Simulation of Late-Twenty-First-Century Changes in Wintertime Atmospheric Circulation over Europe Due to Anthropogenic Causes

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ABSTRACT

Evidence is presented, based on an ensemble of climate change scenarios performed with a global general circulation model of the atmosphere with high horizontal resolution over Europe, to suggest that the end-of-century anthropogenic climate change over the North Atlantic–European region strongly projects onto the positive phase of the North Atlantic Oscillation during wintertime. It is reflected in a doubling of the residence frequency of the climate system in the associated circulation regime, in agreement with the nonlinear climate perspective. The strong increase in the amplitude of the response, compared to coarse-resolution coupled model studies, suggests that improved model representation of regional climate is needed to achieve more reliable projections of anthropogenic climate change on European climate.

1. Introduction

The nature of future climate change due to increasing anthropogenic emissions of greenhouse gas (GHG) concentrations is still a topic of considerable debate. Analyses of both the observed record and transient integrations with climate models forced by scenarios of increasing GHG concentrations have suggested that anthropogenic climate change may manifest itself as a projection onto the dominant modes of natural variability (Hsu and Zwiers 2001; Stone et al. 2001). Support for this paradigm arises from evidence of recent observed trends in the North Atlantic Oscillation (NAO) (Hurrell and van Loon 1997; Thompson et al. 2000) as well as its linear response in several anthropogenically forced transient integrations (Gillett et al. 2002a). A nonlinear perspective of the projection has also been proposed, in which the climate system response to greenhouse forcing would be reflected in a shift of the residence frequency of the system in certain quasi-stationary regimes (Palmer 1999; Corti et al. 1999).

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2. Methodology: Modeling approach and data analysis

The global atmospheric general circulation model (AGCM) used in this study is the variable resolution new version of the Météo-France Action de Recherche Petite Echelle Grande Echelle (ARPEGE) climate model (Gibelin and Déqué 2003). It has a T106 spectral truncation and 31 vertical levels. The variable resolution allows one to increase the spectral and gridpoint resolution in a region of interest. The center of the high-resolution region is called the stretching pole and is located at the center of the Mediterranean basin. The highest horizontal resolution is about 0.5° and stays fairly high over the North Atlantic–European (NAE) sector due to a weak resolution gradient. The high-resolution AGCM is used to obtain an improved regional level simulation over specific periods of interest or time slices from fully coupled coarse-resolution climate models. A first ensemble (hereafter CC) of three time-slice exper-

TABLE 1. Overview of the considered time-slice experiments with respective information on period, anthropogenic and SST forcings, as well as ensemble size. The anthropogenic forcing includes forcing by greenhouse gases (CO_2, CH_4, N_2O, CFC-11, and -12) as well as sulfate aerosols with both direct and indirect effects taken into account in the radiative code.

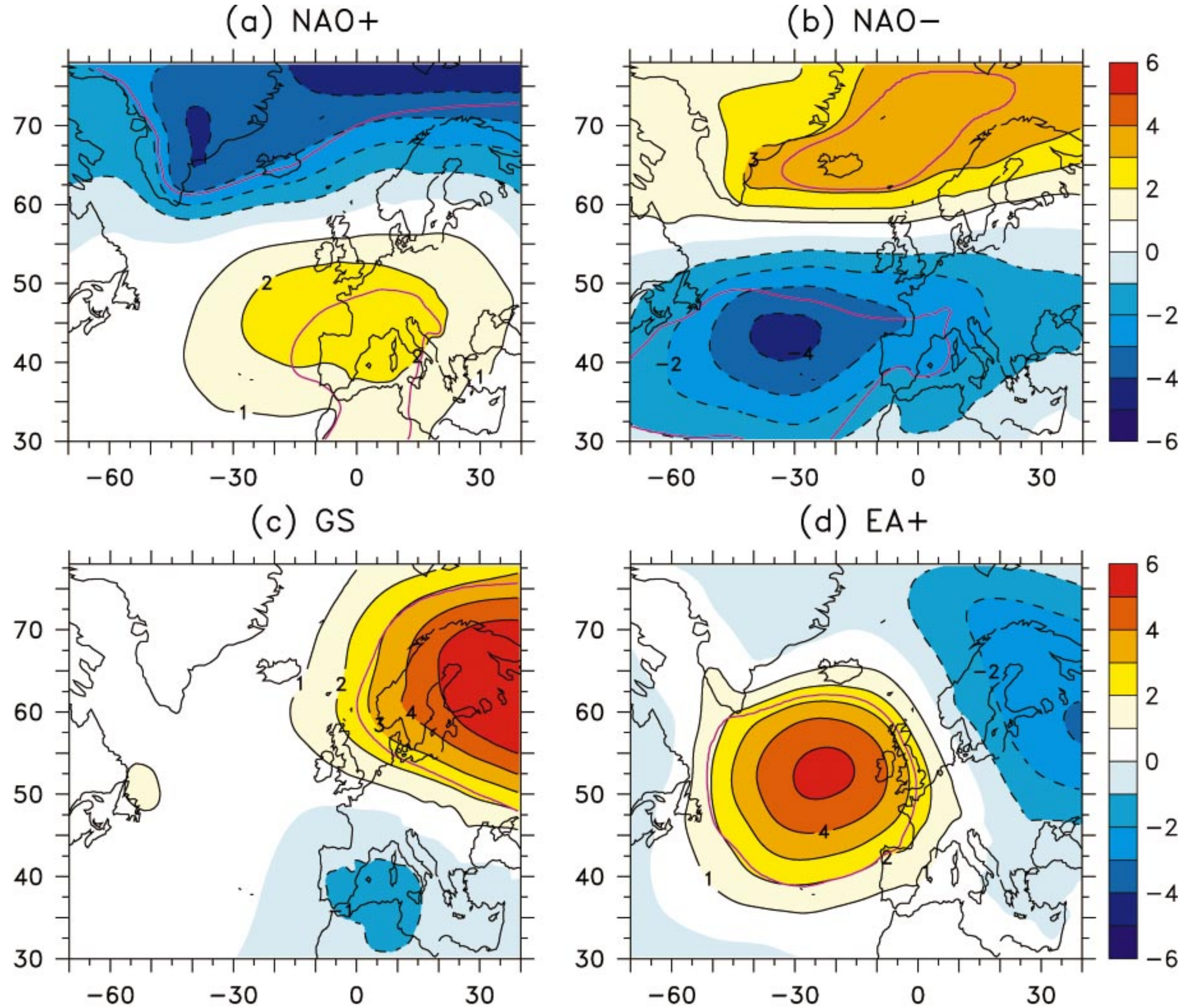
	Time slice	Anthropogenic forcing	SST forcing	Ensemble size
CC	1960–99	Observed	Observed	3
CS (A2, HC)	2070–99	SRES A2	HadCM3	3
CS (B2, MF)	2070–99	SRES B2	ARPEGE–OPA	3
CS (A2, MF)	2070–99	SRES A2	ARPEGE–OPA	1
CS (B2, HC)	2070–99	SRES B2	HadCM3	1

iments has been performed for the current climate (1960–99) where the model is forced by monthly mean observed sea surface temperature (SST) (Smith et al. 1996) and historical GHG and sulfate aerosol concentrations. A second ensemble (hereafter CS) of eight time-slice climate change (2070–99) experiments has been performed using various matching combinations of SST forcing and Intergovernmental Panel on Climate Change (IPCC) A2 and B2 Special Report on Emissions Scenarios (SRES) scenarios of future GHG and sulphur emissions (see Table 1). The SST boundary forcings are combinations of observed SSTs and mean SST changes in response to the radiative forcing such that the observed 1960–89 SST interannual variability is maintained for the 2070–99 period (Gibelin and Déqué 2003). The mean SST changes are derived from transient simulations with the ARPEGE–Ocean Parallélisé (OPA; Royer et al. 2002), and the Third Hadley Centre Coupled Ocean–Atmosphere General Circulation Model (Had CM3; Jones et al. 2003) coupled general circulation models (CGCMs), which have been both forced by the A2 and B2 SRES scenarios.

Clustering analysis based on the *k*-means partitioning algorithm (Michelangeli et al. 1995) has been used to describe possible changes in the NAE winter atmospheric circulation due to anthropogenic influence. The algorithm seeks preferred or recurrent atmospheric patterns (clusters or climate regimes hereafter) in the atmospheric state space. Given a prescribed number of clusters *k*, the algorithm iteratively finds the partition that minimizes the ratio of the variance within clusters to the variance between cluster centroids. Standard reproducibility and classifiability tests are then used to objectively define *k* and to assess the robustness and the consistency of the partition (Michelangeli et al. 1995). The algorithm is applied to mean sea level pressure (MSLP) anomalous monthly means using data from the concatenation of all time-slice experiments (for both current and future climate). Note that the reference climatology used to derive all the anomalous MSLP data is the CC ensemble mean. The partition is performed for the extended winter period (November through March) over the NAE sector defined as 20°–80°N, 90°W–50°E. The analysis is carried out in a reduced phase space spanned by the first 10 empirical orthogonal functions (EOFs), which explain 90% of the total variance.

3. Results

Five winter climate regimes have been found to provide the optimal partition for the simulated MSLP over the NAE sector (Figs. 1a–e). The first two (NAO^+ and NAO^-) capture the two phases of the NAO characterized by out-of-phase pressure variations between the Icelandic low and the Azores high. Here EA^+ (EA^-) displays a strong anticyclonic ridge (trough) off the Irish coast and is reminiscent of the positive (negative) phase of the ''East'' Atlantic mode (Barnston and Livezey 1987). The GS exhibits a large positive anomaly over Scandinavia, indicative of regional blocking over northern Europe. Similar spatial patterns are obtained by separately applying the clustering analysis to the CC and CS climate simulation ensembles. This indicates that the location and structure of the simulated regimes remain unaffected by anthropogenic forcing in agreement with the stability of the climate attractor. Four of the simulated climate regimes (NAO^+, NAO^-, EA^+, and GS) have observational counterparts, with very similar spatial structures (Cassou et al. 2004). The model realistically reproduces the spatial asymmetries of the observed NAO regimes including the northeastward extension of the MSLP anomalies during positive NAO regime months. This nonlinear approach suggests that the NAO is best viewed as the result of differencing between two spatially asymmetric regimes rather than behaving like a linear mode (Hurrell et al. 2003). The fifth one (EA^-) may be due to the overestimated El Niño–Southern Oscillation (ENSO) teleconnection over Europe, a bias shared by most AGCMs. The time history of the five climate regimes is used to calculate the averaged occurrence of the various regimes for each simulation. Figure 2a shows the changes in the residence frequency of the various regimes between the different ensembles. A major conclusion is that, irrespective of the emission scenario or the SST forcing, the simulated climate change mainly reflects in a shift of the residence frequency of the winter climate regimes associated with the NAO, in agreement with the nonlinear perspective. The end-of-century winter NAE atmospheric circulation is characterized by a doubling (halving) of the occurrence of the NAO^+ (NAO^-) climate regime, while the others experience much smaller and insignificant changes. The strongest change (19% increase for NAO^+) is obtained for the ensemble forced by the A2 scenario



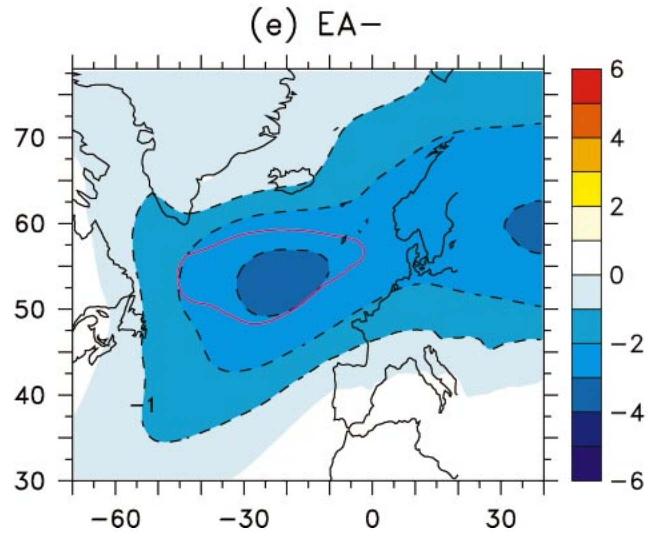


FIG. 1. (a)–(e) Contours of the MSLP composites associated with the five simulated wintertime NAE atmospheric circulation regimes. The selection criterion requires that a given regime is dominant in at least three out of the five winter months for the corresponding year to be included in the appropriate composite. The areas within the purple contours indicate the 99% confidence level of significant MSLP anomalies (hPa) using an alternative procedure (rather than the usual and inappropriate *t* test) for significance testing in composite analysis (Terray et al. 2003).

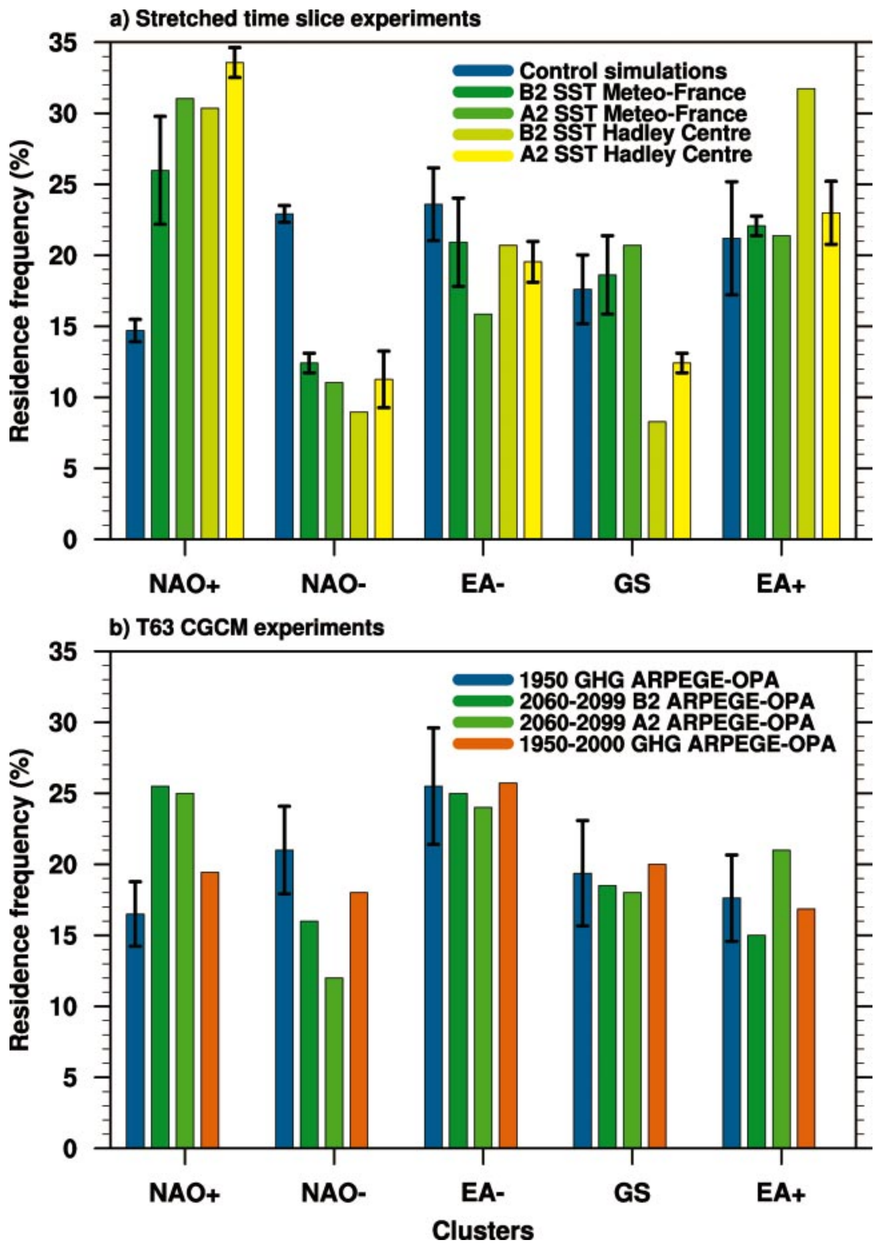


FIG. 2. (a) Changes in regime residence frequency (in %) between the present climate and the four time-slice scenarios of the late twenty-first century as simulated by the variable resolution ARPEGE AGCM. (b) Changes in regime residence frequency (in %) between the control integration (GHG fixed at their 1950 values) and the present and future climate (given by the 1950–2000 and 2060–99 periods of the two transient scenarios, respectively) as simulated by the ARPEGE–OPA CGCM. The black arrows indicate the range of uncertainty due to internal atmospheric variability as given by one standard deviation of the within-ensemble variability (Farrara et al. 2000).

combined with SST forcing from HadCM3, while the weakest one (11% increase for NAO^+) corresponds to the ensemble forced by the B2 scenario and ARPEGE–OPA SST forcing. The remaining two experiments [CS(A2,MF) and CS(B2,HC)] reveal intermediate sensitivity (15 and 16%). This suggests that the sensitivity of the shift in residence frequency of the NAO^+ climate regime to the emission scenarios and SST forcing is weak albeit not negligible. Note that there is no such sensitivity for the NAO^- regime. The same analysis was also applied to MSLP extended winter data from the coarse resolution ARPEGE–OPA control and transient simulations forced by the SRES A2 and B2 scenarios. The ARPEGE–OPA control integration is 150 years long with GHG and sulfate aerosol concentrations fixed at their 1950 values. The two transient integrations cover the 1950–2099 period with observed GHG and sulfate aerosol concentrations for the first 50 years, followed by the SRES scenarios. The cluster analysis is performed using data from the concatenation of the whole (150 years) control integration with the current climate 50-yr period (1950–2000) and the last 40 years (2060–99) of each transient simulation. The monthly MSLP anomalies are calculated for all simulations using the overall mean of the control integration. The number and the spatial structure of the CGCM regimes are found to be very similar to the previous ones (not shown). The changes between the future and current climate show a marginally significant and much weaker response, an increase (decrease) of the residence frequency of the NAO^+ (NAO^-) climate regime by 5%–6%, compared to the high-resolution scenarios (Fig. 2b). Furthermore, the sign of the changes in NAO regimes occurrence between the CGCM control integration and the CGCM current climate (as given by the 1950–2000 time slice from the two transient integrations) suggests a possible influence of increasing observed GHG concentrations during the 1950–2000 period. Note, however, that the small increase (decrease) in NAO^+ (NAO^-) residence frequency is barely significant. These results are coherent with a recent detection study of human influence on MSLP using a multimodel approach (Gillett et al. 2003), which has suggested that current coarse-resolution CGCMs significantly underestimate the amplitude of sea level pressure response to anthropogenic forcing.

4. Summary

In agreement with previous studies (Paeth et al. 1999; Ulbrich and Christoph 1999), we thus suggest that anthropogenic forcing may induce climate change over the NAE sector for the winter period through changes in occurrence of the NAO regimes, in addition to direct radiative forcing. The full understanding of the dynamical mechanism leading to the preferential excitation of the NAO^+ regime requires further study. Our results indicate also that, in addition to the open questions of stratosphere influence (Shindell et al. 1999; Gillett et al. 2002b) and the ocean's role in forcing NAO-type atmospheric fluctuations (Rodwell et al. 1999; Hoerling et al. 2001), high horizontal resolution may be essential to adequately simulate the response (in terms of both spatial pattern and amplitude) of the wintertime NAE atmospheric circulation to greenhouse gas and sulfate aerosol increase. This inference, of course, may be model dependent, and similar ensembles of simulations with additional GCMs should help to confirm or invalidate it.

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