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The North Atlantic Oscillation as an indicator for greenhouse-gas induced regional climate change

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Abstract The time-dependent variability of the North Atlantic Oscillation is examined in an observational data set and several model data sets with greenhouse-gas-induced external forcings. The index of the North Atlantic Oscillation state is derived from the time series of mean latitudinal position and central pressure of the Icelandic Low and the Azores High considering the synchronous meridional shifting of the two pressure systems. While the North Atlantic Oscillation is characterized by intensive interannual variability, the low-pass filtered index time series shows a decadal component with a time scale of about 50 y within almost 120 y of observation. Since the late 1960s we observe a positive trend and a transition to a strong positive phase of the phenomenon indicative of a predominantly zonal circulation over the North Atlantic. This trend occurs equally in the observations and all examined model data sets with increasing greenhouse-gas-concentration and atmosphere-ocean coupling. We find statistical evidence that the radiative forcing by increasing CO_2 concentration has a significant influence on the simulated variability of the North Atlantic Oscillation on time scales of 60 y and longer, independent of the initial conditions and the model version. The seasonal response is strongest in late summer and winter. The interannual variability of the North Atlantic Oscillation states on time scales less than 10 y decreases synchronously with the positive trend of its decadal-mean state implying a stabilization of its present and future zonal state.

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1 Introduction

The North Atlantic Oscillation (NAO) describes an atmospheric phenomenon in the North Atlantic sector as an organized motion of the Icelandic Low (IL) and the Azores High (AH) (Defant 1924; Walker and Bliss 1932). For largely unknown reasons these pressure systems exhibit a synchronous meridional shifting where a northward shifting is accompanied by a strengthening of both centres of action. This results in an enhanced meridional pressure gradient with a mainly zonal circulation over the North Atlantic. In winter this zonalization extends to Western Europe with a typical warm air mass advection from the Atlantic over Europe and cold air advection northwest of the IL centre. The southward shift is combined with a weakening of IL and AH and more meridional circulation (Mächel et al. 1998). Since it explains locally up to 50% of the near surface variance, the influence of the NAO on the interannual low tropospheric temperature variability cannot be neglected. Therefore, interdecadal changes in the NAO are relevant for regional climate variability over Europe and North America (Kapala et al. 1998; Hurrell 1995).

The issue of this study is whether this important atmospheric phenomenon is subject to a change in view of the expected anthropogenic influence on the global climate system. The general idea is that the climate forcing by increasing greenhouse-gas-concentrations may cause a development of the NAO state very relevant for the atmospheric fields and variables over a large part of the Northern Hemisphere. In this case, the NAO would serve as a regional transfer instrument of global climate change. Another aim of the present study is to assess the general skill of coupled models and uncoupled but forced atmospheric model simulations to reproduce a realistic NAO.

2 Data and NAO index

We study the NAO in an observational data set from the German Meteorological Service (DWD) derived from a time series of gridded sea level pressure spanning the period 1880 to 1995 (Stein and Hense 1994). In addition we use several model data sets with different forcing scenarios, periods and initial conditions mostly derived from the coupled atmosphere-ocean general circulation model (AO-GCM) ECHAM-3/LSG in Hamburg with spectral T21 resolution (Roeckner et al. 1992; Voss et al. 1998). In particular, we concentrate on model runs with increasing greenhouse gases according to the observed CO_2 concentrations until 1985 and then to IPCC scenario A ("business as usual") (Houghton et al. 1990), the NEIN simulation for "New Early Industrial".

The usual NAO index ("standard index") employed by Deser and Blackmon (1993), Wilby et al. (1997), Hurrell and van Loon (1997) and many others (see Mächel et al. 1998) is the pressure difference between two fixed locations near Iceland and the Azores. We define the NAO index by the first principal component (PC) derived from four time series of central pressure and mean latitudinal position of IL and AH. This index has advantage compared to other NAO indices based on pressure differences at fixed locations because it always follows the main centres of action and thereby represents the full meridional pressure gradient. In addition, our method of obtaining the NAO index is appropriate for assessing a seasonally varying signal since the pressure systems are subject to a seasonally induced shifting.

The index calculation is based on the following steps (Glowienka-Hense 1985, 1990): time series of latitudinal position of maximum and minimum zonally-averaged sea level pressure (SLP) and the corresponding central pressure in the North Atlantic region are determined from the zonal mean pressure between 70 °W and 10 °W for each data set. This has been proven to be advantageous because especially the accumulation and depletion of mass in the AH is not concentrated at a localized longitude but in a broad zonal region. After normalizing these four time series, an EOF analysis is performed. The resulting first principal component represents the NAO phenomenon indicating that a deepening of the IL is correlated with a northward shifting of IL and AH together with an increasing central pressure of the AH. The leading EOF accounts for 56% of total variance seasonally varying between 50% in summer and over 60% in winter. The relative contributions of each of the four input time series is more or less equal for both latitudes and central pressure of AH, while the influence of IL pressure is slightly underestimated by the model. On the other hand, in the observations all influences are comparable.

Thus, the evident time-dependent shifting of the centres of action (Ulbrich and Christoph 1998) is taken into account. The sign convertion is such that a positive value signifies the northward shifting with zonal circulation regime and vice versa (Glowienka-Hense 1985, 1990).

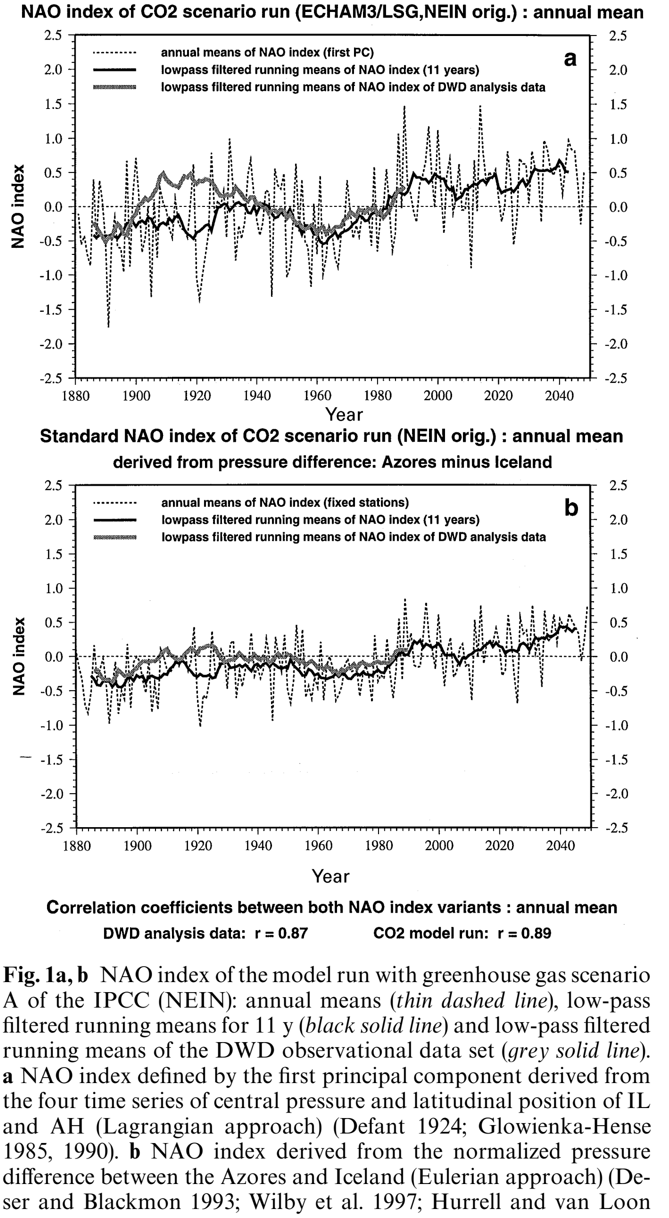

Fig. 1a, b NAO index of the model run with greenhouse gas scenario A of the IPCC (NEIN): annual means (*thin dashed line*), low-pass filtered running means for 11 y (*black solid line*) and low-pass filtered running means of the DWD observational data set (*grey solid line*). **a** NAO index defined by the first principal component derived from the four time series of central pressure and latitudinal position of IL and AH (Lagrangian approach) (Defant 1924; Glowienka-Hense 1985, 1990). **b** NAO index derived from the normalized pressure difference between the Azores and Iceland (Eulerian approach) (Deser and Blackmon 1993; Wilby et al. 1997; Hurrell and van Loon 1997). Due to the different normalizations the amplitude of the two index variants cannot be compared

3 Results

3.1 ECHAM-3/LSG modelled NAO and observations

In Fig. 1 the individual annual means and 11 y low-pass filtered running means of the NAO index are shown for the NEIN scenario A model simulation with external CO_2 forcing as well as the running means of the DWD observational data respectively. In the top panel the NAO index has been derived from the time series of central pressure and latitudinal position of IL and AH (Glowienka-Hense 1985). On the interannual time scale a strong variability can be observed implying the near unpredictability of the year-to-year changes of the NAO. However, the magnitude of interannual NAO variability is realistically simulated by the model compared to the observed NAO. On the other hand, the smoothed curves reveal a low frequency signal on time scales of about 50 y. Additionally, the scenario run predicts the continuation of the recent positive NAO state for the future until the middle of the 21th century. Such a phase of the NAO indicates a predominantly zonal circulation over the North Atlantic and a characteristic pattern of winter temperature anomalies over the surrounding land masses with warming over Eurasia and cooling over Northeast America. Incidentally, this temperature pattern is also expected in connection with the potential greenhouse induced global warming (Hense and Paeth 1997; Paeth and Hense 1998) and has been termed COWL by Wallace et al. (1995). The comparison between simulated and observed NAO leads to an astonishing agreements when comparing the low-pass filtered time series since 1930. On the other hand the model does not reproduce the real NAO during the first half of the overlapping period up to the 1930s. Within the period of conforming NAO development two phases should be distinguished and focused on: a period of declining indices between 1930 and 1965 with cooling trends over Eurasia and a period of increasing values between 1965 and 1994 combined with warming temperatures in winter over Eurasia. We need to determine whether the increase of the greenhouse gases has an influence on the time development of the NAO and if so, whether both phases, cooling and warming, are part of the signal.

The spatial SLP patterns associated with the NAO indices are highly comparable between observations and scenario run. Based on a point wise regression between NAO and SLP we found that over the North Atlantic and the adjacent continents, the structure and magnitude of the regression coefficients in observations and simulation almost coincide. In the Northern Hemisphere subtropical Atlantic where the AH is located, there is a broad zone of positive values extending from central North America to the Mediterranean. A region of negative correlation between SLP and NAO is centred around Iceland. However, the model erroneously reveals a weak NAO influence over the North Pacific which cannot be found in the observations. This might be due to the model resolution which might underestimate the delimiting effect of the mountain ridges between North Atlantic and North Pacific.

Concern may be expressed that such conformities in space and time only appear in relation to our NAO index. In Fig. 1b the NAO index is shown as generally derived from the normalized pressure difference, Azores minus Iceland. Although this index does not register all phase transitions and extreme states of the NAO since 1880, due to the yet unconsidered but proven shifting of the centres of action, (Ulbrich and Christoph 1998), justifying our index determination, the general trend to a strong positive phase from the 1960s onward is confirmed by this usual index variation. The correlation between both index variants is relatively strong reaching nearly 0.9 even on the interannual time scale.

However, the principal problem consists of the relatively short period of observation: there is a low frequency component of about 50 y within only 120 y of observations. Thus, these two to three realizations of the multidecadal NAO variability do not permit us to exclude pure chance as the cause for the NAO analogies between this observed and simulated data set. Further investigation is necessary including more scenario runs of different external forcing parameters (Hense and Paeth 1998), varying initial conditions and alternative model versions in order to be able to identify a greenhouse signal within the NAO.

In addition, the question arises whether a corresponding control experiment with fixed CO_2 reveals similar long-term variability and trends. For these reasons, we have examined the 800-y control run of the ECHAM-3/LSG coupled GCM (Voss et al. 1998). Indeed, we find a comparable low frequency component which obviously does not result from the greenhouse forcing. However there is no systematic drift in the control run that causes a general trend over the whole period of integration. Every 100 to 200 y, events comparable to the observations occur in the control run indicating that within the coupled ECHAM model the CO_2 forcing is not necessarily required in order to reproduce a realistic long period behaviour of the NAO. However, by means of a regression analysis we could show that in contrast to the time structure of interdecadal NAO state variability, the amplitudes are not well simulated. It is the scenario run which reaches the magnitude of the observed NAO extreme states. In addition, the following sections show that the positive trend from 1970 onward is not a peculiarity of this single scenario run.

3.2 ECHAM-4/OPYC modelled NAO

To assess the dependence of the NAO development on model version several model simulations performed with the recent version ECHAM-4/OPYC in Hamburg (Roeckner et al. 1996, 1998) have been taken into consideration. In Fig. 2 we refer to that run, which uses greenhouse forcing analogous to the NEIN scenario, but with a lower rate of increase according to IPCC scenario IS92a (Houghton et al. 1992). We observe the same trend towards a strong and continuously positive NAO phase from 1980 onward. In contrast, the period of low NAO indices between 1930 and the 1960s is not analogously reproduced within this scenario run. Thus, it seems likely that a greenhouse gas climate signal of the NAO can be defined exclusively by the recent positive trend, obviously independent of the considered model version, while the common negative trend before is due to chance.

3.3 ECHAM-3/LSG ensemble NAO

The next step is to determine the persistence of the NAO signal with respect to the initial conditions. We have at our disposal an ensemble of three further ECHAM-3/LSG simulations with the same NEIN scenario as mentioned but with different initial conditions for atmosphere and ocean in January 1880.

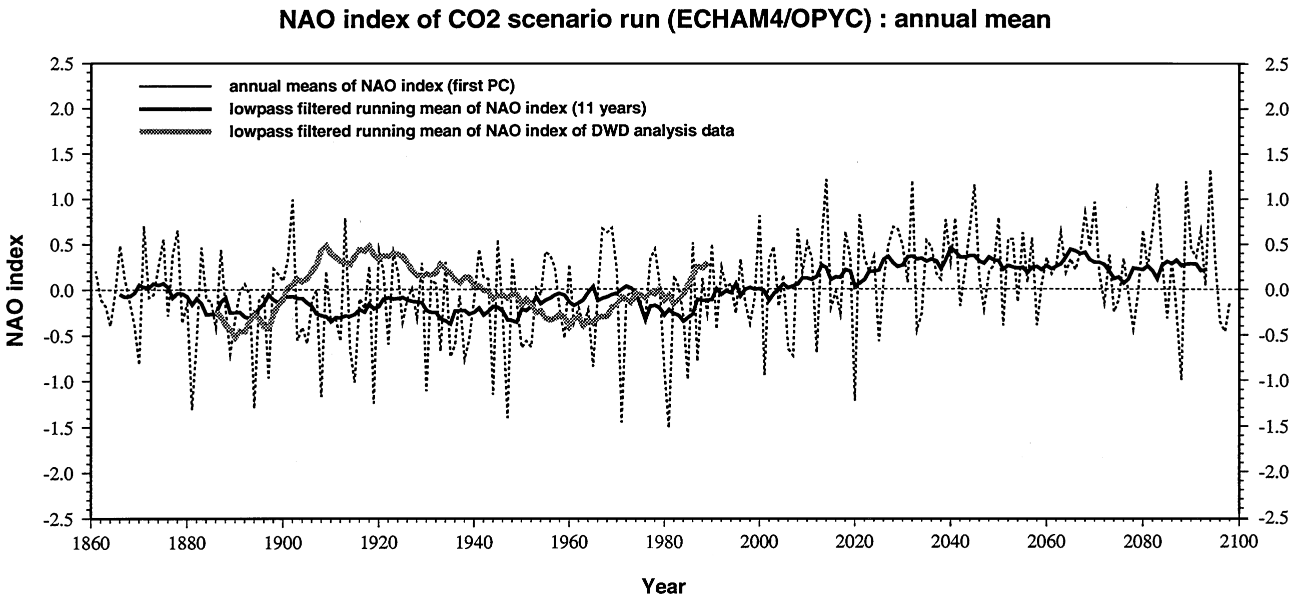

Fig. 2 NAO index of the model run with greenhouse gas scenario A of the IPCC, derived from the recent model version ECHAM-4/OPYC (Roeckner et al. 1996, 1998): legend as in Fig. 1. NAO index defined by the first PC of the four time series. In comparison with the ECHAM-3/LSG model the coupled atmosphere-ocean GCM ECHAM-4/OPYC is based on modified and improved model physics with considerably fewer flux corrections, a spectral T42 resolution and a completely different ocean model. In addition, two scenario runs of the same climate model with additional sulphate aerosol and respectively ozone forcing have also been considered. They confirm the positive trend from the 1980s but with weaker amplitude and persistence. The corresponding control run shows no trend signal

Figure 3 presents the NAO index of these three additional NEIN simulations and the ensemble mean of run 1 to 4. In spite of some specific differences in details such as an occasionally breaking of the future positive phase in runs 2 and 4, the climate signal in the form of the recent positive NAO tendency occurs in each ensemble simulation, especially in the ensemble mean. In this context, it is not essential that the general positive tendency is transiently interrupted since the interannual variability is quite large. Instead we want to focus on the interdecadal time scale where a clear positive trend of the NAO mean state is revealed. In particular, this is expressed in the ensemble mean. There should be no doubt that the NAO in the ECHAM-3/LSG is characterized by a climate signal probably due to the greenhouse forcing that takes effect in the model from the 1970s onward. Therefore, we can reject the objection that the positive NAO trend is rather due to a systematic drift in the control experiment that would create such trends independent of the external forcing. This data set ensemble clearly reveals the effect of the common forcing parameter while a single scenario run could have been misleading.

3.4 Analysis of variance

To handle the NAO signal in a statistically more precise way an analysis of variance (ANOVA) (Morrison 1990) has been carried out based on the NEIN ensemble. By means of the ANOVA the influence of the common external forcing parameter CO_2 on the total variance of the ensemble simulations can be quantified and its statistical significance determined. First the test has been performed for a 20 y running means. On this time scale (Fig. 4a) significant values of the external influence on total variance only appear sporadically and internal variability clearly dominates. In consequence climate prediction on the base of a greenhouse induced NAO change should be difficult even on this climatological time scale (Davies et al. 1997; Griffies and Bryan 1997). On the other hand, if the ANOVA is focused on periods of 60 ys (Fig. 4b), which correspond to the characteristic multidecadal time scales of the NAO low frequency variability, the greenhouse forcing emerges from behind the model internal variability after 1970. With explained variances of almost 25% the null-hypothesis that there is no influence of the external CO_2 forcing on the total NAO variability of the NEIN ensemble has to be rejected with an error level of 5% or less between 1970 and 2020 as middle years of 60 y-long periods, with some deterioration at the end of this simulation period. This deterioration is subject to speculation at present: it might be caused by long term effects of the oceanic circulation. Further investigations have to be carried out. Before 1970 the null-hypothesis cannot be rejected, indicating that the low frequency variability is induced by internal dynamics. The ANOVA clearly indicates a statistically significant influence of the greenhouse forcing on the NAO in the

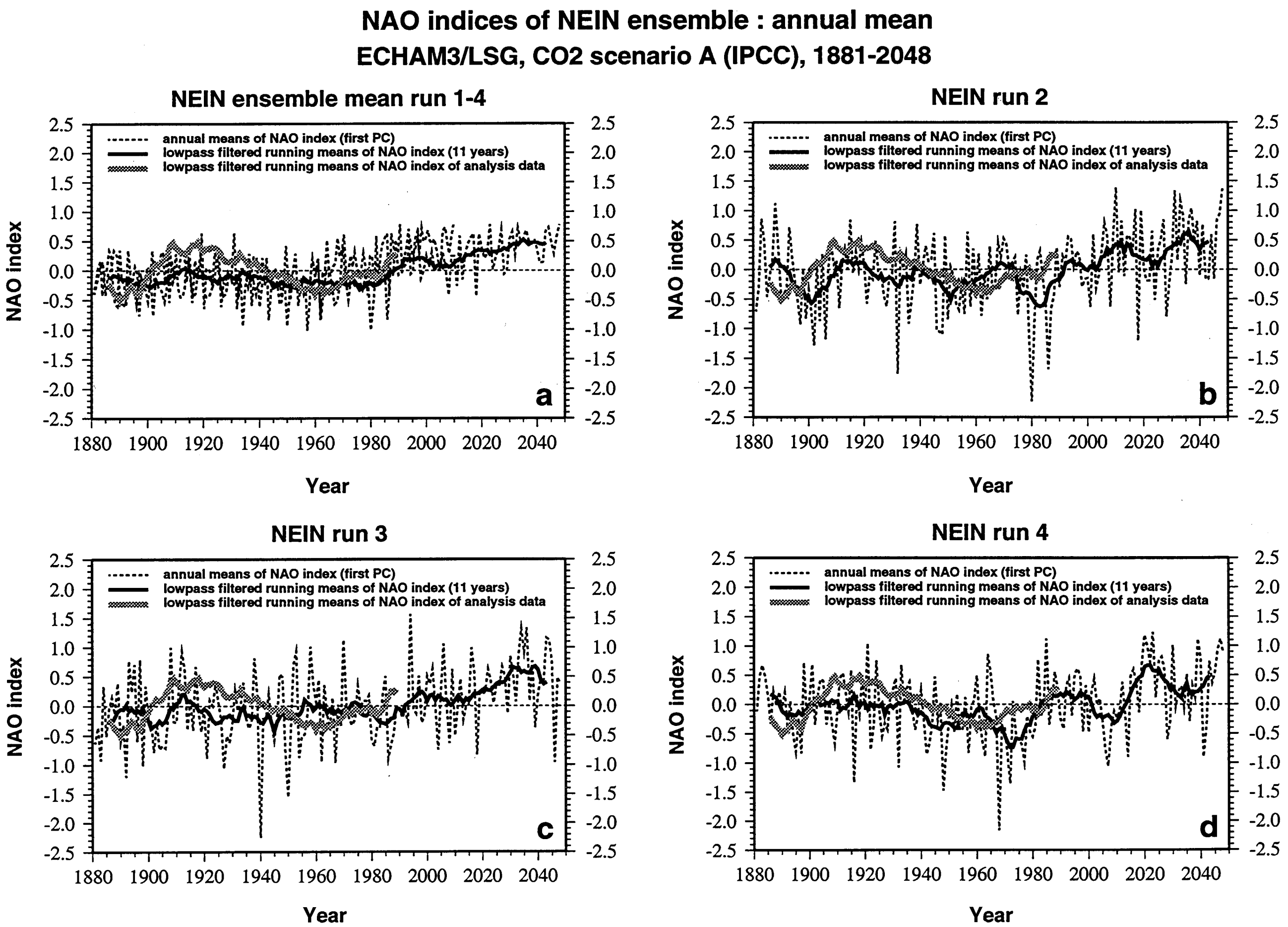

Fig. 3a–d NAO indices of the NEIN ensemble with greenhouse gas scenario A of the IPCC: legend as in Fig. 1. NAO index defined by the first PC of the four time series. The ensemble has been realized by the ECHAM-3/LSG coupled model. Compared with the original NEIN simulation in Fig. 1, the additional runs are based on identical model physics and external forcing parameters (only CO_2) but varying starting conditions derived from three states of the corresponding control run, each 200 y apart. **a** Ensemble mean taking into consideration all 4 scenario runs. **b–d** Additional runs with index number 2–4 according to the chronological order of the control run considered initial states

ECHAM-3/LSG model confirming the existence of a climate signal within the simulated field of sea level pressure. The signal consists of a trend to a positive and continuing phase of the NAO, implicating a typical pattern of temperature anomalies with warming over Eurasia and cooling over North-east America in winter, which proves to be persistent with regard to varying initial conditions as well as different model versions.

3.5 Seasonal response

The seasonal response of the simulated NAO to the NEIN greenhouse is shown in Fig. 5 where the ANOVA is based on 11-y low-pass filtered monthly means of the NAO index. The cold seasons have been centred on because the signal is considered to be clearest there (e.g. Rogers 1997). Indeed, we find the strongest influence in late summer and early autumn (August to November) and winter (December to February) for 60-y periods from 1970 onward reaching values of 40% of explained variance by the external forcing. This seasonal signal is statistically significant with a predominant error level of 5% or less. Surprisingly, the late summer and autumn signal is more striking than the winter one probably due to the pronounced internal variability of the wintertime NAO. As a consequence, the observed and predicted tendency to a zonal NAO state mainly concerns the cold seasons and late summertime implying the advection of humid maritime air masses and, therefore, warm winters in central and northern Europe. On the other hand, in August the positive NAO state should cause lower temperatures over Europe.

3.6 IL and AH attribution

By carrying out the ANOVA for the monthly means of the four time series for latitudinal position and central

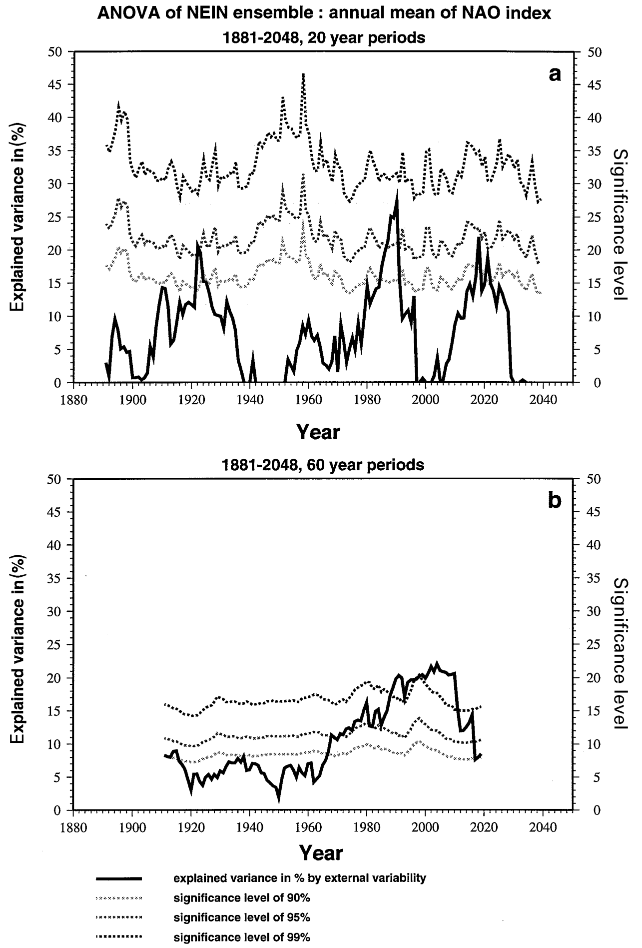

Fig. 4a, b Analysis of variance of the annual means of NAO indices based on the 4 realizations of the NEIN ensemble: explained variance in % by the external forcing parameter (*black solid line*), significance level of 90/95/99% (*dotted lines with grey-scale*). The ANOVA relates the variance of the ensemble mean to the single variances of each ensemble run in order to separate the external forcing from the internal model induced variability. Here, ANOVA refers to **a** 20 y periods and **b** 60 y periods shifted through the whole data set. Therefore, the significance levels also vary. The x-axis' legend corresponds to the middle year of each period

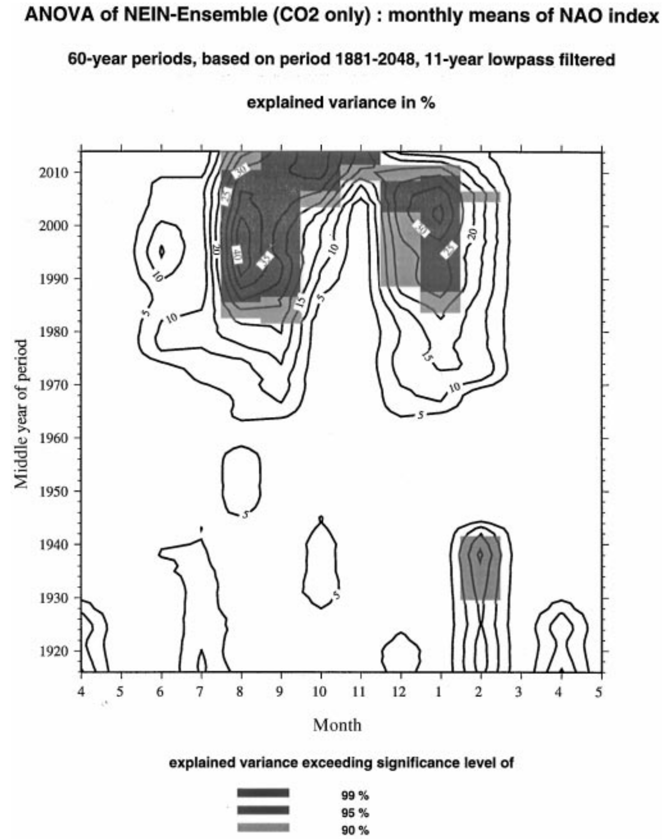

Fig. 5 Analysis of variance of the monthly means of NAO indices based on the four realizations of the NEIN ensemble: explained variance in % by the external forcing parameter (contour lines), significance level of 90/95/99% (*grey-scale background*). Here, we study low-pass filtered NAO time series in the form of 11-y running means. ANOVA refers to 60-y periods shifted through the whole data set. The x-axis' legend describes the months on centring autumn and winter, where the strongest signal is expected. The y-axis' legend corresponds to the middle year of each 60-y period

pressure of IL and AH being the basis of our definition of the NAO index, we are able to judge the importance of these variables in the NAO signal. Generally, the greenhouse gas signal is stronger for the IL time series than it is for the AH ones. Therefore, it is not surprising that the modelled NAO signal is clearly dominated by a northward shifting and a pressure deepening of the Icelandic Low from 1970 onward. On the other hand, AH is subject to a slight northward shift, too, but the pressure is more or less constant during the simulation period. Thus, the change in the simulated North Atlantic Oscillation is basically determined by the IL dynamics.

3.7 NAO variability

Up to now, we have restricted our study to changes in the NAO mean. A further question is whether the variability of the NAO indices shows a time-dependent trend. Therefore, we have estimated probability density functions (PDF) for each decade of the 4 NEIN simulations, each one based on 160 NAO indices derived from the four-winter months November to February. The PDF, describing the relative frequency of classified NAO indices, gives us information about decadal changes in the NAO mean and variation (Wilks 1995). In Fig. 6 the time development of the PDFs is illustrated. The dark colours indicate the approximate position of the mean and the PDFs widths correspond to the variation of the NAO indices within each decade. The time series of the decadal mean and variance reveal a clearly opposite signal: while the NAO mean shows the positive trend described, the variance is subject to a

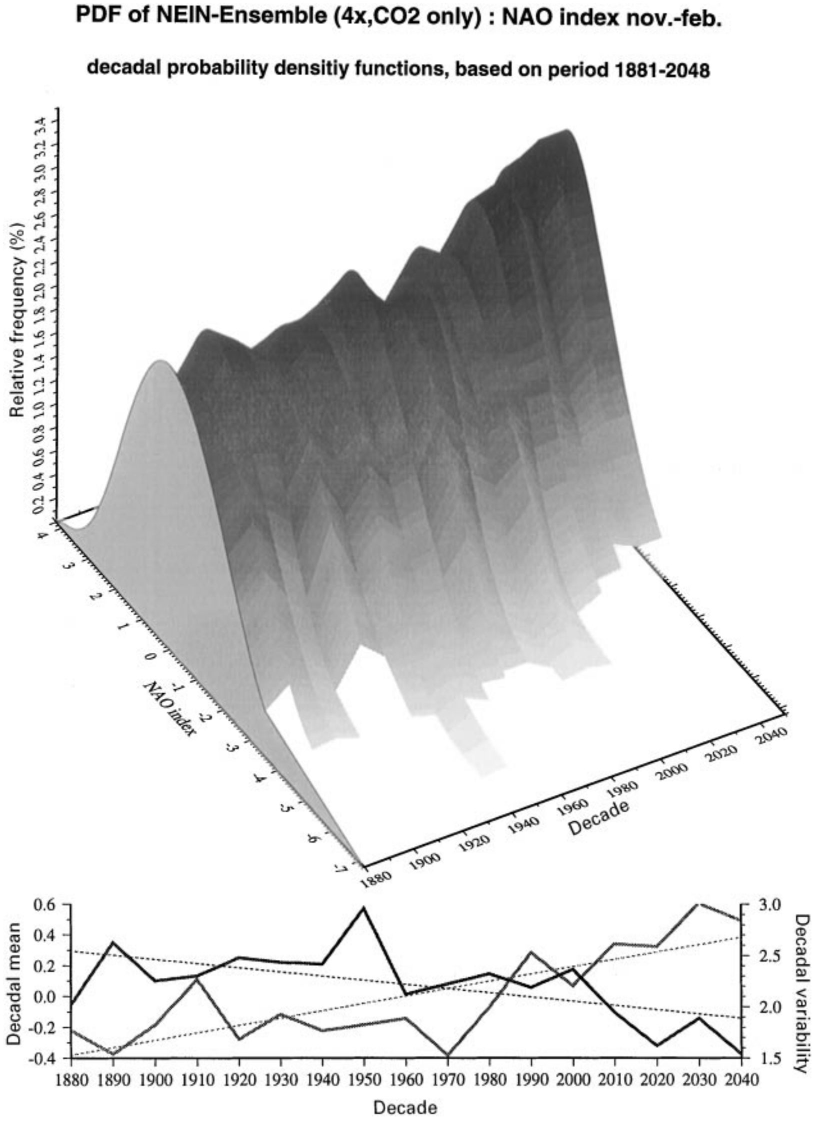

Fig. 6 Decadal probability density functions (*PDF*) of the NEIN ensemble: each PDF (*grey-scale bars*) consists of 160 NAO index realizations including the monthly means of November to February of the 4 NEIN simulations over one decade. The *grey-scale background* indicates the relative frequency of the classified NAO indices based on a kernel function (Matyasovszky 1998). The PDF's width indicates the decadal variability. *At the bottom*, the time series of the decadal mean and variability of each PDF as well as the corresponding linear trends are shown

negative tendency. In other words, the modelled NAO is locked or stabilized in a positive state. One possible explanation for this stabilization is based on the idea that the IL cannot keep shifting northward as much as it can deepen in view of the greenhouse forcing due to constraints imposed by the configuration of the North Atlantic land-ocean-sea ice distribution. In this case, the latitudinal position of IL as one contributor within the first PC representing the NAO index would remain at the northern limits reducing total variability of the NAO phenomenon. Nevertheless, the time series of IL and AH position reveal ongoing trends of northward shifting for both pressure systems until the end of the model integration.

The linear trend of the NAO mean is significant at the 95% level over the whole model period. Concerning the decadal variance, there is no statistical significance for the total time series but only for the decades from 1950 onward. Such a contrasting relationship might be used as a combined fingerprint of greenhouse-gas induced climate change to be detected in the individual observational data sets.

4 Discussion and conclusions

Finally, the most interesting question is whether these results might be transmitted to the real NAO with strong implications for the ongoing discussion of anthropogenic climate change. According to our study the observed state transitions of the real NAO since 1880 are unlikely to be due to the greenhouse forcing. However, the recent positive trend since 1965 might indicate the beginning of the climate signal as it occurs in the scenario A model runs. But in view of the observed strong positive phase at the beginning of the twentieth century, which is most likely based on natural climate variability, the recent 30 y-long trend compared to the multidecadal variability of the NAO has to be considered to be too short to lead to reliable statements.

Statistical evidence whether or not the real NAO is subject to a greenhouse-induced change, might arise in 10 to 30 y, when the NAO signal would really emerge from behind the background noise of natural variability, if it remains in the recent predominantly positive state.

Nevertheless, there is an important methodological implication from our results: since the simulated greenhouse-gas-induced NAO based on the field of sea level pressure reveals a recognizable climate change signal, it seems that pressure data are actually appropriate to detecting climate change although considered to be too noisy up to now.

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