Relative Importance of Northern Hemisphere Circulation Modes in Predicting Regional Climate Change

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ABSTRACT

The Northern Hemisphere annular mode (NAM), North Atlantic Oscillation (NAO), and Aleutian low (AL) are known to be the most prominent components of Northern Hemisphere (NH) near-surface climate variability. In a tremendous number of studies, the impact of these circulation features on regional climate has been demonstrated. More recently, research has gone into the connection between the NAO and NAM and into the physical meaning of the latter. However, the relevance of those circulation modes for climatological issues may also be inferred from another nondynamical point of view: their statistical relationship to various climate parameters. This study comprises two steps: 1) qualifying and quantifying the relative importance of NH circulation modes with respect to twentieth-century near-surface temperature and precipitation, using stepwise multiple regression with cross validation; and 2) using predictor–predictand relationships to access the contributions of each circulation mode to regional climate change in the middle of the twenty-first century, given multimodel predictions of the circulation modes' responses to increasing greenhouse gas (GHG) and sulfate aerosol (SUL) concentrations.

Altogether, the NAM, NAO, and AL account locally for up to 75% of the total interannual temperature and rainfall variability over NH continents. Over the major part of the NH, the NAM appears to be the most important predictor. In some parts of the North Atlantic, temperature and rainfall are more closely linked to the NAO, while the North Pacific is clearly dominated by the AL dynamics. In general, the NAO and AL have a more regionally confined influence.

Climate change experiments mostly predict an intensification of the NAM and AL under GHG+SUL forcing, while the NAO response is much less consistent with different models and generally undergoes no long-term changes. This leads to substantial contributions to temperature and rainfall anomalies, especially over the NH landmasses. Temperature changes amount to ± 1 K over large parts of Russia, North America, and the North Pacific. The major precipitation changes occur over the North Pacific, the North Atlantic, and Scandinavia. This circulation-induced contribution accounts for a considerable part of total expected change in these regions. Given its distinct trend, the NAM plays the main role, except over the Pacific Ocean and North America, where the AL is driving regional climate anomalies. Thus, whether physically relevant or not, the NAM is an appropriate statistical indicator of NH regional climate change.

1. Introduction

Regional climate over the NH is largely governed by cyclonic activity over the North Atlantic and North Pacific Ocean basins, as described by the North Atlantic Oscillation (NAO) and Aleutian low (AL) time series, respectively (Glowienka-Hense 1990; Hurrell and van Loon 1997; Kapala et al. 1998; Sheng 2002). More recently, the Northern Hemisphere annular mode (NAM) has been supposed to be the leading mode of NH atmospheric variability (Thompson and Wallace 2000). It is defined as the first empirical orthogonal function (EOF) of NH monthly mean extratropical mean sea level pressure (MSLP) and describes a tripole of anticorrelated anomalies between the polar region and both northern midlatitude oceans. Thompson and Wallace (2001) have shown that regional climate is closely tied to the NAM dynamics. However, the statistical definition of the NAM has led to speculations about its physical–dynamical meaning (Ambaum et al. 2001; Wallace and Thompson 2002). Here, we provide further evidence that the NAM index time series is a valuable parameter for climatological issues, but from a statistical rather than a dynamical point of view. Given the distinct impact of circulation phenomena on climate, index time series of the NAM, NAO, and AL may also be consid-

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ered as indicators of regional climate dynamics. Particularly, long-term changes in the circulation modes are supposed to contribute considerably to the expected climate change at a regional to even global scale (Hurrell and van Loon 1997; Corti et al. 1999; Gillett et al. 2000; Thompson et al. 2000; Graham and Diaz 2001; Goodess and Jones 2002; Kwok and Comiso 2002).

Indeed, observed NAM and NAO time series, being partially coherent at certain time scales, reveal remarkable trends since the 1970s (Hurrell 1995; Thompson et al. 2000). Graham and Diaz (2001) report that the AL is also intensifying throughout the second half of the twentieth century. These dynamics are associated with a change in storm track intensity and orientation as well as advection processes of moisture and sensible heat over the NH continents. Thus, it is assumed that patterns of temperature (TEM) and rainfall anomalies are closely related to circulation change. Climate model experiments still do not completely agree in simulating the circulation response to anthropogenic greenhouse gas (GHG) and sulfate aerosol (SUL) emissions; some models are highly sensitive to the greenhouse forcing (Fyfe et al. 1999; Paeth et al. 1999; Ulbrich and Christoph 1999). Shindell et al. (1999) have suggested a dependence of the NAM signal on the inclusion of stratospheric ozone dynamics. Other models do not show up with substantial climate change signals in NH circulation (Gillett et al. 2000). In another study, we have carried out a more detailed and broader model intercomparison study in terms of extratropical modes of variability (Rauthe et al. 2003). It turned out that there are some weak but statistically significant multimodel long-term changes, especially in the NAM, its Southern Hemisphere counterpart the Southern Annular Mode (SAM), and the AL, that stand out from internal variability and intermodel variations. On the other hand, the Intergovernmental Panel on Climate Change (IPCC) report gives an estimation of total expected climate change with respect to near-surface TEM and precipitation (PRE) into the twenty-first century (Houghton et al. 2001). Thus, the basic question is to what extent do the individual circulation modes contribute to the overall amplitude of climate change, including the issue of which phenomenon is the most relevant indicator of past and future climate dynamics over different regions of the earth's surface.

This paper incorporates two steps: 1) Stepwise multiple regression with cross validation is applied to time series of the NAM, NAO, and AL as predictors and TEM and PRE, respectively, as predictand during the National Centers for Environmental Prediction (NCEP) observational period in order to access the relative importance of the NAM, NAO, and AL in present-day climate at each grid point over the globe. This method is appropriate to gain insight into the ranking of the predictors and to cut off the multiple predictor approach when the additional predictor does not provide further physical rather than statistical information. 2) The GHG-induced climate change signals in NH circulation are inferred from a multimodel ensemble of various climate models provided by the international modeling community. Given the ''optimal'' regression equation and the predictions of future circulation anomalies, the spatial structure of mid-twenty-first-century circulation-induced TEM and PRE changes is determined, quantitatively attributed to the individual modes, and compared with the overall changes.

2. Data and methods

The multiple regression approach, elucidating the relative impacts of the NAM, NAO, and AL on present-day TEM and PRE, is based on the NCEP–NCAR reanalysis product, covering the period 1948–2001 and the whole globe in a 2.5° resolution (Kalnay et al. 1996). As the peak amplitude of the circulation modes usually occurs in boreal winter, December–January–February (DJF) means are studied. TEM is taken from a 2-m height, precipitation enters as DJF sums, and MSLP is used to determine the index time series of the circulation modes.

The sensitivity of the circulation modes to anthropogenic climate change is inferred from a number of coupled ocean–atmosphere climate models, partly from several versions. We consider most state-of-the-art models that provide ensembles of experiments under GHG+SUL forcing. This scenario (IS92a; Houghton et al. 2001) has been chosen because it is probably more realistic and is certainly a more conservative measure of global warming given that the SUL counteracts the enhanced greenhouse effect. The seven models considered here are the Coupled General Circulation Model (CGCM1/2), the second Hadley Centre Coupled Ocean-Atmosphere General Circulation Model (HadCM2/3), ECHAM4, ARPEGE/OPA, the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES) model, the Geophysical Fluid Dynamics Laboratory (GFDL) model, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) model. A detailed description of these models can be found in Houghton et al. (2001, and references cited therein). The multimodel ensemble mean refers to 24 individual runs under more or less identical forcing. The main overlapping period is 1900–2090, with the ECHAM4 runs stopping in the middle of the twenty-first century and CSIRO runs as well as ARPEGE/OPA runs starting in the middle of the twentieth century (Rauthe et al. 2003). Thus, the number of model runs, entering the calcuation of the multimodel ensemble mean, slightly changes in time. The forecast interval for regional climate change is the decade 2045–55. The multimodel ensemble mean holds the risk that climate change signals are averaged out if different models predict opposite trends in the future behavior of a climate parameter. However, in Rauthe et al. (2003), we have shown that the direction and, to a certain extent, even the amplitude of twenty-first-century century circulation changes are largely consistent with all considered climate models. In terms of the NAO, none of the model experiments reveals a considerable long-term trend under GHG+SUL forcing.

The circulation indices are calculated in the following ways: 1) An EOF analysis of monthly mean NH MSLP north of 20°N is carried out for the observations and each individual model run, based on the original non-detrended datasets. The leading principal component (PC) is defined as the NAM index (Thompson and Wallace 2000). The simulated Arctic Oscillation (AO) patterns are optimally fitted to the observed one, by projecting the simulated leading five EOF patterns of each experiment onto the NCEP AO pattern, in order to ensure that all index time series refer to the same spatial structure of the AO. Actually, all models closely reproduce the observed AO pattern with the leading EOFs. 2) The NAO index is based on a Lagrangian method (Glowienka-Hense 1990; Paeth et al. 1999). It is defined as the leading PC derived from the four time series of meridional position and zonal-mean central pressure of the Icelandic low and Azores high in the North Atlantic sector. This NAO index is largely coherent with the usual Eularian pressure difference index by Hurrell (1995) and others but additionally accounts for the meridional shifting of the centers of action. As it has been shown that this spatial displacement is an important element of the NAO response to global warming (Paeth et al. 1999; Ulbrich and Christoph 1999; Rauthe et al. 2003), our index is assumed to be the more appropriate indicator of a climate change signal in the NAO. 3) The AL index corresponds to the standardized spatial mean of MSLP over the region 30°–65°N, 160°E–140°W.

The basic method of this study is a stepwise multiple regression with cross validation. A detailed description of the proceedings is given by Paeth and Hense (2003); the foundation is explained by von Storch and Zwiers (1999). Stepwise means that the regression model is gradually extended by one predictor—the NAM, NAO, or AL index—with the first predictor being the one that is most closely correlated with the predictand—TEM or PRE—and so on. This approach provides information about the relative importance of the three predictors at each grid point of the NCEP dataset. A trend polynomial of fourth order is removed from all predictor and predictand time series, prior to computing the regression model, in order to exclude the regression relationships that are only based on coincidental long-term trends. The covariance matrix between the circulation indices is incorporated in the regression equation, in order to account for the colinearity of the predictors. Otherwise, the multiple regression model would imply an overfitting with respect to nonorthogonal predictors such as, for instance, the NAM and NAO.

The design of the regression analysis implies that the residual is systematically diminished; correspondingly, the predictability is enhanced when an additional predictor is added to the regression model. This may lead to a multiple regression equation that is subject to statistical artifacts. In order to compose the regression model using only those predictors that provide physical information with respect to the predictand, cross validation is applied. The complete predictor and predictand time series are split up into a training dataset, which the stepwise multiple regression analysis is based on, and a control dataset, which consists of six bootstrap elements. These are chosen from the 1948–2001 NCEP period in a random manner. If the mean square error (MSE) of the regression equation applied to the six-member control dataset starts rising again, the number of predictors in the multiple regression model is cut off at this point. The whole procedure is iterated 100 times, with each iteration referring to different bootstrap elements, in order to account for different results due to the randomized selection process. The mean over these 100 iterations is displayed in the figures called out in the rest of the paper.

The forecast of mid-twenty-first-century circulation-induced temperature or precipitation anomalies is based on the optimal regression equation as mentioned above. The relevant regression coefficients $\overline{a}$ are averaged over 100 iterations, and the multimodel ensemble mean circulation departures during the 2045–55 period with respect to the 1900–80 climatology, $\overline{\mathrm{NAM}}_{2050}$, etc., are inserted in the regression equation as independent variables. This leads to an estimate of the TEM and PRE anomaly $\Delta\hat{C}_{2050}$ in the middle of the twenty-first century and at every grid point in (λ, ϕ):

$$\Delta\hat{C}_{2050}(\lambda, \phi) = \overline{a}_{\mathrm{NAM}}(\lambda, \phi)\overline{\mathrm{NAM}}_{2050} + \overline{a}_{\mathrm{NAO}}(\lambda, \phi)\overline{\mathrm{NAO}}_{2050} + \overline{a}_{\mathrm{AL}}(\lambda, \phi)\overline{\mathrm{AL}}_{2050}. \quad (1)$$

The multiple regression model accounts for a certain part of total TEM and PRE variability. This explained variance R^2 is subject to a Fisher F distribution under the null hypothesis H_0 (expectation of $R^2 = 0$). Thus, the significance level can be estimated given a certain error level. In the following figures, those grid points are masked out where the total explained variance of the multiple regression model does not exceed the 10% significance level.

3. Relative importance in terms of twentieth-century climate

The total explained TEM and PRE variability accounted for by the optimal number of the circulation indices altogether is shown in Fig. 1. It is based on the independent control dataset in order to highlight the physical relevance of the predictors. Nonsignificant values and grid points with $R^2 < 10\%$ are masked out. In terms of TEM, the pattern proves to be compact with clear structures over the NH continents (Fig. 1, top).

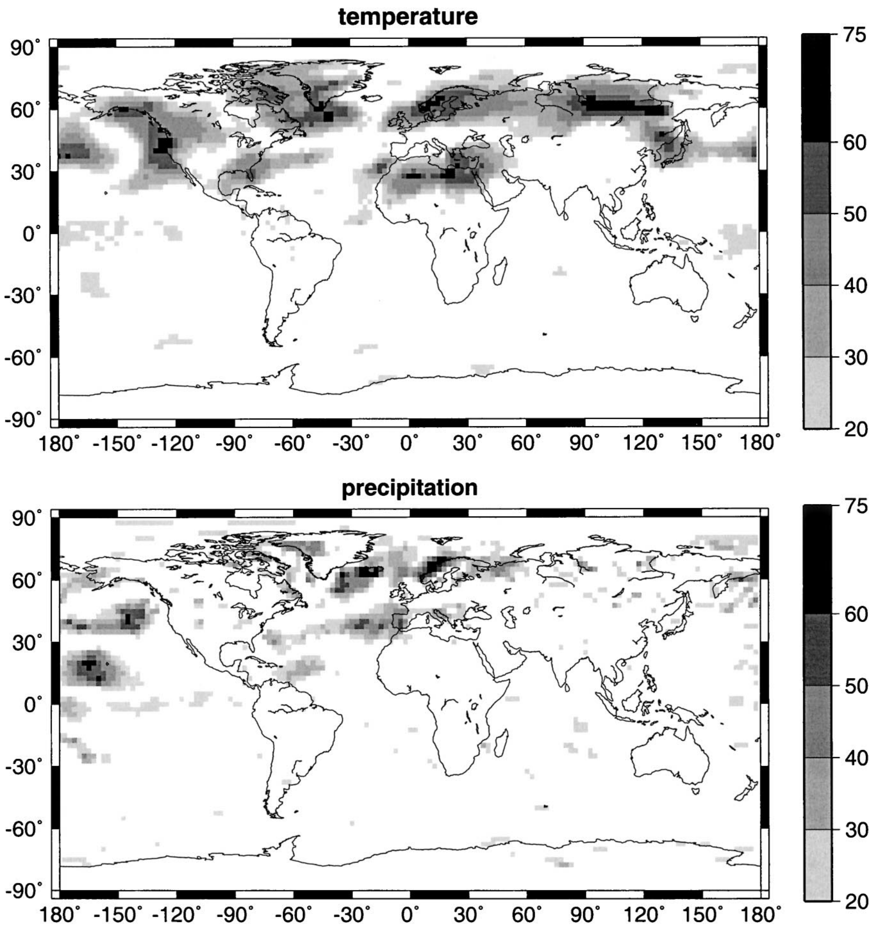

FIG. 1. Total explained variance of (top) TEM and (bottom) PRE variability by multiple regression including NAM, NAO, and AL time series, based on DJF-mean NCEP–NCAR reanalysis data (1949–2001), an independent dataset, averaged over 100 iterations. Scaling is in %.

The pixels with significant relationships in the low latitudes and the Southern Hemisphere (SH) are more diffuse and difficult to interpret. They probably reflect the teleconnections between the El Niño–Southern Oscillation (ENSO) and the North Pacific with the AL responding to changes in the Tropics (Sheng 2002). The areas of maximum explained variance (40%–75%) are over the west coast of North America, Greenland, the North Atlantic south of Greenland, the Sargasso Sea, North Africa, Scandinavia, and especially Siberia. The quadropole around the North Atlantic is described in other studies and is usually related to the NAO (Kapala et al. 1998). With respect to PRE, the regions with significant circulation impact appear to be more isolated (Fig. 1, bottom). Areas of high explained variance (≥40%) are much smaller as for TEM, albeit the amplitude is comparable. Such areas are found over the North Pacific, the North Atlantic, and the west coast of Scandinavia. The strongest relationship between NH circulation modes and PRE is revealed over the subtropical and northern Pacific Ocean. This signal is likely associated with ENSO teleconnections rather than with the regional effect of the AL. In general, atmospheric circulation is more directly linked to TEM than PRE, as the latter is subject to many more factors at the regional to local scale and its internal variability is much higher.

The ranking of the circulation modes in contributing to the total explained variance can be determined from the stepwise approach. Figure 2 displays these ranks at each grid point where the predictability of the regression model is statistically significant (cf. Fig. 1). As cross validation ensures that the number of predictors is restricted to those with physical meaning, the number of pixels drops down with increasing rank. In terms of temperature (Fig. 2, left), the NAM impact covers most parts of the NH, including Eurasia, Greenland, and North Africa. The AL accounts for North Pacific and North American climate. The NAO dominates over smaller regions of the North Atlantic as well as central and western Europe. At lower ranks, the picture is approximately vice versa, with the modes replacing each other. Interestingly, all three modes contribute to the large circulation impact over Siberia amounting to a total of 50%–75%. The predominance of the NAM is

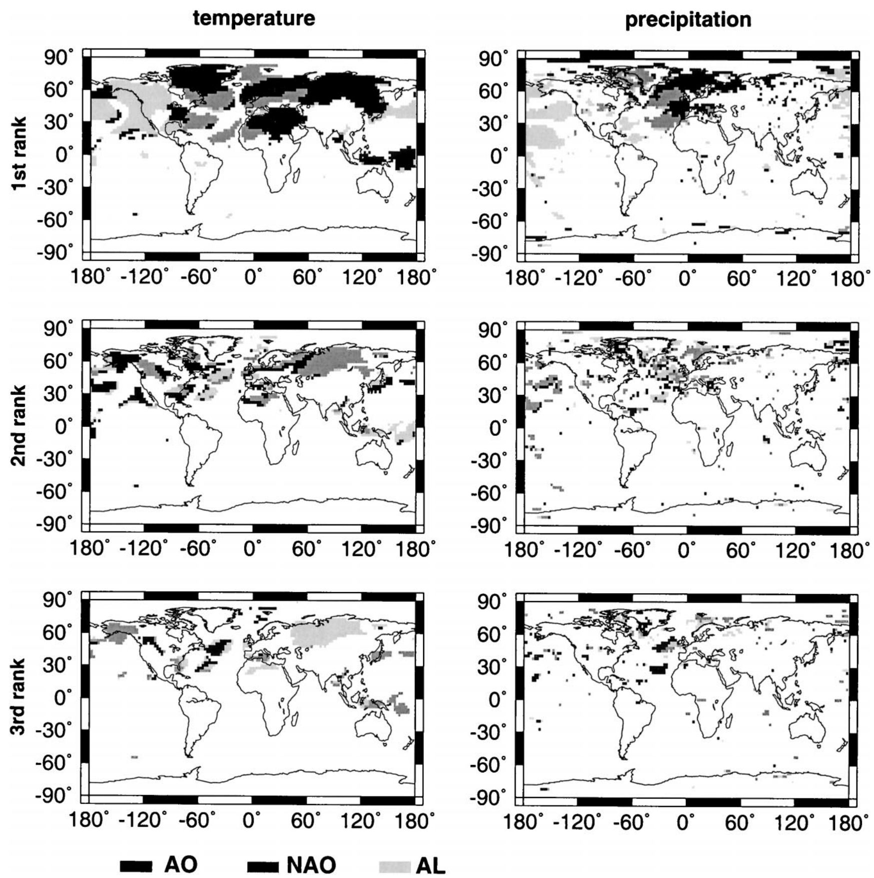

FIG. 2. Ranks of the NAM, NAO, and AL in the stepwise multiple regression approach with respect to DJF NCEP NCAR (left) TEM and (right) PRE, averaged over 100 iterations. Grid points without statistically significant explained variance in Fig. 1 are masked out.

less pronounced with respect to precipitation (Fig. 2, right). However, the NAM is mainly responsible for rainfall anomalies over Scandinavia and the Iberian Peninsula (cf. Goodess and Jones 2002), where the peaks in predictability are located (cf. Fig. 1). As expected, the AL accounts for rainfall changes in the North Pacific region. At most grid points, only one predictor provides physical information on rainfall variability. In general, the NAM plays a major role in affecting TEM and PRE anomalies over large parts of the NH. The influence of the AL is predominating in the Pacific sector, while the NAO impact is of an even more regional nature and mostly confined to the North Atlantic sector. The minor role of the NAO may be explained by its coherence to the NAM, as indicated by Table 1. About 50% of the total variability is reciprocally explained, whereas the

TABLE 1. Correlation coefficients between the predictor time series, DJF-mean NCEP–NCAR reanalysis data (1949–2001), with the fourth-order trend removed.

NAM–NAO	NAM–AL	NAO–AL
0.75	0.34	0.15

AL appears to be largely independent of the other modes. These values are in excellent agreement with Deser (2000). The design of the stepwise multiple regression implies that a subsequent factor, which is correlated with a previous and hence more important factor, is partly dampened out. Thus, given that the NAM index is slightly more relevant to surface climate at a grid point than the NAO index, the NAO impact is largely suppressed.

Furthermore, it may be asked whether atmospheric circulation may also account for TEM and PRE anomalies at the hemispheric scale, instead of being compensated for over the entire hemisphere. A possible mechanism, incorporating heat exchanges with the oceans, has been suggested by Wallace et al. (1995). Therefore, we have applied the multiple regression analysis to the Northern Hemispheric mean temperature and rainfall. It appears that the NH circulation has no statistically significant impact on the hemispheric mean climate, amounting to 16% (12%) of the explained variance relative to total TEM (PRE) variability. Thus, at the hemispheric scale, atmospheric circulation can be understood as Just advection of air masses from one

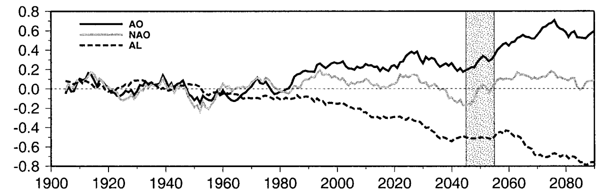

FIG. 3. Departures from the 1900–80 mean of multimodel ensemble mean DJF time series of NAM, NAO, and AL indexes from GHG+SUL-induced climate model experiments (10-yr low-pass filter).

TABLE 2. Correlation coefficients between the predictor time series, DJF-mean multimodel ensemble means (1860–2099), with the fourth-order trend removed.

NAM–NAO	NAM–AL	NAO–AL
0.75	0.39	0.36

region to another, warming and cooling effects simply being averaged out. As a consequence, we do not expect any considerable contribution to future changes in hemispheric mean climate. Rather, circulation governs the spatial structure of climate anomalies without affecting the global or hemispheric mean climate.

4. Inference about future climate change

In the second step, the substantial relationships between NH circulation and near-surface climate are used to determine the role of the NAM, NAO, and AL in future regional climate change. Given projection of future circulation changes, the associated anomalies of TEM and PRE can be estimated by means of the optimal regression equation (see section 2). Despite different resolutions and parameterizations, most climate models agree in predicting a strengthening of the NAM and AL under greenhouse warming conditions (Rauthe et al. 2003). Figure 3 depicts the multimodel ensemble mean time series of the NAM, NAO, and AL derived from 24 coupled model experiments with GHG+SUL forcing until the end of the twenty-first century. All time series are standardized with respect to the 1900–80 climatology, which is assumed to barely be affected by the external GHG+SUL forcing, hence representing internal climate variability, and the standard deviation of the monthly mean values. In order to ensure that these multimodel time series are also representative of the EOF-derived NAM phenomenon, the leading EOF pattern of each individual model simulation is projected onto the observed NAM pattern. It is found that the spatial structure of the observed. NAM is basically reproduced by each model (not shown). In addition, the covariability between the predictors, averaged over all models, is in excellent agreement with the observed values, provided that the time series are detrended (Table 2). However, the climate models overestimate the teleconnection between the North Atlantic and North Pacific basins, which may be related to an underrepresentation of the orographic barrier of the Rocky Mountains. The 10-yr running mean AL index shows a remarkable negative trend, which is accompanied by an intensification of the central pressure and may be related to anthropogenic sulphur sources over East Asia (Houghton et al. 2001), but this physical explanation is purely speculative. Further uncertainty is imposed by the fact that negative anomalies are already simulated from the 1950s onward, when the increasing GHG and SUL concentrations should not have played a major role. It is also conceivable that this early change in the AL is due to model peculiarities other than the external radiative forcing, although it is intriguing that various climate models agree in performing this AL behavior (cf. Rauthe et al. 2003). The NAM shows up with a strong positive trend throughout the second half of this century. The NAO hardly reveals a climate change signal consistent with all considered models, although a slight preference of positive state anomalies is found during the twenty-first century (cf. Paeth et al. 1999). It has been found that especially the sensitivity of the North Atlantic centers of action strongly varies from model to model. Thus, compared with Table 2, multimodel NAM and NAO time series are more clearly distinguishable, if the long-term trends are taken into account. Note that a negative trend in the AL is counteracting a positive one in the NAM. Rauthe et al. (2003) have found that the major signal in the MSLP field takes place over the Arctic (and Antarctic) where surface pressure is clearly decreasing in all model runs.

The 10-yr running mean around the year 2050 (shaded area) is chosen as a typical value of climate conditions in the middle of the twenty-first century and is inserted as predictions of the NAM, NAO, and AL in the optimal regression equation. Although the circulation signals are continuously intensifying until the end of this century, the 2050 mean particularly has been chosen as a reference period for one reason: the IPCC 2001 report provides information about the multimodel total TEM and PRE changes under GHG+SUL forcing until the year 2050 to be compared with the circulation-related anomalies described here. In addition, the amount and role of sulphur emissions during the second half of the twenty-first century, rather than before it, is subject to large uncertainties (Houghton et al. 2001). Given accelerated technologies in catalyzation, it is unlikely that sulphur emissions are increasing according to the IS92A scenario, prescribed in the model experiments. In order to access the realism of at least one model with strong circulation response, we have compared the results in Fig. 1 with the ECHAM3/Large-Scale Geostrophic (LSG) datasets. The observed and simulated patterns and amplitudes are very similar to each other, especially over the NH oceans and adjacent landmasses (not shown). The strong observed signal over Siberia is much less prevailing in the model. Note that all time series are detrended, removing a fourth-order polynomial prior

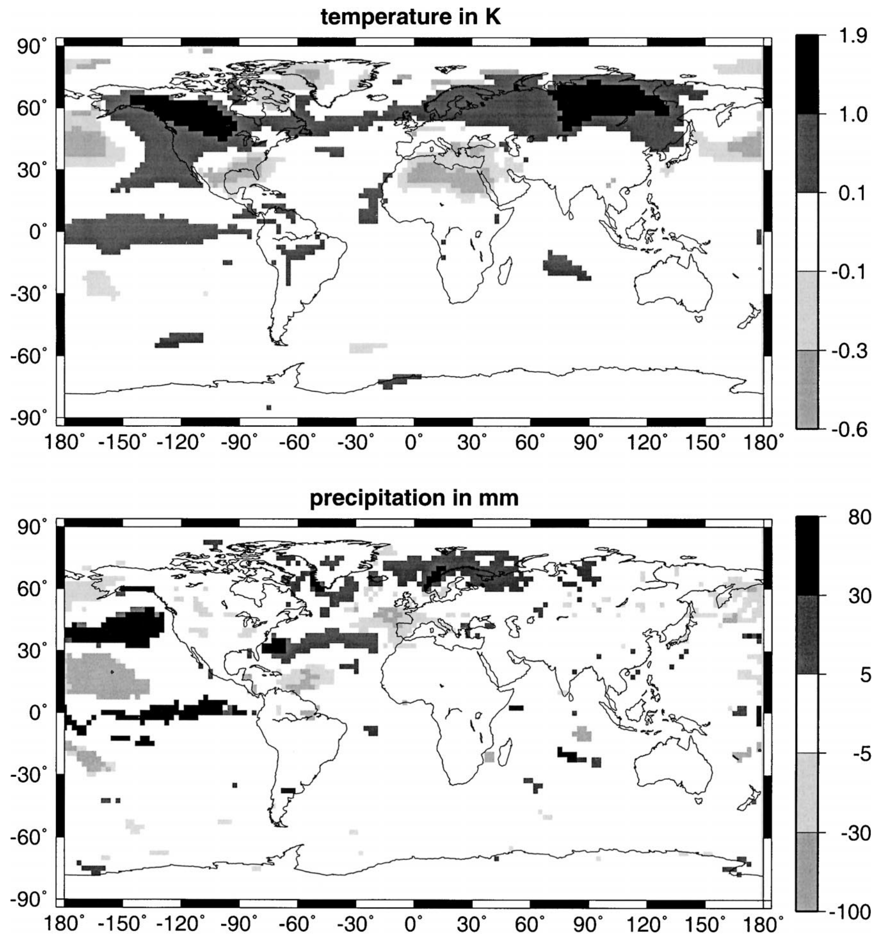

FIG. 4. Forecast of DJF (top) TEM and (bottom) PRE anomalies for the decade 2045–55 as induced by the multimodel predicted change in NAM, NAO, and AL altogether. Note the different scaling. Grid points without statistically significant explained variance or minor changes ($<$0.1 K; $<$5 mm) are masked out.

to computing the simulated regression model. Otherwise, much more explained variance is found all over the globe due to the multidecadal trend.

The associated TEM and PRE changes until the year 2050 are displayed in Fig. 4. For reasons of clarity, nonsignificant areas and grid boxes with minor changes ($\pm$0.1 K, $\pm$5 mm) are left out. The majority of future temperature anomalies has a positive sign, implying a warming up to 1.9 K, particularly over the northern continents (Fig. 4, top). A substantial cooling up to 0.6 K occurs over the North Pacific, the Labrador Sea, and North Africa. This pattern agrees with the idea of changing storm track orientation and enhanced cyclonic activity over the northern ocean basins (Hurrell and van Loon 1997; Kapala et al. 1998; Thompson and Wallace 2001). Two regions are worth mentioning with regard to rainfall changes: the North Pacific reveals a pattern with alternating regions of increasing and reduced PRE, which is certainly linked to an ENSO-related response in extratropical wave activity (Sheng 2002) and in the North Atlantic sector, more rainfall is expected over Scandinavia, and less is expected over southwestern Europe and parts of the Mediterranean. These changes are coming along with an intensification of the NAM and/or NAO, inducing a more northeastward orientation of the storm track (Kapala et al. 1998; Goodess and Jones 2002). Applying the same equation to the hemispheric mean TEM and PRE leads to negligible changes, $+$0.07 K and $+$0.2 mm, respectively. Thus, the atmospheric circulation is not responsible for future climate change on the hemispheric scale.

A basic question is to what extent future circulation anomalies may contribute to the total change in regional climate as simulated in the middle of the twenty-first century. A direct comparison can be drawn with respect to the IPCC 2001 report, which proclaims that the expected overall multimodel ensemble mean changes in near-surface temperature under GHG$+$SUL forcing until the year 2050 amount to, at most $+$3 K over the northern land masses. Total rainfall changes vary between about $-$60 mm over the Mediterranean basin and $+$100 mm over Scandinavia (Houghton et al. 2001, their

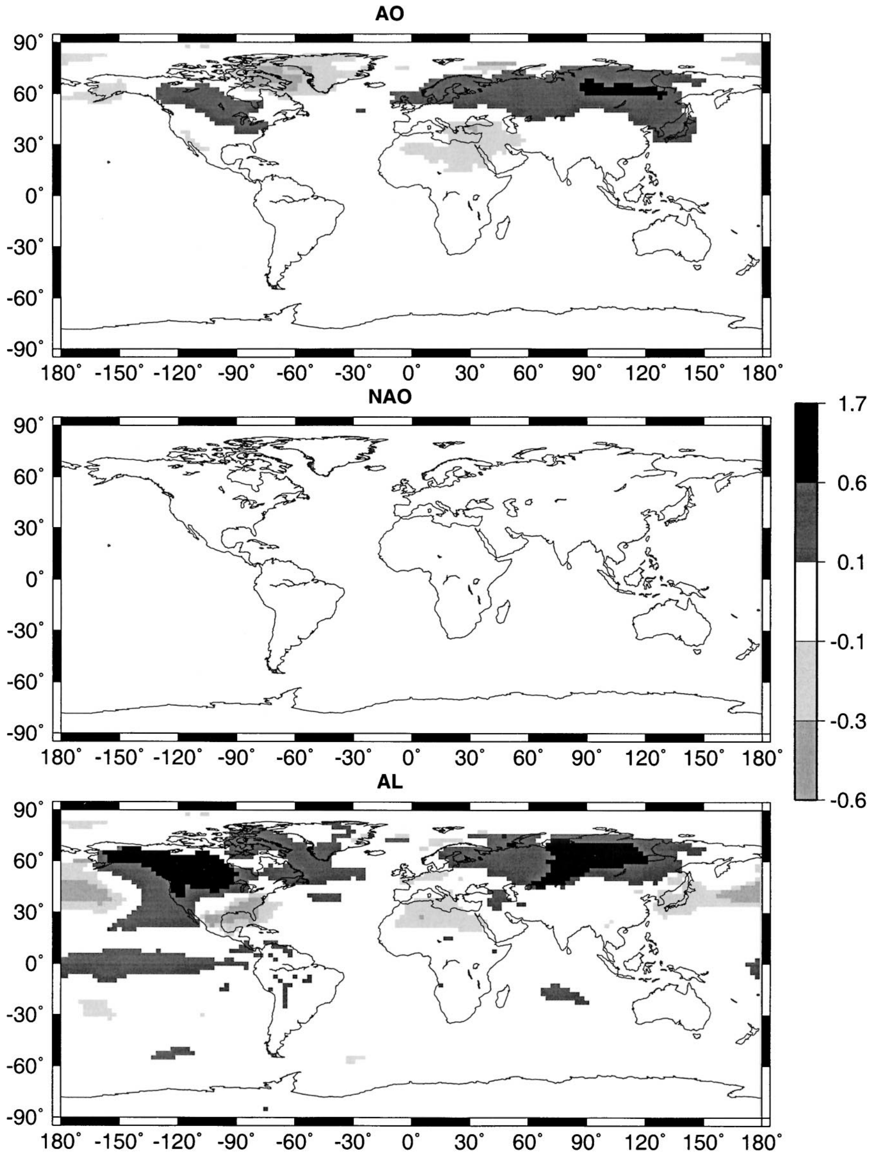

FIG. 5. Same as in Fig. 4, but shown separately for each individual circulation mode and only temperature in K.

Figs. 9.10c and 9.11c). These figures basically rely on the same global climate models and future climate scenarios as are used in our study. It is obvious that the circulation-induced part of future TEM and PRE changes is hardly negligible, amounting to almost 60% of total TEM changes over the NH land masses and even 80% of total PRE anomalies over northern Europe, the Mediterranean, and the North Pacific. Thus, atmospheric circulation is indeed a crucial factor in regional climate change.

The final question is how the individual modes contribute to the pattern in Fig. 4. As TEM is more closely related to circulation, the partitioning of the total circulation-induced changes is only shown for this predictand (Fig. 5). The individual contributions of the circulation modes to the total circulation-induced PRE changes are largely analogous to Fig. 5. The positive NAM state in the middle of the twenty-first century is associated with a substantial warming over Eurasia and central Canada, accounting for half of the total circulation-induced anomalies (Fig. 5, top). Cooling occurs west of Greenland and over the eastern Mediterranean. From our point of view, the NAO does not affect any future climate anomalies (Fig. 5, middle). This is mainly due to the fact that there is no consistent long-term trend in the multimodel ensemble. Multiplying the regression coefficient with a NAO anomaly of 0.003 does not lead to any considerable change in TEM. However, in some models the NAO plays a major role in regional climate change, but under GHG-only forcing (Paeth et al. 1999;

Ulbrich and Christoph 1999). The strongly enhanced AL cyclonic activity is associated with a TEM rise over the western part of North America and contributes to the warming over central and eastern Eurasia (Fig. 5, bottom). Over the Labrador Sea, the AL and NAM are counteracting each other, but the cooling by the NAM finally dominates the warming by the AL. Thus, the total outcome is a cooling tendency, which in turn is overcompensated for by the direct radiative forcing (Houghton et al. 2001). Over Siberia, the NAM and AL make an equal contribution to the substantial warming.

5. Conclusions

Multiple regression reveals that on a spatial average, 30%–50% and locally up to 75% of twentieth-century interannual winter TEM and PRE fluctuations are driven by NH circulation modes, combining the contributions by NAM, NAO, and AL. The stepwise approach reveals that the NAM predominates over large parts of the NH land masses. The AL plays the major role over the North Pacific sector. The NAO impact is confined to some smaller regions over the North Atlantic sector and adjacent countries. The NAM and AL are intensifying in most GHG+SUL-induced coupled climate model experiments into the future, whereas the NAO response is weak with respect to different models. This leads to substantial changes in near-surface TEM and PRE fields until the end of this century, especially over the NH continents. Regional climate anomalies related to circulation amount locally to up to 60% of the total expected changes under radiative forcing, especially over Siberia and North America (TEM) as well as over northern Europe, the Mediterranean, and the North Pacific sector (PRE). The NAM signal is affecting the North Atlantic sector and Europe, and the AL is responsible for the North Pacific region. Over eastern North America, the NAM and AL effects are counteracting each other with the NAM dominating the AL dynamics. Over Siberia, they are concordant and equally contribute to the remarkable warming. The role of the more regional NAO remains unclear since it does not show up with a comprehensive climate change signal in the multimodel ensemble.

There are several conclusions to be drawn from this study: 1) The climate change sensitivity of extratropical circulation is largely relevant to many regions of the globe with high-population density. It accounts for a considerable part of the overall changes due to greenhouse warming. If only those ensemble realizations from the most recent climate models without flux corrections (ECHAM5 and HADCM3) are taken into account, the NAM and AL signals are even stronger (not shown), supporting further evidence of a substantial change in NH circulation. Thus, circulation modes can be interpreted as a major transfer mechanism of global radiative heating to regional climate change. 2) It has been suggested that the NAO is the regional counterpart of the hemispheric NAM, dominating climate around the North Atlantic region. However, this study shows that the NAM is prevailing over large parts of the NH continents even adjacent to the North Atlantic, whereas the NAO influence is restricted to the oceanic region itself. 3) The physical–dynamical meaning of the NAM has been questioned. We cannot directly contribute to this issue, but we provide evidence that the NAM has a close statistical relationship to TEM and PRE, which are climate parameters that directly affect human activity and ecosystems. This makes the NAM a crucial factor of future climate change by mitigating or aggravating the impact of global radiative heating at a regional to hemispheric scale. This main conclusion holds the prospect of downscaling anthropogenic climate change; if we can predict the large-scale NAM response to future anthropogenic emissions in a reliable way, for example, by coarse-grid multimodel ensembles, we can gain some insight into the TEM and PRE changes at much smaller (subgrid) spatial scales, given the statistical relationships between NH circulation and surface climate. However, note that the regression method applied here does not infer anything about the cause–effect relationships between a dynamical forcing by the atmospheric circulation and a response in surface climate. It is also conceivable that circulation and TEM/PRE are simultaneously affected by a third factor that is itself the active player in transferring global radiative heating to regional climate change, such as the oceans, for instance.

There is another basic aspect that requires deeper analysis: When inferring regional climate change from Eq. (1), we assume that the statistical relationships between NH circulation and surface climate are stationary in time. However, Jones et al. (2003) have shown that at least the connection between the NAO and near-surface temperature is subject to changes in time. Unfortunately, we cannot address this aspect properly in the present study, since we do not have the TEM and PRE data of all 24 model experiments at our disposal. Thus, further investigation is needed to reduce this uncertainty in our circulation-related regional future climate change estimates.

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