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The record-breaking cold temperatures during the winter of 2009/2010 in the Northern Hemisphere

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Abstract

In this study, we show that the record-breaking cold temperatures from North America to Europe and Asia during the period of 28 December 2009 to 13 January 2010 are associated with extremely negative values of the North Atlantic Oscillation (NAO) index, which produce northerly surface wind anomalies and cause the southward advection of the cold Arctic air. Corresponded to longer-term variations of Pacific and Atlantic Sea Surface Temperatures (SSTs), the downward trend of the NAO has occurred since the early 1990s. It is speculated that if the downward trend of the NAO continues, more frequent cold outbreaks and heavy snow are likely in the coming years. Published 2010 by John Wiley and Sons, Ltd.

Keywords: North Atlantic Oscillation; Pacific Decadal Oscillation; Atlantic Multidecadal Oscillation

1. Introduction

The weather and climate in the Northern Hemispheric winter are greatly influenced by atmospheric pressure patterns in the northern middle and high latitudes. The Arctic Oscillation (AO), also known as the North Atlantic Oscillation (NAO), is referred to the fluctuation of the low in the high latitudes and the high in the middle latitudes (Hurrell, 1995; Thompson and Wallace, 2001). Similarities and dissimilarities between the NAO and AO are still in debate (e.g. Itoh, 2008 and references there). Some studies argued that the NAO and AO are synonyms – they are different names for the same variability, not different patterns of variability (Wallace, 2000). The difference between the two lies in whether the variability is interpreted as a regional pattern controlled by Atlantic sector processes or as an annular mode whose strongest teleconnections lie in the Atlantic sector. The NAO was discovered in the 1920s/1930s by Sir Gilbert Walker as a seesaw in sea-level pressure (SLP) of the Icelandic low and the Azores high (Walker and Bliss, 1932). Unlike the El Niño-Southern Oscillation phenomenon in the Pacific Ocean, the NAO is mainly an atmospheric mode arising from climate noise (Feldstein, 2000). It is one of the most important manifestations of climate fluctuations in the North Atlantic and its surrounding continents.

The winter of 2009/2010 was an unusual winter because it was extremely cold in many places and was the snowiest on record for many cities, e.g. about 72 in. of snow has fallen in Washington, DC this winter up to 10 February 2010. Some media sources even report that 'the mini ice age starts here' (e.g. on 10 January 2010 a report at www.dailymail.co.uk/sciencetech/index.html). In particular, the weeks of 28 December 2009 to 13 January 2010 (hereafter referred to as D28–J13) were the coldest from North America to Europe as well as in Asia, during which record-breaking cold air temperatures were measured in many cities. For example, the National Weather Service reported 36 °F (2.22 °C) at the Miami Airport on 11 January 2010, beating an 82-year-old record of 37 °F (2.78 °C). The purposes of this article were to (1) describe and report that strongly negative phases of the NAO (i.e. extreme weakening of the Icelandic low and the Azores high) in the winter of 2009/2010 were responsible for the recent cold outbreak in the Northern Hemisphere and (2) investigate possible factors that may account for the secular downward trend of the NAO index since the early 1990s.

2. Data sets and indices

The National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis field (Kalnay *et al.*, 1996) from January 1950 to January 2010 is used in this study. Both the daily and monthly data of surface air temperature (SAT), SLP and surface wind fields are downloaded from http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html. These data are on a grid of 2.5° latitude by 2.5° longitude. The observed daily temperatures in Miami, Florida (Miami station with station ID of 72202012839) and St Louis, Missouri (St Louis/Lambert station with station ID of 72434013994) are downloaded from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) at http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html#monthly. The monthly extended reconstruction sea surface temperature (ERSST.v3b) on a grid of 2° latitude by 2° longitude (Smith *et al*., 2008) is from NOAA/NCDC at http://www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php.

Both the monthly and daily NAO/AO indices are from the NOAA Climate Prediction Center (CPC; http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao_index.html). The monthly NAO index is defined as principal component (PC) time series of the first leading mode of rotated empirical orthogonal function analysis of the monthly mean 500-mb height over the Northern Hemisphere. The daily NAO index is constructed by projecting the daily 500-mb height anomalies over the Northern Hemisphere onto the loading pattern of the NAO. The temporal coverage of both the daily and monthly NAO indices is from January 1950 to January 2010. The monthly AO index at NOAA/CPC from January 1950 to December 2009 is defined as PC time series of the leading mode of empirical orthogonal function analysis of the monthly mean 1000-mb height during 1979–2000. The monthly Pacific Decadal Oscillation (PDO) index is from the Joint Institute for the Study of Atmosphere and Oceans at University of Washington, derived as the leading PC of the monthly sea surface temperature (SST) anomalies in the North Pacific Ocean poleward of 20 °N (Mantua *et al*., 1997). The temporal coverage of the PDO index is from January 1900 to December 2009. The unsmoothed monthly Atlantic Multidecadal Oscillation (AMO) index from January 1948 to December 2009 is calculated from the area-weighted SST averaged over the North Atlantic of 0–70 °N (Enfield *et al*., 2001) using the Kaplan's SST data set.

3. NAO-related air temperatures in the Northern Hemisphere

As stated in Section 1, previous studies have viewed that the NAO and AO represent the same variability – the fluctuation of the low in the high latitudes and high in the mid latitudes in the Northern Hemisphere. It is thus expected that the NAO index highly correlates with the AO index, with some remaining differences (Wang *et al*., 2005; Itoh, 2008). We find that correlations of the NAO and AO time series for the winter (December to February), monthly, 1-year running mean, and 7-year running mean indices are 0.76, 0.60, 0.71 and 0.83, respectively. We understand that the NAO may not be a fitting name for climate impact on the global middle Northern Hemisphere (Thompson and Wallace, 1998; Xie *et al*., 1999; Itoh, 2008). Nevertheless, in this article, the term NAO is still used and the NAO index is used for most of the calculations. Note that similar patterns and results will be obtained if the AO index is used. Figure 1(a) shows the monthly NAO index since 1950 and its associated 7-year running mean time series. An obvious feature is its longer-term variation. The NAO secularly increases from 1950 to 1990, and after the early

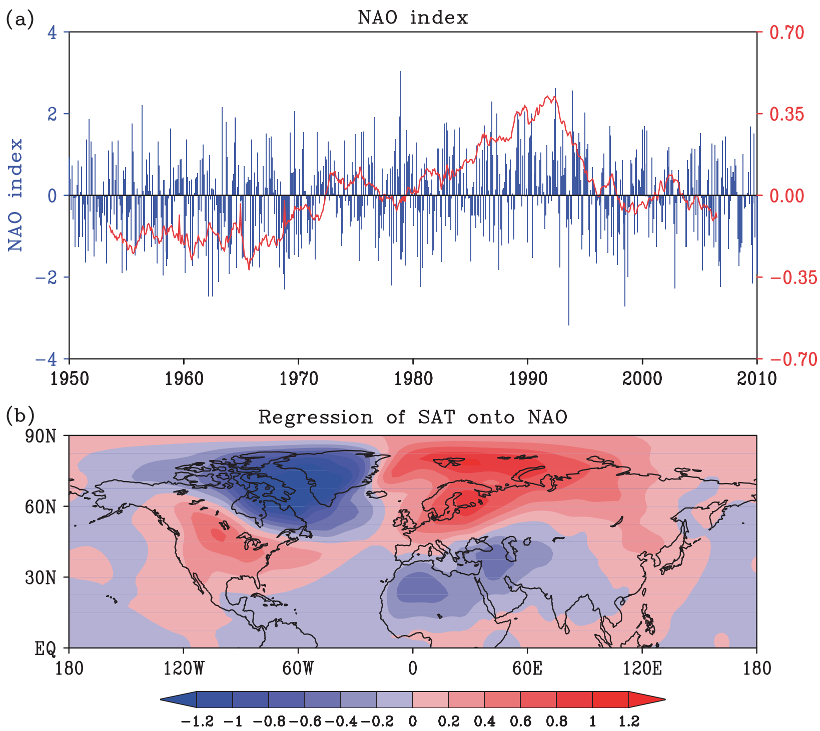

Figure 1. (a) Monthly NAO index from 1950 to 2009. (b) Regression (°C/NAO) of monthly surface air temperature onto the monthly NAO index. The red line in (a) is the 7-year running mean NAO index.

1990s it generally decreases except for a brief period of small amplitude fluctuations around the early 2000s.

Previous studies have documented the influence of the NAO or the AO on climate and weather in the Northern Hemisphere (Hurrel, 1995; Thompson and Wallace, 2001). A regressed map of the monthly SAT anomalies onto the monthly NAO index is given in Figure 1(b), which shows a dominant quadripole pattern of SAT in the Northern Hemisphere. The negative regressed SAT anomalies are located in Greenland/eastern Canada and North Africa/the Middle East, whereas the positive SAT anomalies are located in the United States and Europe as well as in Asia. This indicates that a positive (negative) phase of the NAO is associated with warm (cold) SAT anomalies in the United States and Europe as well as in Asia, and cold (warm) SAT anomalies in Greenland/eastern Canada and North Africa/the Middle East. As the NAO index varies, the relative strengths and positions of the Icelandic low and the Azores high are changed, leading to the changes of wind speed and wind direction and thus to changes in SAT. Note that the regressed pattern of winter SAT anomalies onto the winter NAO index is similar to that of all seasons in Figure 1(b), but with a larger amplitude (not shown). This indicates that the NAO can induce larger air temperature changes in the winter than in other seasons.

4. Cold air outbreak during 28 December 2009 to 13 January 2010

The daily time series of temperatures at Miami, Florida and St Louis, Missouri along with the daily NAO index are shown in Figure 2(a). As the season progresses from the fall to the winter, air temperatures decrease and so does the NAO index. In addition to the seasonal transition, Figure 2(a) also shows

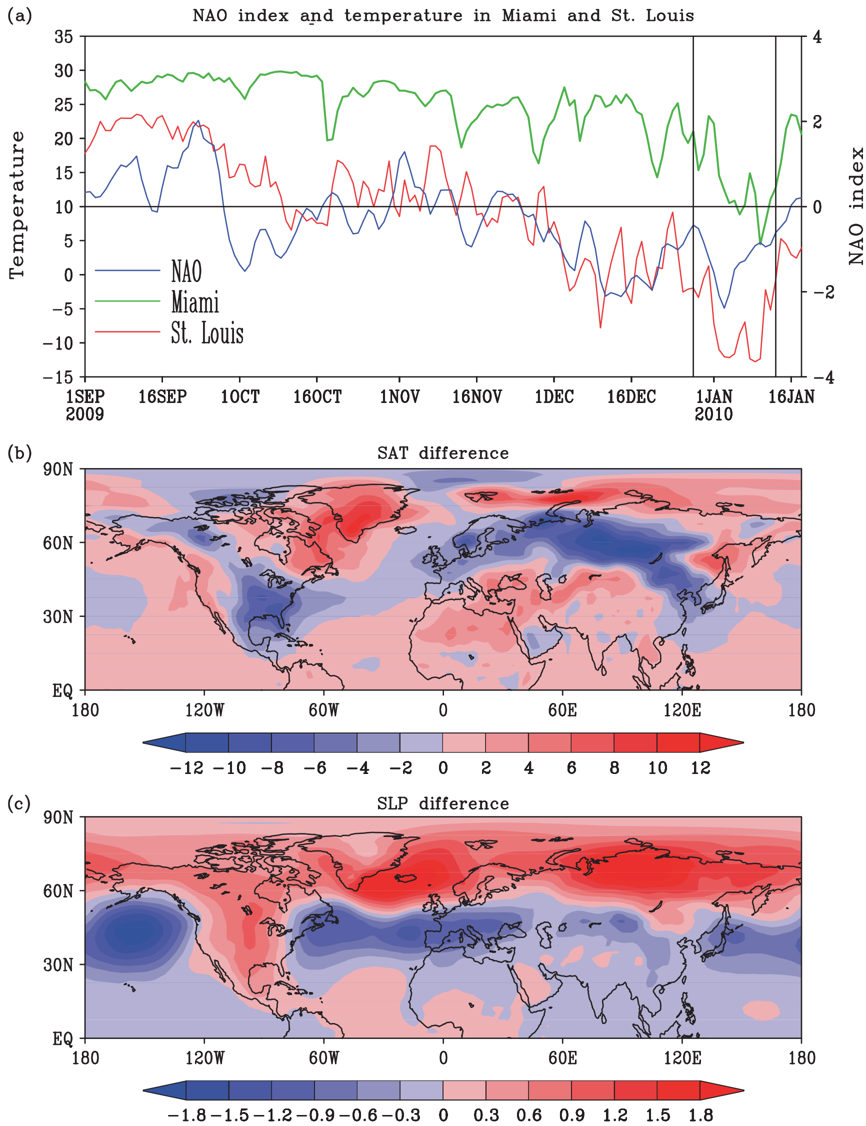

Figure 2. (a) Daily temperatures (°C) in Miami and St Louis and daily NAO index from 1 September 2009 to 18 January 2010. (b) SAT difference (°C) between the period of 28 December 2009 and 13 January 2010 (D28–J13) and the same time period of previous 60 years. (c) SLP difference (hPa) between the period of D28–J13 and the same time period of previous 60 years. Two vertical lines in (a) represent the weeks of D28–J13.

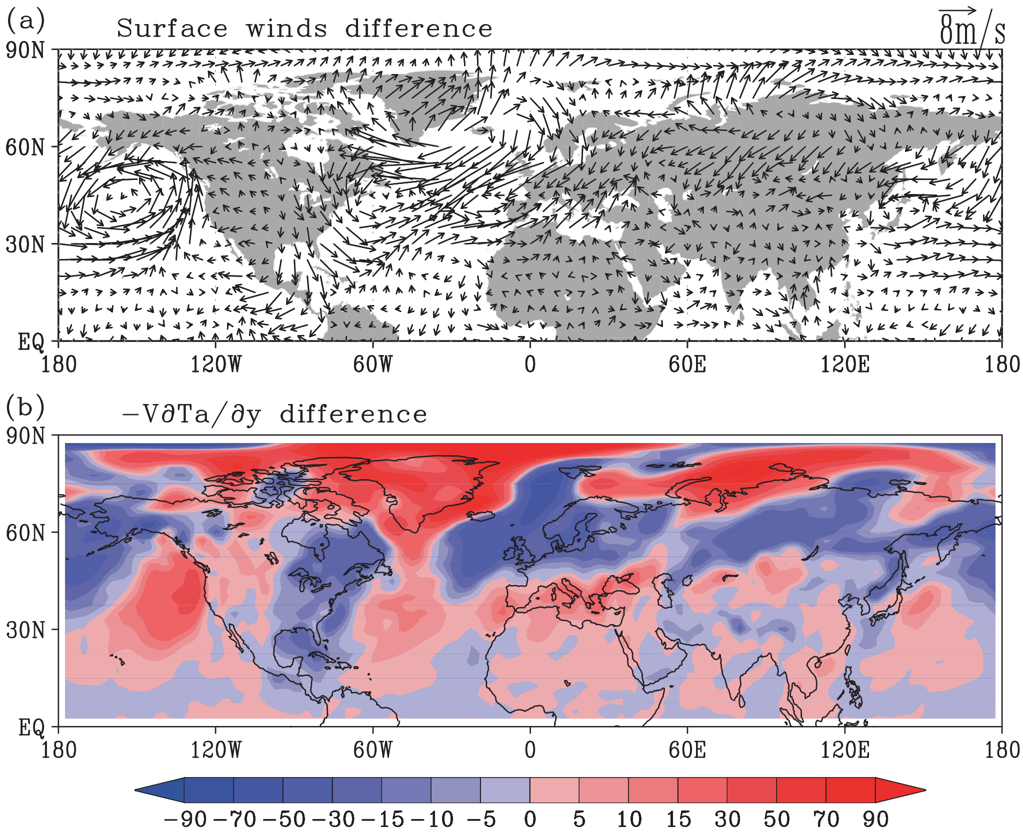

Figure 3. (a) Surface wind difference (m/s) between the period of 28 December 2009 and 13 January 2010 (D28–J13) and the same time period of previous 60 years. (b) Meridional temperature advection difference ($-V\partial T_a/\partial y$; 10^{-4} °C/s) between the period of D28–J13 and the same time period of previous 60 years.

the relatively long period of D28–J13 with cold temperatures in both Miami and St Louis. Such a long duration of cold air temperatures is extremely unusual in South Florida. Associated with the drop of air temperatures is a decrease in the NAO index. Of importance is that the lowest value of the NAO index leads the coldest air temperatures, indicating that the NAO is responsible for the decrease in air temperatures. Interestingly, the cold air temperatures in Miami and St Louis still persist even after the NAO index starts to recover on 3 January 2010.

To examine the spatial distribution of air temperatures during the cold period, we calculate the SAT difference between the D28–J13 period and the same time period of previous 60 years (Figure 2(b)). In essence, the air temperature pattern is similar to the regressed SAT pattern in Figure 1(b), just with signs reversed. In particular, air temperatures show cold SAT anomalies in the southeastern United States, Europe and even in Asia. This suggests that the more than 2-week cold temperatures during D28–J13 were due to a decrease in the NAO index (note that the NAO index during D28–J13 was −1.20, which is much lower than the previous 60-year average of −0.12 during the same time period). Indeed, the spatial distribution of cold air temperatures is consistent with the corresponding pattern of SLP anomalies. The SLP pattern shows a band of strongly positive SLP anomalies circled in the high latitudes of the globe and a band of negative SLP anomalies in the middle Northern Hemisphere (Figure 2(c)). In the North Atlantic sector, the SLP anomalies display a pattern similar to that of the negative NAO phase (Hurrel, 1995; Hoerling *et al*., 2001). This confirms that the extremely negative phases of the NAO cause the cold air temperatures in the middle Northern Hemisphere during D28–J13.

With the extremely negative phases of the NAO during D28–J13, how do the cold air temperatures occur in the middle latitudes? We calculate the surface wind and meridional temperature advection differences between the D28–J13 period and the same time period of previous 60 years (Figure 3). During these weeks, the surface wind anomalies are northerly in the middle latitudes from the eastern United States to Asia, with the largest northerly wind anomalies in the North Atlantic (Figure 3(a)). These northerly wind anomalies can bring the cold air of the high latitudes to the middle latitudes. Indeed, the meridional temperature advection (i.e. $-V\,\partial T_a/\partial y$) anomalies (Figure 3(b)) do show the negative values in the eastern United States, Europe, and Asia, explaining the cold air temperature pattern in Figure 2(b). Note that the zonal temperature advection anomalies are not important for the cold air temperatures during D28–J13 period (not shown).

To further examine the cause of the cold air temperatures during D28–J13, we divide the temperature advection difference in Figure 3(b) into three terms of $-V'\partial\overline{T}_a/\partial y$, $-\overline{V}\partial T'_a/\partial y$ and $-V'\partial T'_a/\partial y$, where the

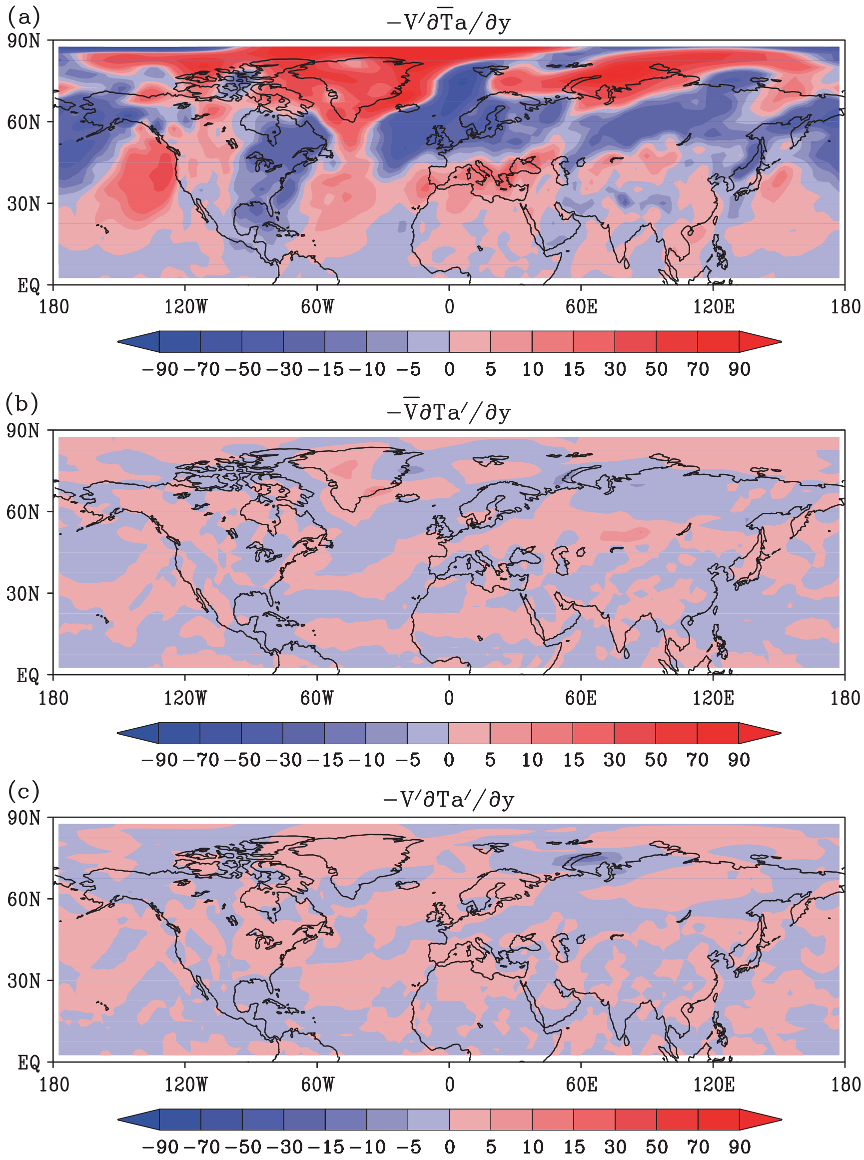

Figure 4. The contributions of the meridional temperature advection difference in Figure 3(b) by (a) the advection of mean temperature gradient by anomalous wind $(-V'\partial\overline{T}_a/\partial y)$, (b) the advection of anomalous temperature gradient by mean wind $(-\overline{V}\partial T'_a/\partial y)$ and (c) the nonlinear advection $(-V'\partial T'_a/\partial y)$. The unit is 10^{-4} °C/s.

prime represents the difference between the D28–J13 period and the same time period of previous 60 years and the bar represents the mean during the same period of previous 60 years. These three terms are referred to the advection of mean temperature gradient by anomalous wind, the advection of anomalous temperature gradient by mean wind and the nonlinear advection, respectively. Figure 4 shows their respective contributions. The advection by the anomalous meridional wind of Figure 4(a) is almost the same as Figure 3(b). This confirms the importance of the northerly wind anomalies in the cold air temperatures of the middle Northern Hemisphere during D28–J13. The advection by the mean meridional wind and the nonlinear term were not important for the cold temperatures during D28–J13 (Figure 4(b) and (c)).

Figure 1(a) also displays a longer-term variability of the NAO index. The next issue that we attempt to address is the relationship between the longer-term NAO variability and extreme NAO events like the one that occurred during D28–J13. Here, we use the daily NAO index from 1950 to 2009. From these daily NAO values, we define the smallest of 200 NAO values as the extreme negative events and the largest of 200 NAO values as the extreme positive events. Table I shows the occurrences of these extreme NAO events over the past six decades. We see that during the decades of longer-term lower NAO phases (the red line in Figure 1(a)) such as in the 1950s, 1960s, 1970s and 2000s the extreme negative NAO events are more than the extreme positive events, whereas the opposite is true during the decades of longer-term higher NAO phases such as in the 1980s and 1990s. This indicates that when the longer-term NAO is in its negative (positive) phase, the extremely negative (positive) NAO events are more likely. It is implied that more frequent extreme negative NAO events will likely occur in the

Table I. Occurrences of the extreme NAO events during the past six decades[a].

Occurrences	50–59	60–69	70–79	80–89	90–99	00–09
Extreme negative NAO events	16	44	39	26	29	46
Extreme positive NAO events	14	32	24	48	65	17

[a] Based on the 21 915 daily values of the NAO from 1950 to 2009, the smallest 200 NAO values are defined as the extreme negative events and the largest 200 NAO values are defined as the extreme positive events.

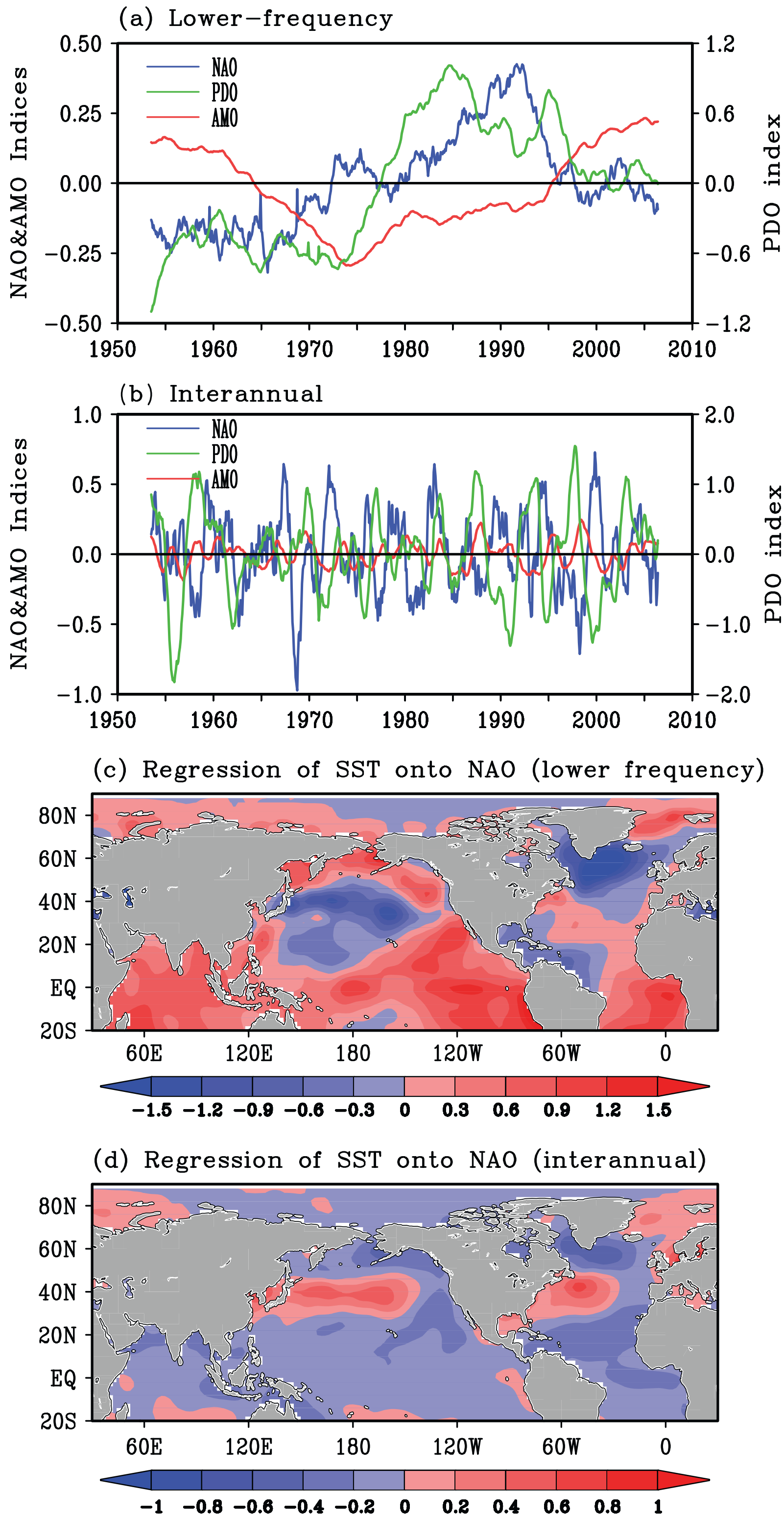

Figure 5. (a) The lower-frequency (7-year running mean) NAO, PDO and AMO (°C) indices. (b) The interannual NAO, PDO and AMO indices. (c) Regression (°C/NAO) of monthly SST onto the lower-frequency NAO index. (d) Regression (°C/NAO) of monthly SST onto the interannual NAO index. The interannual index is calculated as the difference between the 1-year running mean index and the 7-year running mean index.

forthcoming years if the longer-term downward trend of the NAO index continues (Figure 1(a)).

5. Secular downward trend of the NAO since the 1990s and SST variations

We have shown in the preceding section that the extremely negative NAO index may be responsible for the cold air temperatures occurring during D28–J13. A natural question one may ask is: Why is the NAO index extremely negative during D28–J13? Do the oceans play a role in the NAO variation, besides the atmospheric internally induced NAO variations? Here, we focus on the lower and higher frequency variabilities by separating the NAO, PDO and AMO into decadal and interannual timescales (Figure 5). Both the PDO and AMO seem to be closely related to the NAO on lower-frequency variations (i.e. lower than decadal timescale). In this regard, Figure 5(a) shows that the downward trend of the PDO index from the late mid-1980s to the present is associated with the downward trend of the NAO from the early 1990s to the present. Similarly, the upward trend of the AMO since the 1990s corresponds to the downward trend of the NAO from the early 1990s. These suggest that the longer-term variations of the NAO may be related to or forced by the lower-frequency SST in the Pacific and Atlantic (Rodwell *et al*., 1999; Xie *et al*., 1999; Hoerling *et al*., 2001). Table I and Figure 1(a) show that the downward trend of the NAO index in the 2000s is favorable for the extremely negative NAO events during D28–J13. Thus, it is possible that the longer-term SST variability such as the PDO and AMO also contributes to the extremely negative values of the NAO index during D28–J13.

On the interannual timescale, both the PDO and AMO are negatively correlated to the AMO (Figure 5(b)). The correlations of the interannual NAO index with the interannual PDO and AMO indices are −0.26 and −0.24, respectively, both of which are above the 95% significance level. But the interannual PDO index leads the interannual NAO by 2 months, whereas the AMO lags the NAO by 2 months. The role of the Pacific and Atlantic SSTs in the NAO deserves a further study.

A regressed map of SST anomalies onto the lower-frequency NAO index, given in Figure 5(c), shows that the regressed SST pattern in the Pacific is the PDO-like, whereas it resembles the AMO in the Atlantic. This again suggests that on longer-term timescales the NAO is forced by the lower-frequency SST variations. We also calculate the regressed pattern of SST anomalies onto the interannual NAO index as shown in Figure 5(d). The tropical Pacific SST is very weak (Wang, 2002) and the North Pacific shows a positive SST pattern. The Atlantic SST distribution is the conventional SST tri-pole pattern, with negative SST anomalies in the North Atlantic and tropical North Atlantic and positive SST anomalies in the middle North Atlantic. This tri-pole SST pattern is consistent with the NAO-forced SST distribution through latent heat flux (Xie and Tanimoto, 1998; Tanimoto and Xie, 1999; Okumura *et al*., 2001), which is supported by the lagged correlation between the interannual AMO and NAO indices in Figure 5(b).

Previous modeling studies have emphasized the importance of longer-term tropical SST (especially over the tropical Pacific and Indian Oceans) variations (Hoerling *et al*., 2001) and of multidecadal North Atlantic SST (Rodwell *et al*., 1999) in the NAO. In addition, Xie and Tanimoto (1998) suggested that a cold tropical North Atlantic could induce a positive NAO phase, which is consistent with the interannual SST regressed map in Figure 5(d). However, few modeling investigations have been done to understand the causes of the secular downward trend of the NAO since the 1990s. As this study indicates a strong correlation between the downward trend of the NAO and winter SAT, it is highly desirable to study the causes of the NAO's downward trend in the future using general circulation models.

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