

The intensification and shift of the annual North Atlantic Oscillation in a global warming scenario simulation

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ABSTRACT

The impact of global warming on the annual North Atlantic Oscillation (NAO) is investigated with a global warming scenario simulation of the ECHAM4/OPYC3 coupled general circulation model. It is shown that the annual meridional pressure gradient over the North Atlantic is significantly strengthened, and the two centers of action of the NAO, the Icelandic low and the Azores high, are intensified and shifted northeastward by 10° to 20° in latitude and 30° to 40° in longitude in the global warming scenario. The shift of the centers of action leads to a failure in capturing the NAO change with the traditional definition of the NAO index. A modified index is introduced that allows for this shift, and exhibits a tendency toward the positive phase and an enhancement of its intensity. The intensification of Icelandic low is tied up with zonal mean state change, and the strengthened Azores high is related to the stationary wave change. The shift of the centers of action of the NAO is associated with the stationary wave change.

1. Introduction

The North Atlantic Oscillation (NAO) is the primary mode of the atmospheric variability over the North Atlantic basin and ties closely to the changes in the surface westerlies across the North Atlantic into Europe. It is usually defined as the surface pressure gradient between the Azores high and Icelandic low, and the main characteristics of the NAO in winter include a robust spatial pattern and strong temporal stochastic variation (Hurrell, 1995; Wunsch, 1999; Christoph et al., 2000; Stephenson et al., 2000; Marshall et al., 2001). NAO variability is related to the interaction between high-frequency eddies and low-frequency waves (Lau and Nath, 1991; DeWeaver and Nigam, 2000; Kimoto et al., 2001), to the coupling among atmosphere, ocean, and land (snow cover) systems (Rodwell et al., 1999; IPCC 2001; Marshall et al., 2001; Bojariu and Gimeno, 2003), and to the interplay of the troposphere and the stratosphere (Kodera et al., 1999; Baldwin and Dunkerton, 1999, 2001).

The winter NAO has had a persistent positive phase and a spatial pattern shift since the mid-1970s (Hurrell 1996; Hilmer and Jung, 2000), which corresponds to milder and wetter winters in northern Europe. Meanwhile, over the 20th century, the global-averaged surface temperature has increased by 0.4–0.8°C, and

most of the observed warming over the last 50 yr is likely to be related to the increase in greenhouse gas concentrations (IPCC 2001). This raises the question whether global warming is responsible for the upward trend and the spatial pattern shift of the winter NAO in observations (Osborn et al., 1999).

There is still no consensus, although many studies have been conducted on the topic. Hurrell (1996) revealed the strong relationship between atmospheric general circulation change and surface temperature anomalies. The circulation changes over the past decades result in a surface temperature anomaly pattern of warming over the continents and cooling over the extratropical oceans. There are also some modeling studies to explore the possible causes of the observed low-frequency variations of the NAO. Rodwell et al. (1999) and Latif et al. (2000) have shown that much of the interannual and multidecadal variabilities of the winter NAO over the second half of last century can be reconstructed from the knowledge of sea surface temperature (SST). Hoerling et al. (2001) explored the role of the tropical oceans in the wintertime NAO trends over the past several decades, and indicated that the low-frequency NAO variation contains a response of North Atlantic climate to changes in the surface boundary (SST). Schneider et al., 2003 demonstrated that observed climate trend in the past half century in the Northern Hemisphere (NH) is indeed dominated by the forced signal in the Pacific and North American sector. However, over the rest of the NH, and especially the North Atlantic sector, the climate

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trend could be primarily interdecadal time-scale internal atmospheric noise with an annular structure. Osborn et al. (1999) found, by analyzing two ensembles, each of four Hadley Center for Climate Prediction and Research (HadCM2) integrations that were forced with historic and possible future changes in greenhouse gas and sulfate aerosol concentrations, that a small part of the recent observed winter variation may be a result of anthropogenic forcing. Even combining this anthropogenic forcing and internal variability cannot explain all of the recent observed variations, indicating either some model deficiency or that some other external forcing is partly responsible (Osborn et al., 1999). The lack of a convergent view on explaining the observed NAO change is likely to affect understanding of the projected future change of the NAO in the global warming scenario.

Model simulations with increasing greenhouse gas concentrations give various projections of the NAO. The simulations of the Canadian Center for Modelling and Analysis and the Goddard Space Flight Center coupled general circulation models (CGCMs) indicate that the Arctic Oscillation (AO) exhibits a positive trend in the global warming scenario (Fyfe et al., 1999; Shindell et al., 1999). However, the NAO index in the simulations of the Max-Planck-Institute for Meteorology (ECHAM4/OPYC3) CGCM showed only a moderate increase within a 240-yr scenario run, and its long-term trend exceeded the variability of the control climate in the period near the end of the simulation (Ulbrich and Christoph, 1999). In contrast, the steadily growing storm track activity over northwestern Europe is much more apparent. Ulbrich and Christoph (1999) found that the disagreement between the NAO index change and the storm track intensification results from the northeastward shift of the northern center of action of the NAO. By examining the same scenario run, Hu et al. (2001) also found that there is no significant change of the NAO index. Zorita and González-Rouco (2000) demonstrated the disagreement of the simulated long-term trends of the AO intensity between the HadCM2 and ECHAM4/OPYC CGCMs, although the simulated winter temperature increases averaged over the NH in the two models are very similar. The HadCM2 experiments indicate that the anthropogenic effect should reverse early next century, weakening the winter pressure gradient between Gibraltar and Iceland (Osborn et al., 1999).

From this discussion we see that simulated future NAO changes and the relationship between the NAO and global warming are model-dependent and remain unclear (Gillett et al., 2003). Further analysis will help us to understand the NAO change in the global warming scenario. Using the same scenario simulation of the ECHAM4/OPYC3 CGCM used by Ulbrich and Christoph (1999), Zorita and González-Rouco (2000), and Hu et al., (2001), we further examine the impact of increasing greenhouse gas concentrations on the temporal and spatial change of the NAO, including the possible changes of the NAO intensity and frequency, and the location shift of the two centers of action of the NAO. In Section 2, the model, data, and methods are

briefly described. In Section 3 we present detailed analyses of the NAO change in the model simulation. Section 4 contains a summary and further discussions of the results.

2. Model, data, and methods

2.1. Model and data

The model data come from a 240-yr integration of global coupled atmosphere–ocean–sea-ice–land surface climate model under the transient greenhouse gas warming scenario. The model is the ECHAM4/OPYC3 CGCM, which is described in (and references therein Roeckner et al., 1996 and references therein), Oberhuber (1993a, b), and Bengtsson (1996). In the simulation, the annual concentrations of the greenhouse gases are specified as observed from 1860 to 1990, and prescribed based on the Intergovernmental Panel on Climate Change (IPCC) scenario IS92a (IPCC, 1992) after 1990. The integration starts at January 1860 and ends at December 2099. More details on the simulation can be found in Roeckner et al. (1999).

All months of the years are analyzed here, thus, this study is not focused on any individual season. The data used in this study include mean surface temperature (TS), and mean sea level pressure (SLP). Our focus is on the differences between the climate in 1860–1959 and the simulated future climate in the periods with significant warming (represented by 2000–2049 and 2050–2099) in the model. To compare the spatial patterns of teleconnections in the simulations and in observations, we also use the monthly mean SLP of the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data from January 1948 to December 2000 (Kalnay et al., 1996).

The data sets of model simulations have been analyzed extensively to determine the simulation of various phenomena. Bengtsson (1996) compared the low-frequency variability, feedback processes, energy cycle, and hydrological cycle of this long-term integration with the corresponding control run of fixed present greenhouse gas concentrations. Ulbrich and Christoph (1999) found that the shift of the northern active center of the NAO and the intensification of storm track activity over Europe resulted from the increase of greenhouse gas concentrations. Hu et al. (2001) examined the impact of the global warming on the trend, the standard deviation, and climate modes of geopotential height at 500 hPa in winter. Christoph et al. (2000) analyzed the control run and indicated that the model produces a realistic spatial pattern and temporal evolution of the NAO. These studies demonstrate that the ECHAM4/OPYC3 CGCM simulates the present climate and its variability reasonably well, and may serve as a useful tool to look into future climate change.

2.2. Methods

By using linear low-pass filters, the simulated NAO index is divided into four parts with different time-scales: trend (≥ 50 yr),

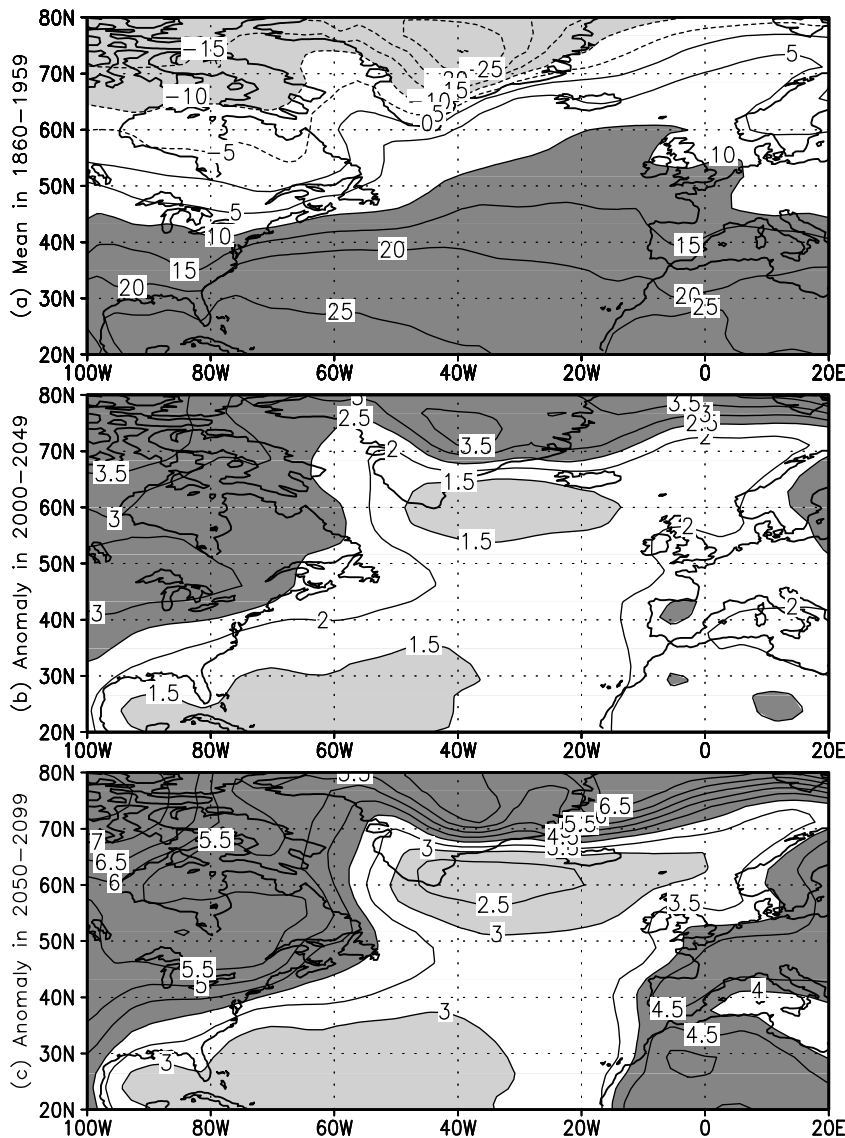


Fig. 1. ECHAM4/OPYC3 CGCM simulated TS mean and anomaly composite over the North Atlantic region: (a) the mean of January 1860 to December 1959; (b) and (c) the anomalies in January 2000 to December 2049 and January 2050 to December 2099, respectively. The reference period of (b) and (c) is January 1860 to December 1959. The contour interval is 5 °C in (a), and 0.5 °C in (b) and (c). The dark (light) shaded regions are for values greater than 10 °C (less than -10 °C) in (a), 2.5 °C (less than 1.5 °C) in (b), and 4 °C (less than 3 °C) in (c).

interdecadal (10–50 yr), interannual (1–10 yr), and intermonthly (1–12 month) variations. The present calculation is not sensitive to the specified filter method, which is evident from the comparison of the results with those obtained using a nonlinear, non-stationary time series filter based on the Empirical Mode Decomposition (Huang et al., 1998; Wu et al., 2001). The boundary effect of the linear filter is largely eliminated by extending the data at the ends. Details about the linear filters can be found in Press et al. (1989). In addition, composite and linear regression methods are also used.

3. NAO-like change in the global warming scenario

Under the global warming scenario, the ECHAM4/OPYC3 CGCM simulates significant warming trends in the whole NH.

Warming is more intensive over land than over oceans, and in high latitudes than in low latitudes (figure not shown). The averaged surface temperature in 2000–2049 increases by 3–4 °C over lands and 1–2 °C over oceans with respect to the mean of 1860–1959. The temperature increase in the second half of the 21st century almost doubles that of the first half. If the temperature changes are expressed as deviations from the zonal means, the contrast of the warming between lands and oceans shows a pattern which agrees with the so-called the Cold Ocean–Warm Land (COWL) pattern (Wallace et al., 1995; Broccoli et al., 1998). Figure 1 presents the corresponding mean TS (the average of monthly TS from January 1860 to December 1959) and TS anomaly composites (the averaged departure of a period from the mean) for the North Atlantic region. The warming is weaker over the North Atlantic and subtropical Atlantic regions than that in the surrounding regions (Figs. 1b and c).

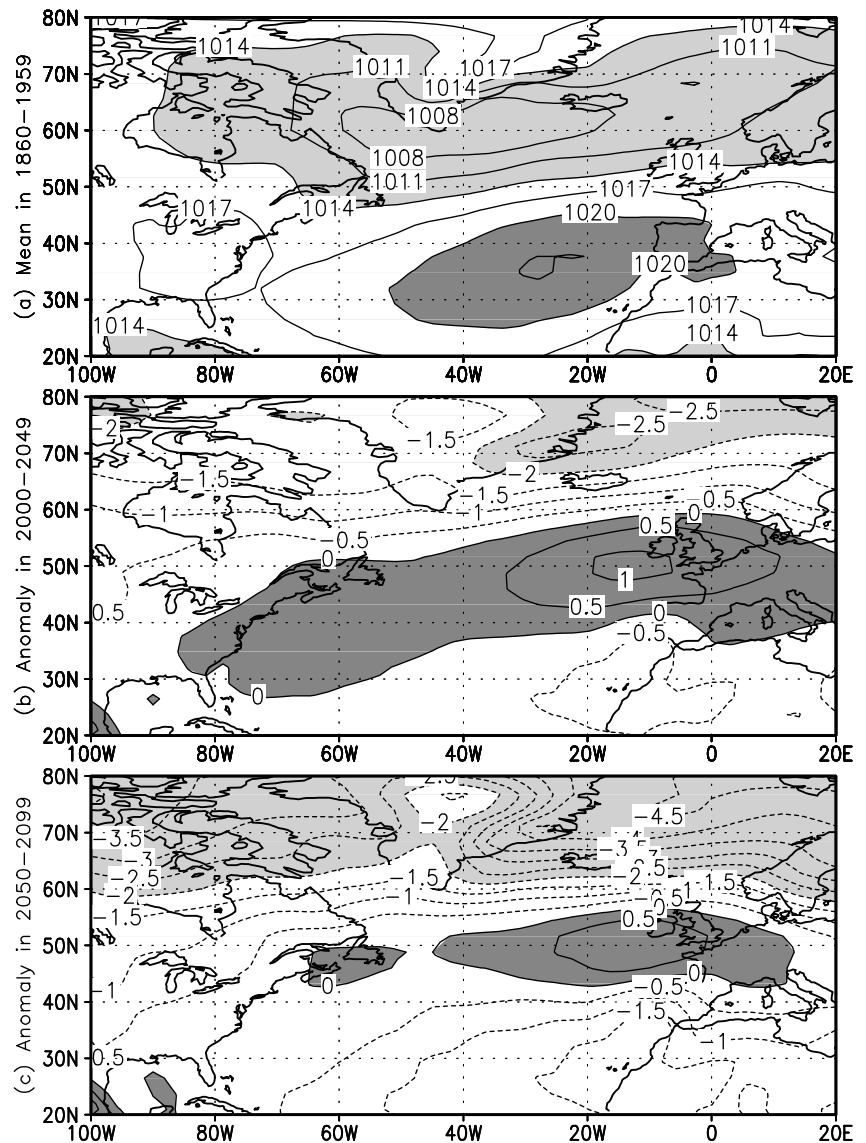


Fig. 2. Same as Fig. 1, but for SLP mean and anomaly composites. The contour intervals are 3 hPa in (a), and 0.5 hPa in (b) and (c). The dark (light) shaded regions are for values greater than 1020 hPa (less than 1014 hPa) in (a), and 0.0 hPa (less than -2.0 hPa) in (b) and (c).

The mean SLP of the present climate is well simulated by the model in the NH (figure not shown) and over the North Atlantic (Fig. 2a). Compared with the climate mean SLP over the North Atlantic (Fig. 2a), the SLP falls significantly in high latitude and subtropical regions, including the polar region, southern Spain, and northern Africa, and rises in middle latitudes in the global warming scenario. Intensification of the Icelandic low and the Azores high, and increase of the meridional SLP gradients over the North Atlantic region occur with the increases of greenhouse gas concentrations (Figs. 2b and c). In addition to the intensification, there is also a northeastward shift of the centers of the Azores high and the Icelandic low.

The above results seem not to be consistent with what may be inferred from the analysis of the traditional NAO index (Fig. 3) and its occurrence frequency distribution (Fig. 4). The occur-

rence frequency distribution measures the influence of the increases of greenhouse gas concentrations on the relationship between the amplitude and occurrence frequency of the NAO index in different periods of the model integration. From the NAO index time series and its time-scale decomposition (Fig. 3), it is seen that the high-frequency (monthly and interannual) components (Figs. 3b and c) are dominant, although there are some low-frequency variations (Figs. 3d and e). This supports the hypothesis that the NAO is similar to a white-noise process in the model, as indicated by Christoph et al. (2000). However, observational studies have shown that the winter NAO can be characterized as having a weakly red spectrum with some long-range dependence (Stephenson et al., 2000; Stephenson and Pavan, 2003). Figures 3 and 4 also show no significant differences of NAO behavior between the first and second halves of the model

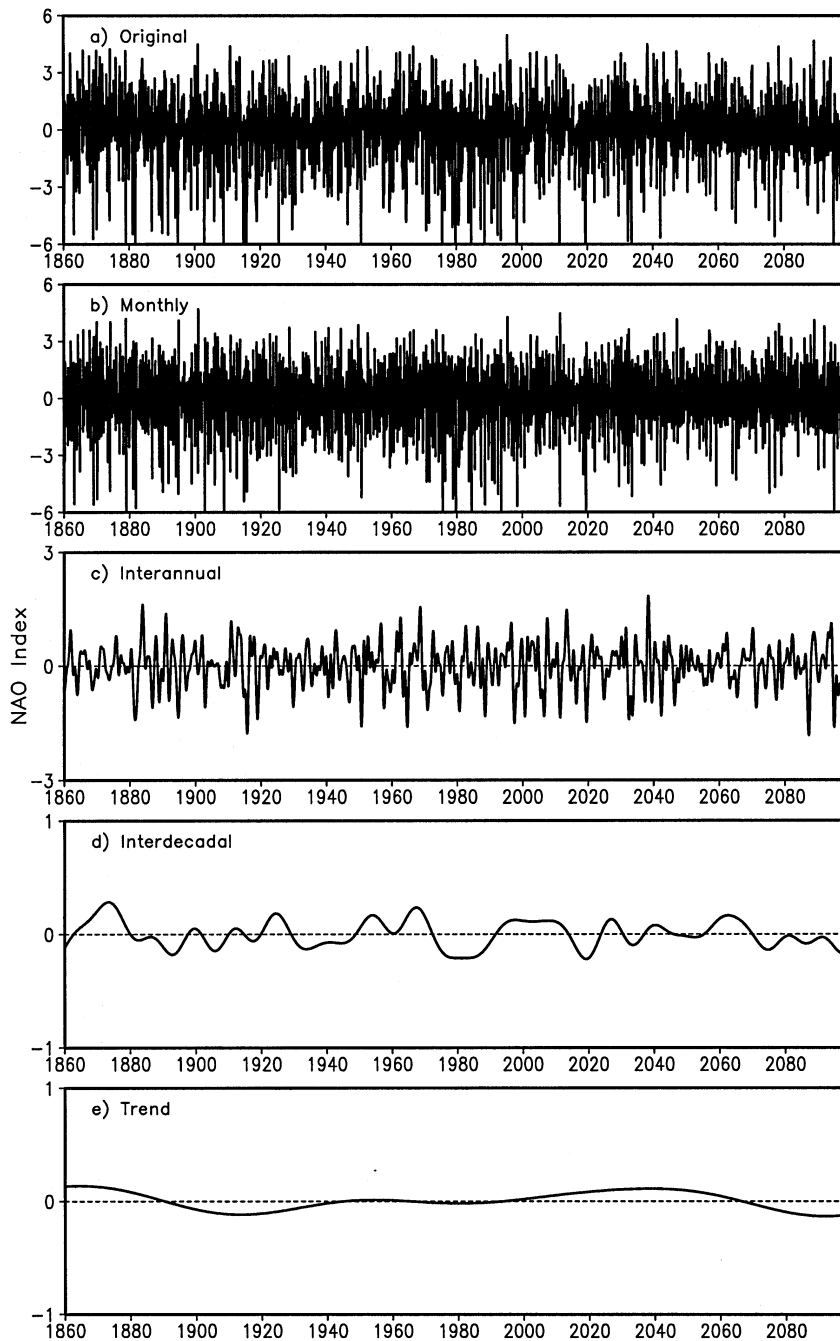


Fig. 3. Time-scale decomposition of monthly NAO index from January 1860 to December 2009: (a) original time series; (b) intermonthly (1–12 month); (c) interannual (1–10 yr); (d) interdecadal (10–50 yr); (e) trend (> 50 yr) components. The NAO index is defined as the difference of normalized SLP between two grid points which are the nearest to Lisbon (38.8°N , 9.1°W) and Stykkisholmur (65.1°N , 22.7°W), respectively. The climate from January 1860 to December 1959 is used as reference.

integration, which is consistent with previous results (Ulbrich and Christoph, 1999; Hu et al., 2001).

Disagreement between Figs. 2, 3 and 4 in terms of the inferred influence of global warming on the NAO is due to fixed reference locations used to define the traditional NAO index of Fig. 3. These two reference locations do not reflect the shift of the centers of the action of the NAO in the global warming scenario. According to the definition of Wallace and Gutzler (1981), the teleconnectivity is calculated and shown in Fig. 5. The tele-

connectivity is defined as the absolute values of the strongest negative correlation obtained from the respective one-point correlation maps. Comparing with the teleconnectivity map calculated from the NCEP/NCAR reanalysis data in January 1948 to December 2000 (Fig. 6), it is clear that the model (Fig. 5a) simulates a reasonable teleconnection pattern over the North Atlantic region during the period of January 1860 to December 1959, although the locations of the centers of action relative to the base period are displaced westward by about 10° . The shift of the

Fig. 4. Frequency distributions of the model simulated NAO index in Fig. 3. The bars represent the frequency distribution of the NAO index for January 1980 to December 2099, and the line is that for January 1860 to December 1979.

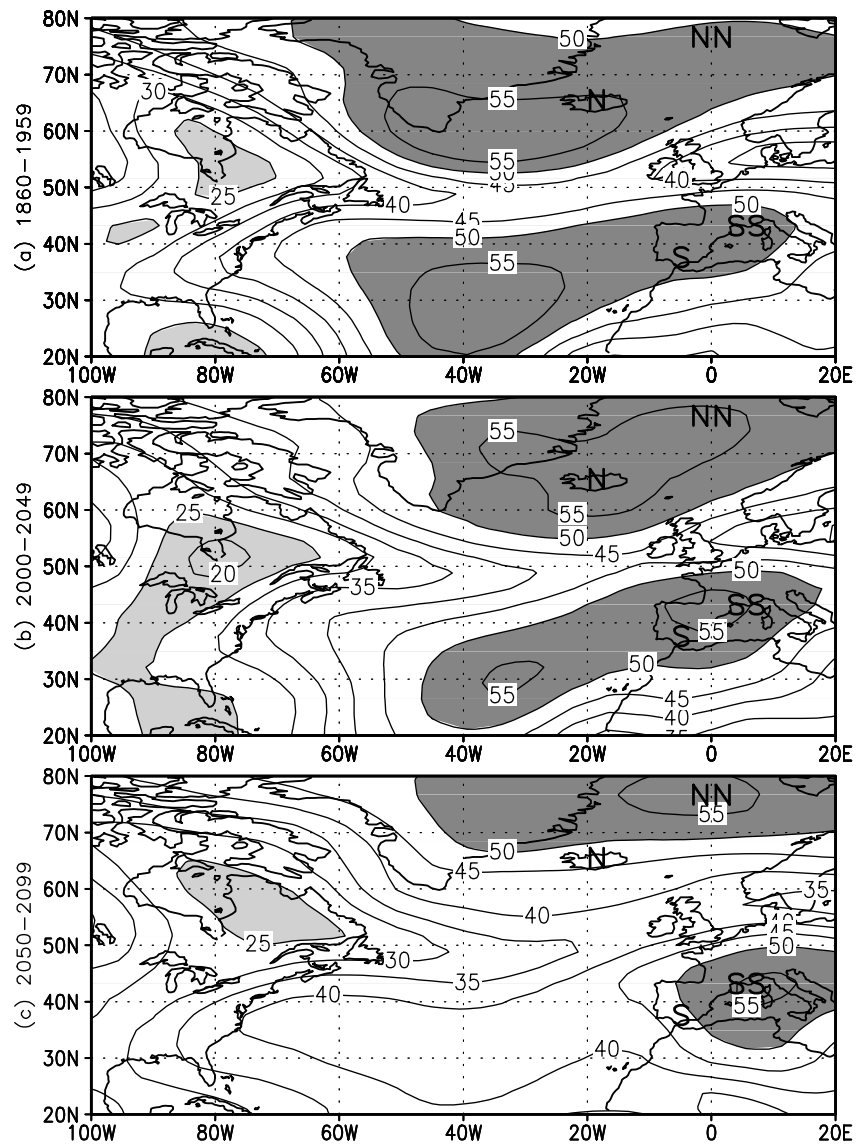
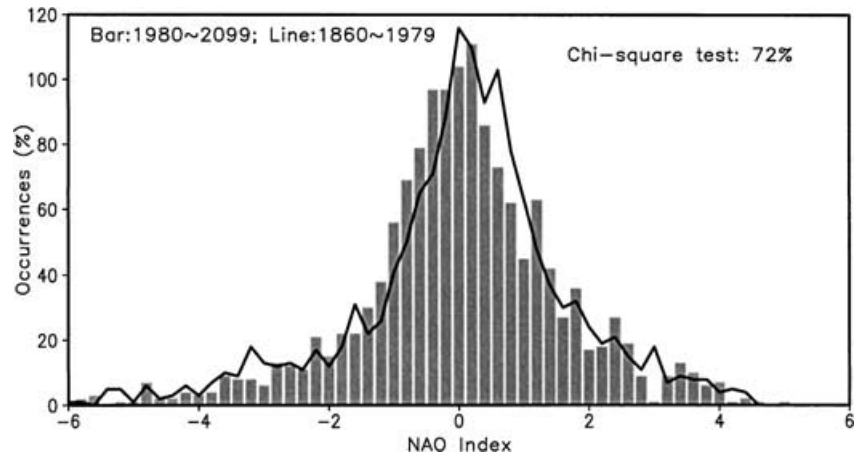


Fig. 5. Teleconnectivity of SLP for (a) January 1860 to December 1959, (b) January 2000 to December 2049, and (c) January 2050 to December 2099. The values are multiplied by 100. The contour interval is 5. The dark (light) shaded regions are for values greater than 50 (less than 25). The grid points marked with *S* and *N* are used in the NAO index definition in Fig. 3, and with *SS* and *NN* in Fig. 8.

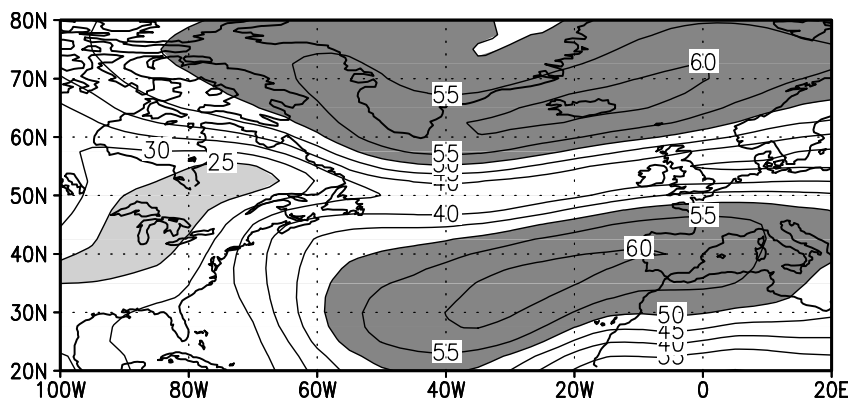


Fig. 6. Same as Fig. 5, but for the NCEP/NCAR reanalysis monthly mean SLP for January 1948 to December 2000.

centers of action is clearly found in the January 2000 to December 2049 map (Fig. 5b), and in the January 2050 to December 2099 map (Fig. 5c). It should be noted that there are SLP trends in the simulation. The shift may include two parts: the interannual variability change and the mean state change.

We now show that there is a change in the location of the NAO pattern consistent with that in the time mean circulation. To do so, we calculate 10-yr running teleconnectivity maps of the monthly SLP with a 50-yr window (Fig. 7). The years shown in Fig. 7 represent the mid-point of the samples in the teleconnectivity calculations. The locations of the northern (the Icelandic low) and southern (Azores high) centers of action of the NAO are defined by the maximum values of the teleconnectivity in the regions (51°N – 90°N , 50°W – 10°E), and (10°N – 49°N , 50°W – 10°E), respectively. For the Icelandic low, the center is shifted by 10° to 20° in latitude and 30° to 40° in longitude. The shift for the Azores high is also obvious with comparable amplitudes of the shift of the Icelandic low. This is consistent with the analysis of Fig. 2. Thus, it is indicated that the whole system of the NAO, including its northern and southern centers, is shifted northeastward in the global warming scenario. The NAO system shift and intensification are accompanied by a consistent change of storm track (Ulbrich and Christoph, 1999).

There are some similarities in the spatial pattern shift between the simulation (Figs. 5 and 7) and the observed winter NAO-related anomalous SLP for the periods 1978–1997 and 1958–1977 (fig. 4d in Hilmer and Jung, 2000). Hilmer and Jung (2000) indicated an interdecadal eastward shift of the centers of action of the winter NAO from 1958–1977 to 1978–1997. Meanwhile, Rogers (1997) found an association of increasing baroclinic wave activity over the Northeast Atlantic and Europe and a northeastward shift of the subpolar low and the subtropical high in observation data in the winter of 1900–92. Rogers (1997) also noted that increased winter wave activity is accompanied by an increase of the mean pressure gradient between the centers in winter. The similarity in the spatial pattern shift between the observation and the simulation implies that global warming may be one of the reasons causing the observed interdecadal shift of the NAO-related SLP pattern in winter.

The eastward displacement of the Icelandic low in winter has been noted by Ulbrich and Christoph (1999). However, the shift of the Azores high in the time mean field shown in Figs. 2 and 5 did not appear in the first mode of the empirical orthogonal function (EOF) analysis (see fig. 9 in Ulbrich and Christoph, 1999). The difference between the time mean and the EOF analysis about the shift of the Azores high may be a result of the limitation of the EOF method as pointed out by Dommenget and Latif (2002). Another possibility is that the shift might exist in a higher EOF mode. The difference related to the shift of the Azores high may be caused by analyzing different pieces of the same data set. We analyzed monthly data, while Ulbrich and Christoph (1999) used only winter data.

From Figs. 5 and 7, we also note that the largest value of the teleconnectivity do not coincide with the reference locations used in the traditional NAO index definition, even in the period of January 1860 to December 1959 of the model simulation (Fig. 5a). Therefore, it seems reasonable to redefine the NAO index. Based on the teleconnectivity in Figs. 5 and 7 and the SLP anomaly pattern in Fig. 2, we define a modified NAO index as the difference of normalized SLP between the point at (43°N , 6°E) and the point at (77°N , 0°). The time series of the modified NAO index and its time-scale decomposition are shown in Fig. 8 and the occurrence frequency distribution is given in Fig. 9. Figures 8e and 9 demonstrate the frequency distribution shift of the modified NAO index in the global warming scenario. Climate warming induced by human activities causes the positive phase of the modified NAO to become more likely. The shifts of the NAO phase and the NAO centers of action, and the enhancement of its intensity in the global warming scenario will alter the mean wind speed and direction, heat and moisture transport, as well as the intensity and number of storms, their paths, and the weather associated with them over the North Atlantic and the surrounding continents (Knippertz et al., 2000).

4. Summary and discussion

The model simulation produces a significantly strengthened annual-mean meridional pressure gradient over the North

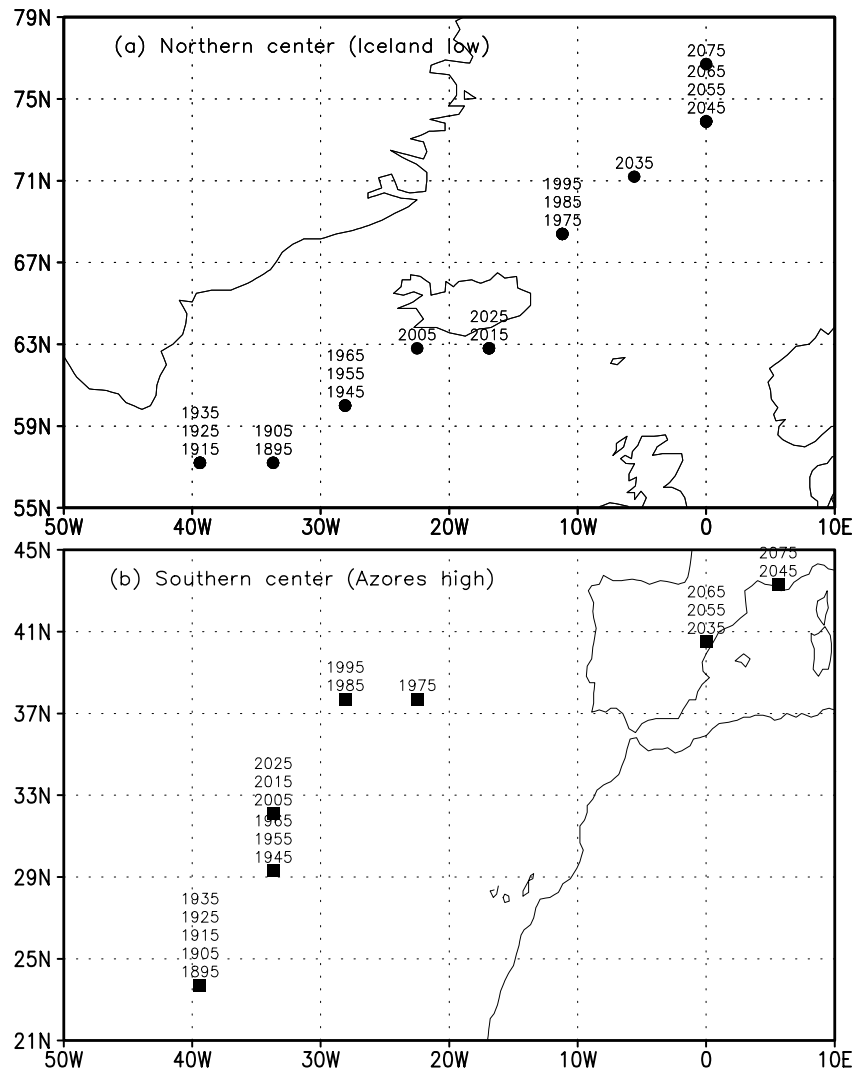


Fig. 7. Shift of the locations of the (a) northern and (b) southern centers of action of the NAO. See the text for details of the calculations.

Atlantic associated with projected global warming, and the two centers of action of the NAO, the Icelandic low and the Azores high, are intensified and shifted northeastward by 10° to 20° in latitude and 30° to 40° in longitude in the global warming scenario. The shift of the centers of action leads to a failure in capturing the NAO change with the traditional definition of the NAO index. A modified index is introduced that allows for this shift, and exhibits a tendency toward the positive phase and an enhancement of its intensity.

Both zonal mean state and stationary wave, which is defined as the departure of SLP from its zonal mean averaged in all longitudes, contribute to the NAO-like change. The stationary wave change (Figs. 10b and c) is similar to the corresponding composites for the raw SLP data (Figs. 2b and c). The positive anomalies in the region around Britain and in the northeastern part of North American continent, and negative anomalies over the north part of the North Atlantic are associated with the north-

eastward shift of the centers of action of the NAO. Thus, the shift of the centers of action of the NAO is mainly associated with the stationary wave change. From Fig. 11, it is also found that there is a remarkable change of the zonal mean SLP in high latitudes in the global warming scenario, which is related with the intensification of the Icelandic low. These results suggest that the intensification of the Icelandic low is tied up with zonal mean state change, and the strengthened Azores high is related to the stationary wave change.

There is no consensus explanation for the observed upward trend of the NAO in the recent decades and the projected NAO phase and spatial pattern shifts in the global warming simulation. However, there are a few candidate mechanisms to interpret the low-frequency variations of the NAO.

One of the main candidate mechanisms is extratropical response to tropical SST. For instance, Hoerling et al. (2001) indicated that North Atlantic climate change in winter since 1950

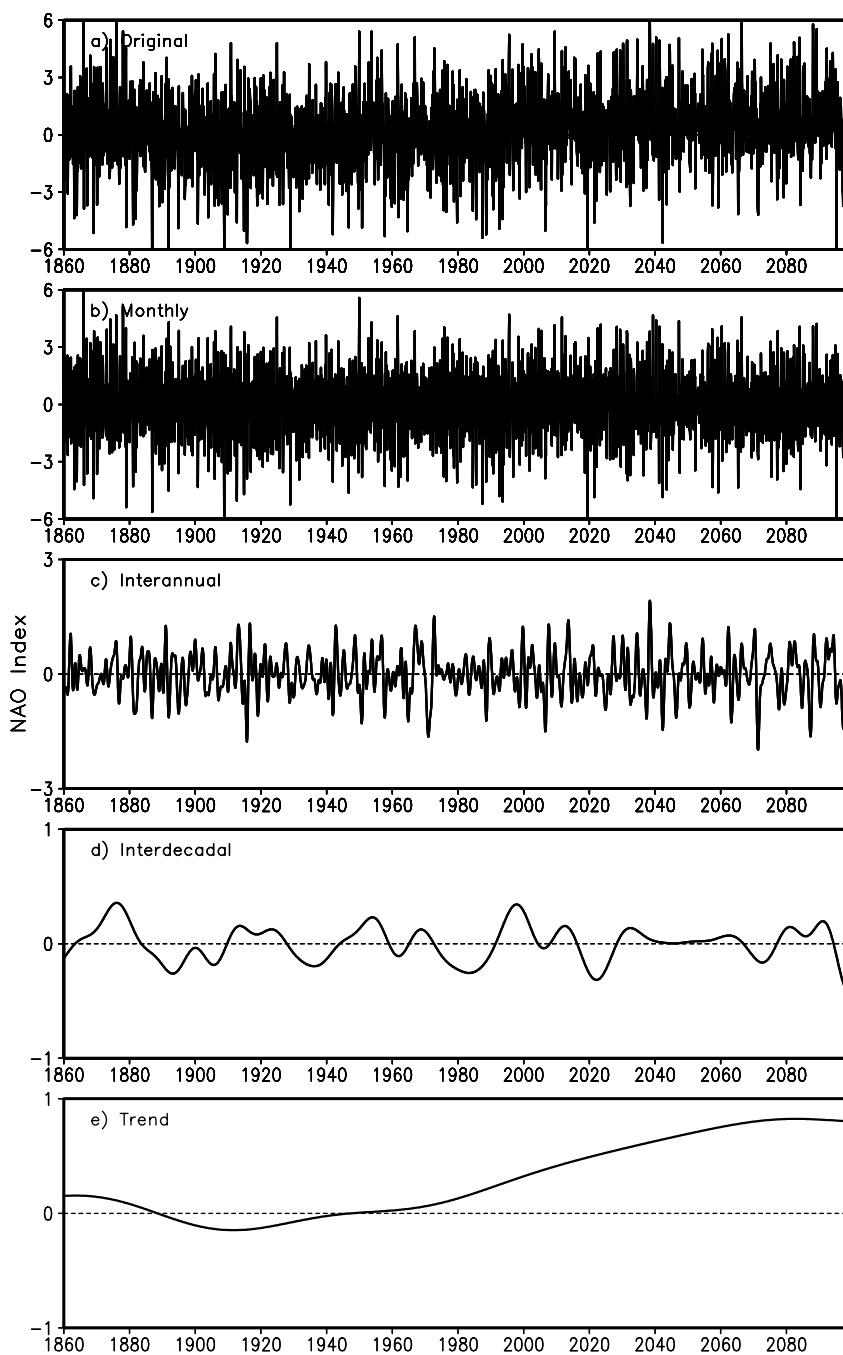


Fig. 8. Same as Fig. 3, but for the modified monthly mean NAO index, which is defined as the difference of normalized SLP between (43°N , 6°E) and (77°N , 0°).

is linked to a progressive warming of tropical SST, especially over the Indian and Pacific Oceans. The tropical SST changes have forced a trend toward one extreme phase of the NAO during the past half-century by altering the pattern and magnitude of tropical rainfall and atmospheric heating. The upward trend of the NAO-like variation in the global warming scenario is indeed accompanied by the tropical ocean warming (Fig. 12), although of course the ocean is warming in mid-latitudes also. However, their results do not agree with Schneider et al. (2003), who found

that the climate trend pattern in the North Atlantic sector is primarily interdecadal time-scale internal atmospheric noise with an annular structure.

Another possible mechanism involves stratospheric climate change. Some investigations emphasize the impact of the stratospheric circulation on NAO-like variation. With observational data in winter and composite analyses, Baldwin and Dunkerton (1999); Baldwin and Dunkerton (2001) have shown that the Arctic Oscillation related anomalies typically first appear

Fig. 9. Same as Fig. 4, but for the modified monthly mean NAO index. The difference between the two frequency distributions is significant at the level of 99.9% using a χ^2 test.

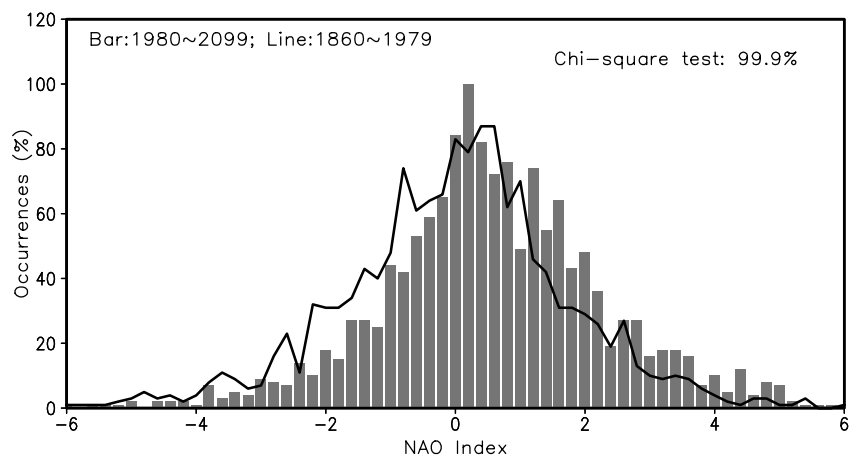
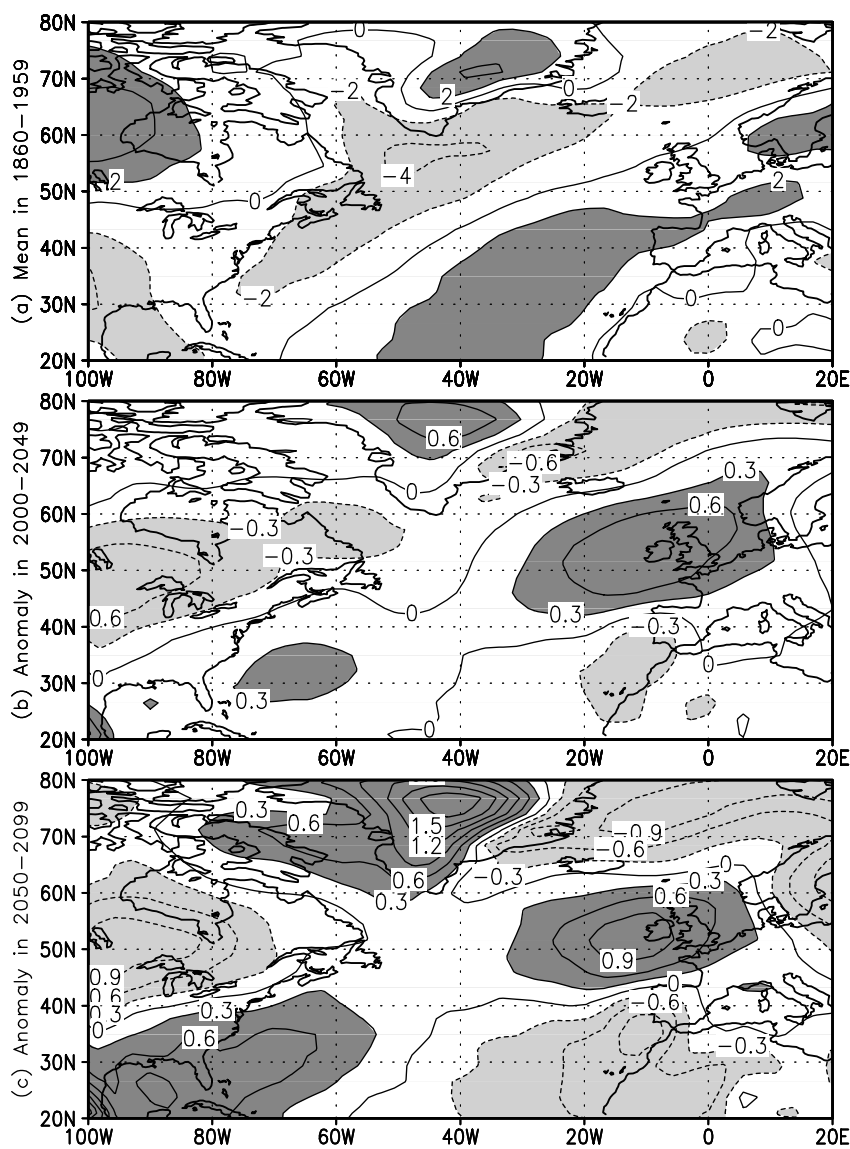


Fig. 10. Same as Fig. 1, but for deviations from zonal mean averaged in 100°W–20°E. The contour intervals are 2 hPa in (a), and 0.3 hPa in (b) and (c). The dark (light) shaded regions are for values greater than 2 hPa (less than -2 hPa) in (a), and 0.3 hPa (less than -0.3 hPa) in (b) and (c).



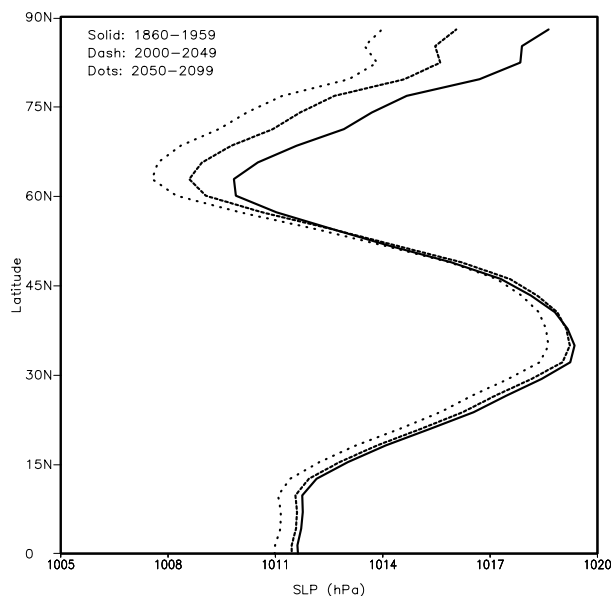


Fig. 11. Zonal mean SLP averaged in 100°W – 20°E over (a) January 1860 to December 1959 (solid line), (b) January 2000 to December 2049 (dashed line), and (c) January 2050 to December 2099 (dotted line).

in the stratosphere and propagate downward. Strong anomalies above the tropopause appear to favor tropospheric anomalies of the same sign. Over the Atlantic sector, the storm tracks are displaced significantly farther north (south) during strong (weak) stratospheric vortex regimes. Baldwin and Dunkerton (2001) pointed out the possibility of using the intensity of the stratospheric vortex as a harbinger of climate change over the Atlantic Ocean. Using data from the same experiment used in the present work, Hu (2001) analyzed the polar vortex change in the lower stratosphere in the global warming scenario. By examining the linear trend of temperature and zonal velocity component at 50 hPa in winter for 1990–2099, he found a significant enhancement of the polar vortex in the global warming scenario (Fig. 13),

which might be associated with the northward shift and intensification of the NAO. However, due to the poor quality of the stratosphere data in observations and simulations, the physical interpretation for the connection between the NAO and stratospheric vortex needs to be verified, and further evidence for the connection is also needed.

In the global warming scenario, the tropical oceans become warm and the stratospheric polar vortex is intensified. These changes favor the positive phase of the NAO and enhancement of its intensity, and northward shift of the centers of action. In addition, the spatially heterogeneous distribution of local warming (Fig. 1) in the ocean and land might play a role in the NAO change.

Some studies indicated that the centers of the NAO show a strong seasonality in both their locations and intensities in observations (e.g. Portis et al., 2001). However, results displayed in this study are not sensitive to season, and both the winter-only and summer-only composites show the intensification and shift of the NAO (figures not shown). At this time, coupled models are associated with a large uncertainty in projecting future regional climate change, particularly when using one realization instead of multimodel and multiscenario ensemble. For instance, Campbell et al. (1995) detected a western shift of the Azores high, Liang et al. (1996) showed a general weakening of the NAO, Huth (1997) revealed a southward shift of the winter pattern of the NAO, and Paeth et al. (1999) suggested a significant influence of the increase of CO_2 concentrations on the simulated NAO variability on time-scales of 60 yr and longer. Therefore, further investigation using simulations with different models and scenarios is necessary for reducing the uncertainty of projected climate change in the North Atlantic.

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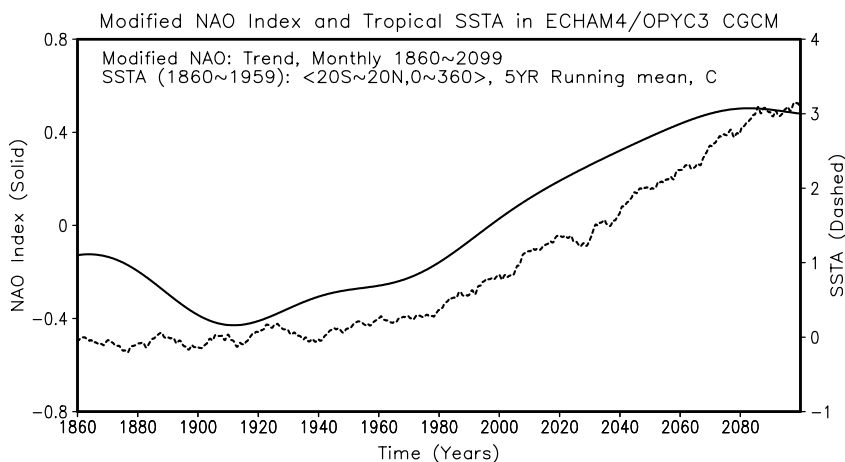


Fig. 12. The trend of the NAO index (solid line, adopted from Fig. 8e) and tropical SST anomaly averaged in 20°S – 20°N , 0° – 360° . For the SST anomaly, the reference period is January 1860 to December 1959, and a 5-yr running mean is used.

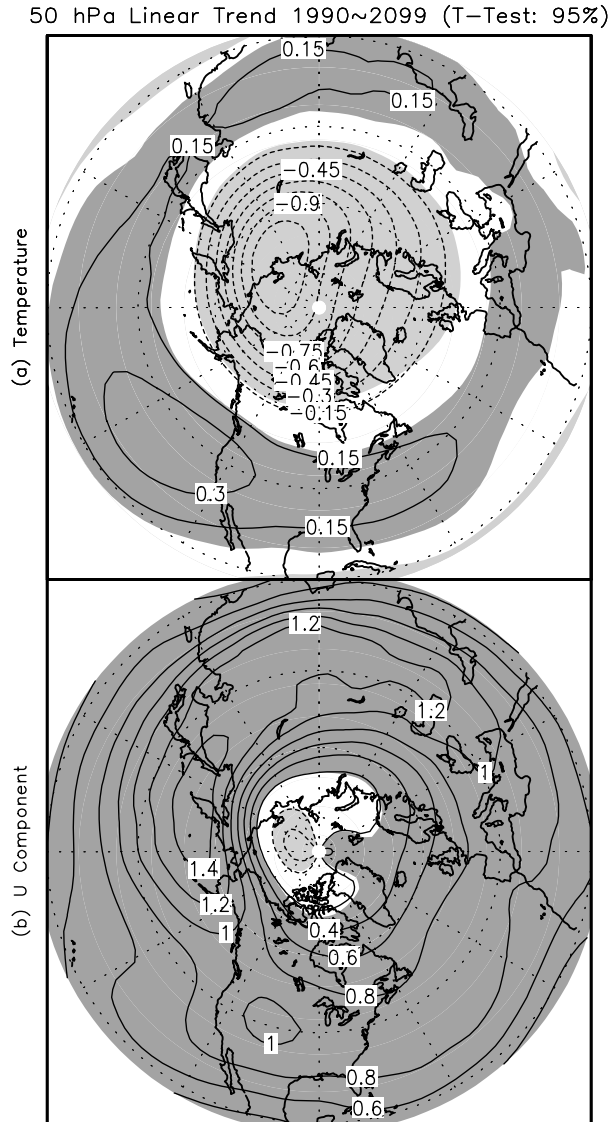


Fig. 13. Linear trends of the (a) temperature and (b) zonal u component at 50 hPa in 20°N north in the NH winter (DJF) during the period from the year 1990 to the year 2099. The contour intervals are 0.15°C per decade in (a) and 0.2 m s^{-1} per decade in (b). Solid (dashed) lines represent positive (negative) values, and zero lines are saved. Heavy (light) shaded regions indicate the positive (negative) trends significant at the level of 95% using the T -test.

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