencies may lie in the model representation of the stratosphere[16], since versions of the atmospheric model GISS (Goddard Institute for Space Sciences) with a more realistic stratosphere representation (up to a height of 85 km) show a NAO trend consistent with the recent observations, whereas versions of the same model with a resolution in the stratosphere similar to the models ECHAM and Had2 do not. However, the results presented here indicate that a detailed representation of the stratosphere is not needed for the simulated NAO to be clearly sensitive to anthropogenic greenhouse-gas forcing. Thus, the prediction of the future NAO trend may be more problematic.

The diverging NAO trends in each model should therefore have an opposite impact on air-temperature change: in the Had2 model, decreasing temperatures over Eurasia and Southeastern USA and increasing temperatures over Greenland and Western Canada; in the ECHAM model, the opposite tendencies. This hypothesis would be supported if the climate change signal simulated by both models converge when the impacts of the NAO are subtracted. The simulated total air-temperature change described by the mean differences between the periods 2091-2100 and 1961-1990 in both models differ (Fig 4). Large discrepancies of about 5 K occur in Northern Siberia, Western Canada and the Labrador Peninsula. The overall spatial correlation between both climate change signals is low (r=.30).

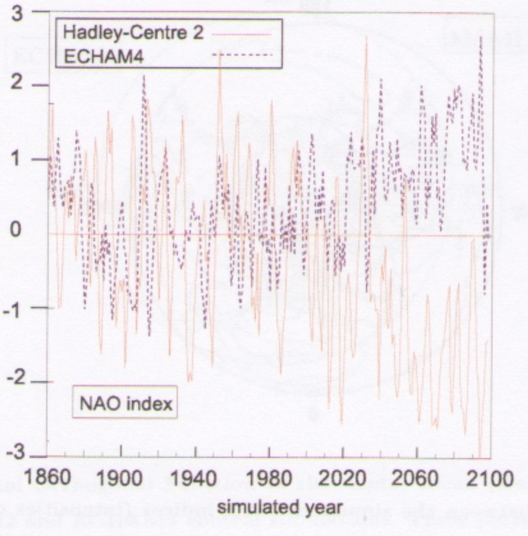


Figure 3: The NAO indices simulated by the Had2 and ECHAM4 models under the same greenhouse-gas scenario: observed greenhouse-gas concentrations until 1990 and about 1% annual increase thereafter. These indices have been obtained by projecting the winter sea-level pressure anomalies onto the NAO patterns in Fig. 1 and indicate the intensity of those patterns in the simulations.

The linear effect of the simulated NAO on the temperature change, denoted as ΔT_{NAO}, can be estimated by:

$$\Delta T_{NAO}(\vec{x}) = \Delta\alpha_{NAO} P(\vec{x}), \quad (1)$$

where $\Delta\alpha_{NAO}$ is the change of the NAO index (mean difference between 2091-2100 and 1961-1990 means) and P_{NAO} is the NAO pattern. Once the NAO influence is subtracted from the absolute

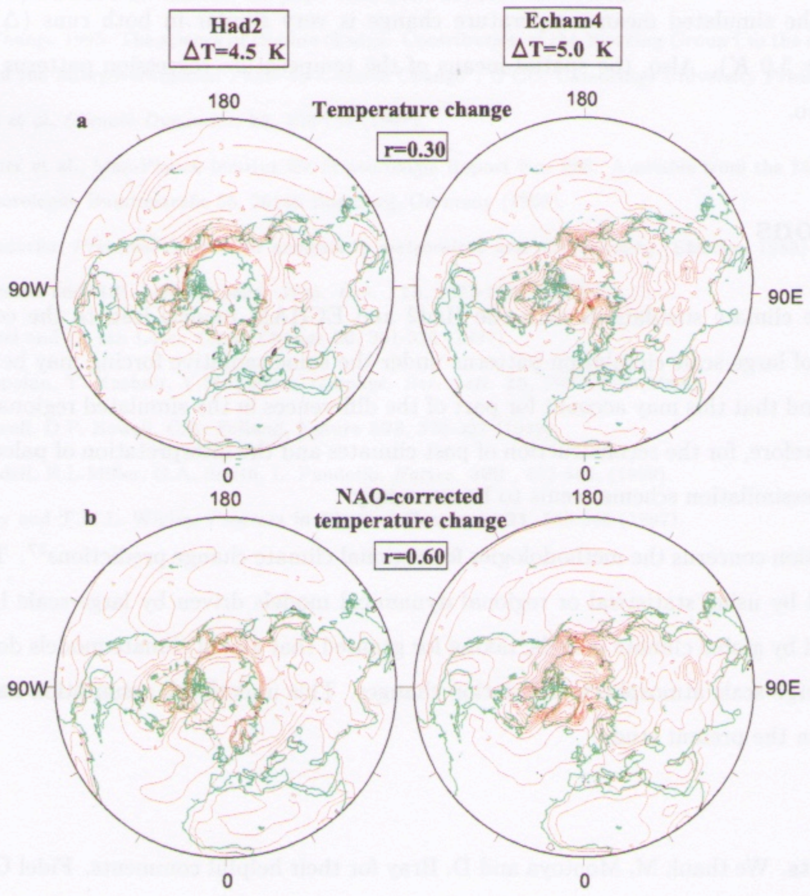


Figure 4: Changes in the near-surface winter air-temperature between the 2091-2100 and 1961-1990 means simulated by the Had2 and the ECHAM4 models. The hemispheric-mean temperature change is indicated in the squares. Upper panel, absolute temperature changes; lower panel, temperature changes after the effects of changes in the NAO circulation have been linearly subtracted out. The effects of the long-term changes of the NAO on temperature have been estimated by multiplying the temperature regression patterns of Fig. 2 by the changes of the NAO index between the periods 2091-2100 and 1961-1990. r denotes the spatial correlation between the patterns. Units are K. Contour interval is 1 K.

temperature change at each grid point the simulated temperature signals in both models increase in similarity (Fig. 4) (spatial correlation r=.60).

The second question raised concerns the effect of the NAO 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 NAO can induce hemispherically averaged net heat transfers to the atmosphere, and vice versa for negative index periods[4]. According to this hypothesis, in the climate change context, the predicted NAO 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 ($\Delta T_{Had2} = 4.5\ K, \Delta T_{ECHAM} = 5.0\ K$). Also, the spatial means of the temperature regression patterns (Fig. 2) are very close to zero.

4 Conclusions

The results of these climate simulations with the Had2 and ECHAM models lead to the conclusion that the behaviour of large-scale circulation patterns under the same radiative forcing may be strongly model-dependent, and that this may account for part of the differences in the simulated regional climate change signals. Therefore, for the reconstruction of past climates and the interpretation of paleoclimatic proxy data, a data-assimilation scheme seems to be neccesary.

A second conclusion concerns the methodologies for regional climate change predictions[17]. These are currently performed by using statistical or regional dynamical models driven by large-scale boundary conditions simulated by global climate models, taking for granted that global climate models do, indeed, properly simulate large-scale atmospheric circulation changes. This underlying assumption has proved to be unsupported in the present study.

Acknowledgements. We thank M. Montoya and D. Bray for their helpful comments. Fidel González-Rouco was supported by a fellowship of Foundation Ramón Areces (Spain). The climate model output was obtained from the IPCC Data Distribution Center.

REFERENCES

1. P. Lamb and R. Peppler,*Bull. Amer. Meteor. Soc.* **68**, 1218-1225.
2. Y. Kushnir and J.M. Wallace, *Journal of Atmos. Sci* **46**, 3122-3142 (1989).
3. J.W. Hurrel, *Science* **269**, 676-679 (1995).
4. J.M. Wallace, Y. Zhang, J.A. Renwick, *Science* **270**, 780-783 (1995).
5. M.E. Mann and J. Park,*J. of Climate* **9**, 2137-2162 (1996).
6. J.W. Hurrel,*Geophys. Res. Lett.* **23**, 665-668 (1996).
7. D.W.J.Thompson and J.M. Wallace, *Geophys. Res. Lett.* **25**, 1297-1300 (1998).
8. "Climate Change 1995- The science of climate change: Contribution of the Working Group I to the second Assessment Report of the Intergovernmental Panel on Climate Change", IPCC, Cambridge University Press (1996).
9. T.C. Johns et al, *Climate Dynamics*, **13**, 103-134 (1997).
10. E. Roeckner et al., Max-Planck-Institut für Meteorologie Report No. 266. Available from the Max-Planck-Institut für Meteorologie, Bundesstraße 55, 20146 Hamburg, Germany (1998).
11. R. Preisendorfer, *Principal component analysis in meteorology and oceanography* (Elsevier, 1988) 418 pp.
12. A.G. Barnston and R.E. Livezey, *Mon. Wea. Rev.* **115**, 1083-1126 (1987).
13. J.W. Hurrel and H. van Loon, *Clim. Change* **36**, 301-326 (1997).
14. B. Rajagopalan, Y. Kushnir, Y.M. Tourre, *Geophys. Res. Lett.* **25**, 3967-3970 (1998).
15. M.J. Rodwell, D.P. Rowell, C.K. Folland, Nature **398**, 320-323 (1999).
16. D.T. Shindell, R.L.Miller, G.A. Smith, L. Pandolfo, *Nature*, **399** , 452-455, (1999).
17. R.L. Wilby and T.M.L. Wigley, *Progress in Physical Geography* **21**, 530-548 (1997).