The NAO, the AO, and Global Warming: How Closely Related?

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ABSTRACT

The North Atlantic Oscillation (NAO) and the closely related Arctic Oscillation (AO) strongly affect Northern Hemisphere (NH) surface temperatures with patterns reported similar to the global warming trend. The NAO and AO were in a positive trend for much of the 1970s and 1980s with historic highs in the early 1990s, and it has been suggested that they contributed significantly to the global warming signal. The trends in standard indices of the AO, NAO, and NH average surface temperature for December–February, 1950–2004, and the associated patterns in surface temperature anomalies are examined. Also analyzed are factors previously identified as relating to the NAO, AO, and their positive trend: North Atlantic sea surface temperatures (SSTs), Indo–Pacific warm pool SSTs, stratospheric circulation, and Eurasian snow cover.

Recently, the NAO and AO indices have been *decreasing*; when these data are included, the overall trends for the past 30 years are weak to nonexistent and are strongly dependent on the choice of start and end date. In clear distinction, the wintertime hemispheric warming trend has been vigorous and consistent throughout the entire period. When considered for the whole hemisphere, the NAO/AO patterns can also be distinguished from the trend pattern. Thus the December–February warming trend may be distinguished from the AO and NAO in terms of the strength, consistency, and pattern of the trend. These results are insensitive to choice of index or dataset. While the NAO and AO may contribute to hemispheric and regional warming for multiyear periods, these differences suggest that the large-scale features of the global warming trend over the last 30 years are unrelated to the AO and NAO. The related factors may also be clearly distinguished, with warm pool SSTs linked to the warming trend, while the others are linked to the NAO and AO.

1. Introduction

The teleconnection pattern known as the North Atlantic Oscillation (NAO) is characterized by a dipole in the sea level pressure field with one anomaly center over the Arctic, near Greenland, and another center of opposite sign across the midlatitude sector of the North Atlantic Ocean. In terms of sensible climate, the NAO is associated with a seesaw pattern in temperature and precipitation between northern Europe and Greenland. For a review of the observational aspects of the NAO see, for example, Wanner et al. (2001), Hurrell et al. (2003), and references within.

In addition to linking the NAO and interannual temperature variability, Hurrell (1995) suggested a possible link between the NAO and global warming. Based on similarities between the temperature variations associated with the NAO and the trend in surface temperatures, he suggested that the major warming over the Northern Hemisphere (NH) landmasses was forced in large part by the strong and persistent duration of the NAO in its positive phase. The NAO index, constructed by Hurrell from individual station data from Iceland and Portugal dating back to 1864, was in an unprecedented upward trend at the end of the twentieth century. Hurrell (1996) further suggested that almost all of the observed warming over Eurasia since the mid-1970s was directly attributable to interannual trends in the NAO. Linking trends in the NAO to trends in NH surface temperature have important implications to the debate of global warming. The NAO could dynamically amplify or dampen changes in surface temperature initially forced by radiative changes due to global warming. Moreover, the NAO is a mode of natural variability, and a close relationship with

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warming trends makes it difficult to distinguish between warming due to natural variability and anthropogenically forced warming.

The NAO had been mainly thought of as a pattern of variability limited in extent to the North Atlantic sector. However, Thompson and Wallace (1998) argued that the NAO was, in fact, a regional manifestation of a hemispheric-wide pattern of variability referred to as the Arctic Oscillation (AO) or the annular mode (Thompson et al. 2000). Rather than using station data to derive the AO index, Thompson and Wallace (1998) used the principal component (PC) or the time series and spatial loading pattern associated with the first empirical orthogonal function (EOF) of the NH sea level pressure (SLP) poleward of 20°N. The temperature pattern associated with the AO closely resembles that associated with the NAO. It has also been shown that the recent positive trend in the AO, concurrent with the NAO index, is difficult to reconcile with natural variability (Feldstein 2002). Thompson et al. (2000) argue that the observed positive trend in the AO index over the last three decades of the twentieth century significantly contributed to the observed warming trend over Eurasia and North America, accounting for as much as 50% of the winter warming over Eurasia.

A number of factors have been identified as related to trends in the NAO and AO: North Atlantic sea surface temperatures (SSTs), the stratosphere and cooling thereof, and strong warming of the west Pacific tropical ocean and Indian Ocean SSTs known as the warm pool. Rodwell et al. (1999) proposed that North Atlantic SSTs are forcing observed trends in the NAO/AO. While there are supporting GCM experiments (Deser and Blackmon 1993; Mehta et al. 2000), there are also several GCM studies that have not shown an extratropical oceanic forcing on observed trends in the NAO/AO (Bretherton and Battisti 2000; Robertson 2001; Josey et al. 2001; Cohen et al. 2005). Shindell et al. (1999) proposed that the observed trends in the NAO/AO could not be simulated by GCMs without a properly resolved stratosphere. They were the first to report that anthropogenically forced change in stratospheric trace-gas concentration, that is, increased greenhouse gases, is forcing a positive trend in the AO both in the stratosphere and consequently in the troposphere. Thompson and Solomon (2002) reported that ozone depletion in the stratosphere was cooling the polar vortex in the Southern Hemisphere stratosphere, which was forcing positive trends in the annular mode in the lower troposphere. Furthermore, this relationship was applicable to the NH; therefore ozone loss in the NH stratosphere should be considered as forcing a positive trend in the AO both in the stratosphere and in the troposphere. However other GCM studies have shown that the stratosphere is not critical in simulating trends in the NAO/AO (Fyfe et al. 1999; Zorita and Gonzalez-Rouco 2000; Gillett et al. 2000). Finally, Hoerling et al. (2001) proposed that warming in the tropical western Pacific and Indian Oceans is forcing the observed trends in the NAO/AO. Since then, other studies have provided additional support for their findings (Bader and Latif 2003). Schneider et al. (2003) found the Indo–Pacific region to be important in forcing trends in the North Atlantic climate, although the pattern of variability does not project onto the NAO/AO pattern.

Although snow cover has not been linked to the observed positive trend in the AO, it has been linked with interannual variability of the NAO/AO (Cohen and Entekhabi 1999; Saito and Cohen 2003) and so is included for consideration.

There are several potential complicating factors in considering the trends in the AO, NAO, and global warming. The relationship between the AO and NAO is not yet fully understood; furthermore, there are several alternate approaches to construct the indices, derived from both EOF pattern-based techniques and station-based approaches. Therefore, for a comprehensive analysis of the general circulation trend we consider both the AO and the NAO derived from PC and station-based indices. Finally, multiple datasets are used to consider hemispheric surface climate trends. Analysis of multiple surface temperature and sea level pressure datasets and different versions of each index is needed to ensure that the results are robust and not data or technique dependent.

Using these datasets, summarized in section 2, we analyze trends in the NAO, AO, and surface temperature for December–February 1949/50–2003/04, considering both the EOF- and station-based indices; the results are presented in section 3. In section 4, the spatial patterns of surface temperature associated with these phenomena are intercompared. These trends and patterns are used to evaluate the links to SSTs in the Indo–West Pacific and North Atlantic Oceans, Eurasian snow cover, and stratospheric circulation. A summary and discussion are given in section 6.

2. Data

For atmospheric data we used the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) for the years 1949 through 2004. For snow cover data we used the monthly dataset, produced by the National Oceanic and Atmospheric Administration (NOAA), which covers the period from 1972 through 2004 (Robinson et al. 1993). For NH-averaged station temperature data we used the Goddard Institute for Space Studies (GISS) temperature dataset (Hansen et al. 1999). For spatially varying station temperature data our primary dataset is the NCEP Climate Analysis and Monitoring System (CAMS) gridded temperature (Ropelewski et al. 1985), which has the benefit of being readily accessible in real time. While the operational nature of CAMS precludes the inclusion of data that is not available in real time, we have verified the results reported here in both the GISS dataset (Hansen et al. 1999) and the Hadley Centre dataset (Jones 1994)—the large-scale patterns of trend and of NAO/AO relationships are quite consistent. For global SST data we used the Kaplan reconstructed SSTs (Kaplan et al. 1998).

For Figs. 1–6 we derived the AO index using the NCEP–NCAR reanalysis. We computed the first PC of gridded SLP poleward of 20°N for the winters 1972/73–2003/04, as defined by Thompson and Wallace (1998). To extend the series back to 1949/50, this leading EOF mode is projected onto the winter mean SLP anomalies during the earlier period. All time series are normalized by the standard deviation of the winter index (1972/73–2003/04 base period). For indices of the AO and NAO, for Figs. 7–8, we used the indices provided by the NOAA Climate Prediction Center (CPC) on their Web site—these have the advantage of being readily available in real time—but we have verified these indices against the corresponding indices of Hurrell (1995), Thompson and Wallace (1998), and our EOF analysis. We correlated the AO index that we derived with the AO index derived by CPC ($r = 0.95$) and repeated the analysis for both AO indices, and the results are not sensitive to choice of index. We have also compared these EOF-based indices derived from reanalysis data to the station-based index of Jones et al. (1997) and a simple polar-cap average of SLP to verify that neither the use of EOF analysis nor the consideration of reanalysis data has biased the results.

3. Analysis of indices

The observed interannual trend is dependent on the period chosen for analysis. To provide several different perspectives, we consider the last half century subdivided in a number of ways. The overall period is 1950–2004; as always, this period should be borne carefully in mind when considering the results. (The dates given represent the year of the end of the December–February, so 1950–2004 goes from December 1949–February 1950 through December 2003–February 2004). Additionally, 1973–2004 is specifically considered, as according to Hurrell (1995) the early 1970s is the beginning of the strong positive trend in the NAO; and this period is further subdivided in half, 1973–1988 and 1989–2004, based on differences in behavior, as will be seen.

a. NAO, AO, and NH average surface temperatures

In Fig. 1a we plot the time series for NH station temperatures and the AO index for December–February (DJF) 1950–2004. The NH temperature index is the area-weighted average of all land temperatures and, in contrast to the AO index, is not based on EOF analysis. In Fig. 1b we plot the time series for NH station temperatures and the AO index both for DJF 1973–2004. Also included for both series are the linear trend lines for the entire period and only for the most recent 16 years of the time series. The most striking result from the figure is the strong positive trend in the NH surface temperatures (T_s), consistent both in the full record shown in the figure and in the most recent half of the record. In Table 1, we present the Spearman rank correlation of each time series presented in this study as a measure of the robustness of the trend. [The Spearman rank correlation (Wilks 1995) assesses the degree to which a series increases monotonically; a value of 1 corresponds to any series where each term is larger than the preceding term. This approach provides a robust and resistant alternative to linear trend calculations.] Northern Hemisphere winter T_s exhibits a strong upward trend that is consistent throughout the record and statistically significant. In contrast, the winter AO exhibits a neutral trend over the entire period and a statistically significant negative trend over the most recent half of the record. We also computed the linear trend over the entire reanalysis period, shown in Fig. 1a (1950–2004), and the trend was slightly negative (not shown).

Therefore, despite the positive AO trend visually evident in the first half of the trend analysis (1973–89; but note that the Spearman rank correlation does not show a consistent positive trend even for this period) and a strong negative AO trend in the second half of the analysis (1989–2004), the trend in winter temperatures is consistent throughout the analysis. For the average surface temperatures, both the linear trend and the Spearman rank correlations show a robust positive trend throughout the period and in both subperiods. There appears to be little evidence of dynamic amplification of the hemispheric warming due to the decadal trends in the phase of the AO. The correlation between the two time series is $r = 0.20$; the AO time series only explains 4% of the variance in the average NH surface temperatures. One note of interest is the unusually good correspondence between the two time series from

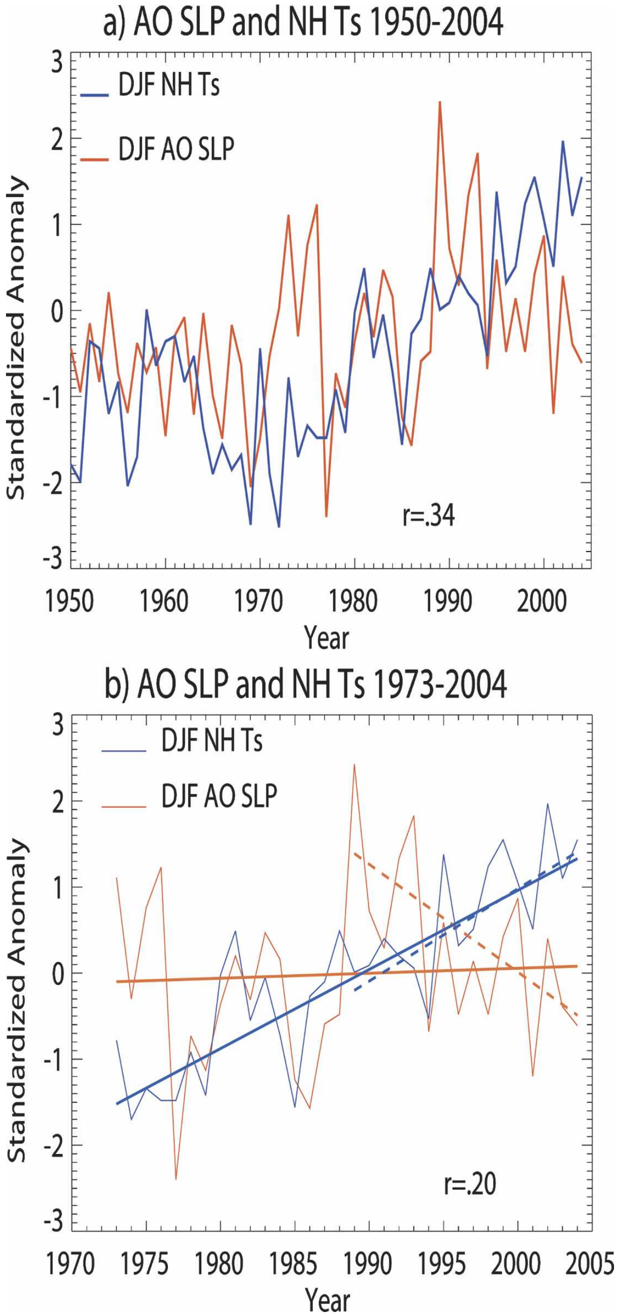


FIG. 1. (a) Plot of the normalized anomalies for the AO index and NH station temperatures for the winters 1949/50–2003/04. (b) Plot of the normalized anomalies for the AO index and for NH surface temperatures for the winters 1972/73–2003/04. Also plotted is the linear trend for the entire 32 years (solid line) and the most recent 16 years (dashed line). Correlation coefficient between time series is also shown. We calculated the AO time series as the first principal component of NH SLP poleward of 20°N for the winters 1972/73–2003/04. For the AO time series in (a), we calculated the pattern correlation between the first EOF of winter SLP for 1972/73–2003/04 and each individual winter.

TABLE 1. The Spearman rank correlation for the time series presented in Figs. 1–6. Those correlations found to be significant using the Student's *t* test at the 99% (95%) confidence limit are listed with a single (double) asterisk. Second column lists the correlations for the entire 32-yr period studied, third column for only the first 16 years of the period studied, and the fourth column for the last 16 years of the period studied.

	Spearman rank correlation		
Time series	Correlation 1973–2004	Correlation 1973–88	Correlation 1989–2004
DJF NH surface temperatures	0.86*	0.56**	0.77*
DJF AO SLP	−0.01	−0.43	−0.54**
DJF NA SSTs	0.22	−0.09	0.15
DJF WP SSTs	0.56*	0.52**	0.63*
DJF AO 50 hPa	−0.21	−0.24	−0.65*
DJF AO 10 hPa	−0.24	0.11	−0.53**
Oct snow cover	0.08	0.52**	−0.79*

the late 1970s through the late 1980s. The correlation after the winter of 1976/77 and before the winter of 1988/89 is much higher at $r = 0.56$. These two years have been identified as years in which climate shifts have occurred (Trenberth 1990; Watanabe and Nitta 1999). Why the correlation between the two time series is so much higher between the two climate shifts than before or after is an interesting question but beyond the scope of this paper.

We also calculated the linear trend and the Spearman rank correlations for different start and end dates (see Table 2). The positive trend in surface temperature warming is quite robust and independent of the start and end date, while the AO index exhibits a modest trend (measured in terms of rank correlation) only for specific start and end dates with no significant trend overall or for most of the start and end dates. Similar calculations for the linear trend yield similar behavior, as can be seen in Table 2. A positive trend in the AO can only be identified for a very specific subperiod. The period of years with the greatest positive trend in the AO index occurs between 1977 and 1989 when the linear trend is equal to +1.4 standard deviations per decade. This is equal and opposite of the AO trend for the most recent period, 1989–2004, when the trend is −1.3 standard deviations per decade. Despite the large trend swing in the AO index, the trend in surface temperatures for these same two periods is comparable to the values shown in Table 2, +0.89 for the former and +1.07 for the latter, so, in fact, the positive trend in temperatures accelerated faster during the most recent period of the negative AO trend!

We repeated the analysis for November–January and January–March; the results did not vary significantly.

TABLE 2. The linear trend per decade (units shown are standard deviation decade^{-1}) and Spearman rank correlation for the Artic Oscillation and Northern Hemisphere station temperature time series presented in Fig. 1 using different start and end dates from 1966 to 2004. Asterisks denote confidence limit as listed in Table 1. Regardless of start and end dates shown, Northern Hemisphere station temperature time series are found to be in a significant positive trend while the AO varies from almost no trend to a modest positive trend, though none is found to be significant. Values from Fig. 1a were used for AO time series and surface temperatures.

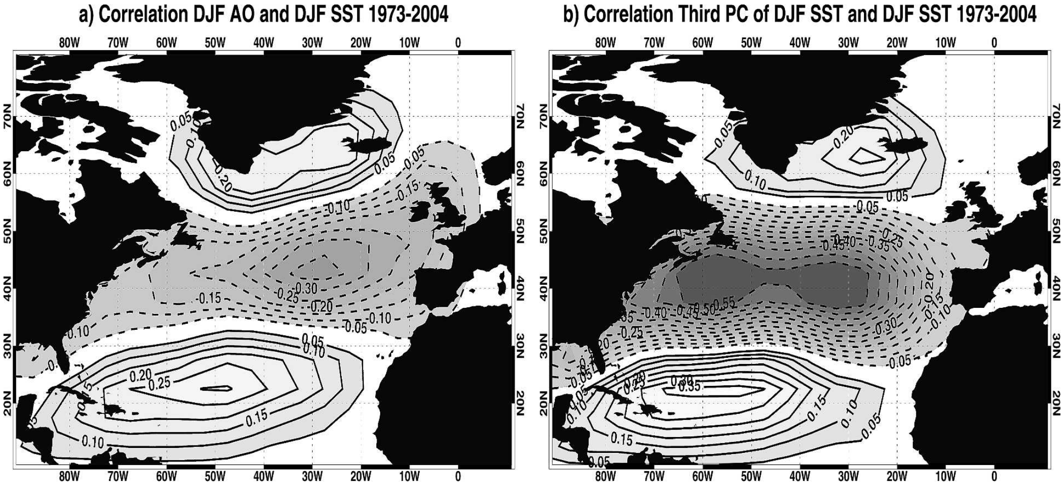
	Linear trend/decade		Rank correlation	
Years	AO	Surface temperature	AO	Surface temperature
1966–2004	0.24	0.91	0.25	0.89*
1967–2004	0.21	0.93	0.19	0.89*
1968–2004	0.22	0.94	0.21	0.88*
1969–2004	0.22	0.95	0.17	0.87*
1970–2004	0.14	0.92	0.10	0.86*
1971–2004	0.07	0.98	0.03	0.89*
1972–2004	0.05	0.97	−0.01	0.88*
1973–2004	0.06	0.92	−0.01	0.86*
1974–2004	0.14	0.96	0.06	0.86*
1975–2004	0.13	0.94	0.06	0.85*
1973–2003	0.10	0.91	0.03	0.85*
1973–2002	0.14	0.93	0.07	0.84*
1973–2001	0.13	0.87	0.04	0.83*
1973–2000	0.24	0.92	0.13	0.82*
1973–99	0.20	0.92	0.08	0.80*
1973–98	0.19	0.87	0.05	0.78*
1973–97	0.26	0.82	0.10	0.75*
1973–96	0.29	0.83	0.11	0.72*
1973–95	0.39	0.87	0.17	0.71*

The primary AO index shown here is based on the first PC of gridded SLP poleward of 20°N, following Thompson and Wallace (1998), but we have verified the results in both the AO and NAO indices provided by CPC, as well as the station-based index of Jones et al. (1997) and a simple polar-cap average, and we have additionally verified that these indices are representative of the Hurrell (1995) and Thompson and Wallace (1998) indices (see section 2). Therefore, we have verified that these results for the AO—the peaking of the rapid increase in the 1990s followed by a rapid decrease through the present, resulting in little to no trend over the past 30 years—are not sensitive to whether the AO or NAO is considered, the technique used to compute the indices, whether the reanalysis or station data is used to compute the indices, or the definition of winter season.

b. *North Atlantic SSTs*

As mentioned in the introduction, GCM experiments have suggested that the observed positive trend in the AO is linked with three different forcing factors: North Atlantic SSTs, the stratosphere, and the warm pool SSTs. Rodwell et al. (1999) were able to simulate the interannual variability and long-term trend of the NAO index by forcing their GCM with the SST pattern most closely associated with the NAO, referred to as the tripole pattern. This pattern is generally characterized by one signed anomaly of SSTs covering the high-latitude and tropical North Atlantic and an opposite signed anomaly in the midlatitude North Atlantic. The SST patterns associated with the AO and NAO are similar; the correlation of the AO index onto SSTs is shown in Fig. 2a. (cf. Fig. 2 of Rodwell et al. 1999). To diagnose the SST variability associated with this pattern, we performed an EOF analysis, and the third EOF (Fig. 2b) is the pattern that most closely resembles the AO regression (we show the correlation of the third PC and SSTs so that values are directly comparable to Fig. 2a). EOF analysis is not the only possible approach to extracting the SST variability, and thus our results are to some degree technique dependent; however, the frequent consideration of the North Atlantic tripole SST EOF in many studies (e.g., Deser and Blackmon 1993) suggests that it is a relevant approach to examine.

Cause and effect cannot be convincingly evaluated from comparing the time evolution of the atmospheric and oceanic variability. However, analysis of the trends in each is one useful measure of how closely they are related. We plot the time series for the tripole pattern in Fig. 3a. The overall trend for the entire 55-yr period (1950–2004) is slight. The first half of the record (through the early 1970s) is dominated by a fairly strong negative trend, while an analogous trend is not observed in the AO. During the 1973–2004 period (Fig. 3b), the trend in the tripole pattern is characterized by an overall modestly positive trend, and the positive trend is consistent even during the two subperiods. However, the Spearman rank correlations do not demonstrate either of the trends to be significant. And though the SST trend and the AO trend are neutral to positive over the entire period, they diverge in the latter half (dashed lines in Fig. 3b) with the AO exhibiting a statistically significant negative trend while the SST trend is positive. Although the possibility that the AO index is at least partially forced by North Atlantic SSTs cannot be discounted, it appears probable that the recent negative trend in the observed AO cannot be explained by the tripole pattern of North Atlantic SSTs. Cohen et al. (2005) examined GCM output from AMIP-2 simulations forced with observed SST, showing that a range of state-of-the-art GCMs was able to simulate neither the observed interannual variability of


a) Correlation DJF AO and DJF SST 1973-2004

b) Correlation Third PC of DJF SST and DJF SST 1973-2004

FIG. 2. (a) Plot of the correlation between the winter SLP AO index and winter North Atlantic SSTs for 1972/73–2003/04. (b) Plot of the correlation between the third PC of winter North Atlantic SSTs and winter North Atlantic SSTs for 1972/73–2003/04. Shading interval is ±0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, and 0.5. Note the tripole pattern of SST anomalies in both figures.

the AO index nor its long-term trend when forced by observed SSTs. So, although our observational analysis is not suited for demonstrating cause and effect between SST and atmospheric circulation trends in the North Atlantic, a suite of GCMs forced with observed SSTs also suggests that recent observed trends in the NAO could not be attributed to North Atlantic SST variability, consistent with the results shown here.

c. Stratosphere

The interaction between the stratosphere and the troposphere is complex and not yet fully understood. It is widely accepted that the troposphere influences the stratosphere through the vertical propagation of planetary waves (Charney and Drazin 1961). What is debatable is whether the stratosphere influences the troposphere through "downward control" (Baldwin and Dunkerton 1999, 2001; Plumb and Semeniuk 2003). In the greenhouse gas forcing study of Shindell et al. (1999), only the GCMs with a properly resolved stratosphere could correctly simulate the trends in the AO observed at the time. In their GCM experiments, increasing greenhouse gases caused the stratosphere to cool, strengthening the polar vortex and forcing a strong positive trend in the stratospheric AO, which continued unabated until late into the modeled twenty-first century. The stratospheric positive AO in turn forced a similar positive trend in the AO measured at sea level, enhancing the radiatively forced surface warming. In their study, GCMs without a properly resolved stratosphere exhibited no trends in the SLP AO.

In Fig. 4 we plot the AO index computed both from EOF analysis of SLP, as before, and the geopotential height field at 50 hPa, representing the lower stratosphere (variability is similar at 10 hPa). The two time series suggest that the troposphere and stratosphere are coupled, with a high correlation between the two time series and similar trends. Through the simple use of trend analysis, the direction of the forcing cannot, of course, be determined. As with the tropospheric AO, inclusion of the most recent data shows that the stratospheric AO is in a *negative* trend over the 1973–2004 period and that, over the most recent subperiod, it is in a strong negative trend—a distinct change from the positive trend evident in the mid-1990s reported by Shindell et al. (1999), Thompson et al. (2000), and Hoerling et al. (2001). The Spearman rank correlation confirms that the negative trend is, indeed, significant. Every winter from 2000/01 through 2003/04 has been characterized by a negative stratospheric AO, with the most negative departure being observed in the winter of 2003/04. The stratospheric trends presented here from the reanalysis data are consistent with other recent trend analyses reported in Lanzante et al. (2003) using radiosonde data and Manney et al. (2005) using several available meteorological datasets. Therefore, it can be convincingly concluded that the NH stratospheric AO is not in a meaningful positive trend with respect to both the last 32 years and the most recent period, during which it was actually in a robust negative trend.

d. Warm pool SSTs

Tropical oceans are considered an important source of extratropical atmospheric variability (Barnston et al.

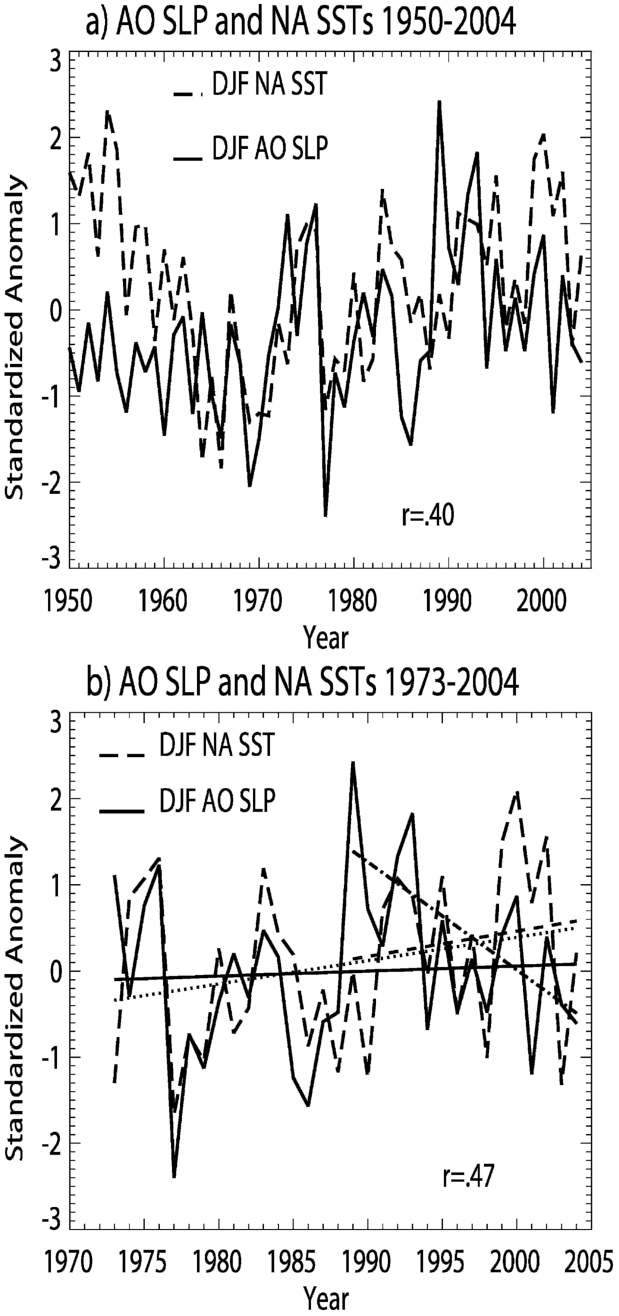


FIG. 3. (a) Plot of the normalized anomalies for the AO index and North Atlantic SSTs for the winters 1949/50 through 2003/04. (b) Plot of the normalized anomalies for the AO index and for North Atlantic SSTs for the winters 1972/73 through 2003/04. Also plotted is the linear trend for the entire 32 years (dashed–three dotted line for solid curve and dotted line for dashed curve) and the most recent 16 years (dashed–dotted line for solid curve and short dash for dashed curve). Correlation coefficient between time series is also shown.

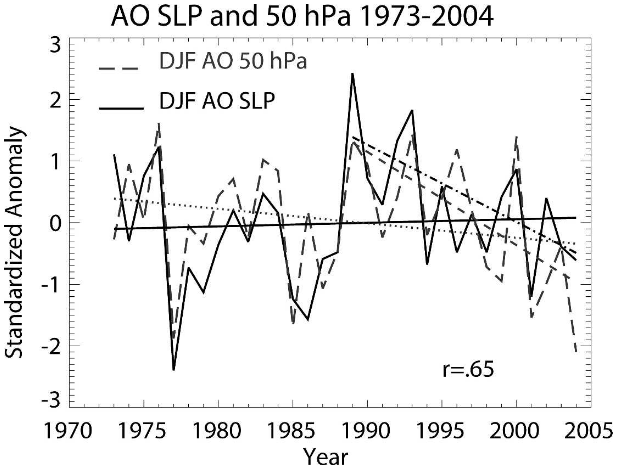


FIG. 4. As in Fig. 3b except for AO index and time series of first EOF for 50 hPa.

1999). The strongest tropical–extratropical teleconnection observed is between equatorial Pacific SSTs and variability in the North Pacific (Spencer and Slingo 2003). However, Hoerling et al. (2001) successfully simulated trends in the North Atlantic sector throughout the troposphere with a GCM forced by observed global SSTs, where most of the skill was derived from SSTs in the warm pool region (in the tropical western Pacific and Indian Oceans).

To represent the warm pool variability, we computed the first EOF of SSTs in the warm pool region of the Indo–Pacific Ocean and also calculated an area-weighted box average of the SST anomaly region bounded by 5°S–5°N, 75°–155°E. The EOF explains a full 75% of the variance and is characterized by a regionwide warming. The time series for the first EOF and the area-weighted anomaly are almost identical, with the correlation between the two equal to 0.98. We compared our warm pool indices with that of Sun (2003), defined as the maximum SST in the region bounded by 5°S–5°N, 120°–160°E. The trends for all indices are similar; since 1950 the warm pool has been experiencing a strong positive trend, particularly since the early 1970s (see their Fig. 1). In Fig. 5a we plot the time series of the area-weighted anomaly with the AO SLP time series for 1950–2004, and in Fig. 5b we plot the two time series with trend lines from 1973 to 2004. Similar to NH T_s, the SSTs in the warm pool region have been in a strong upward trend throughout the period analyzed; for both subperiods and based on the Spearman rank correlations, the positive trend is robust throughout. When plotted against the AO index over the same period, it is notable how divergent the two time series are, especially over the most recent subperiod where the differences are dramatic.

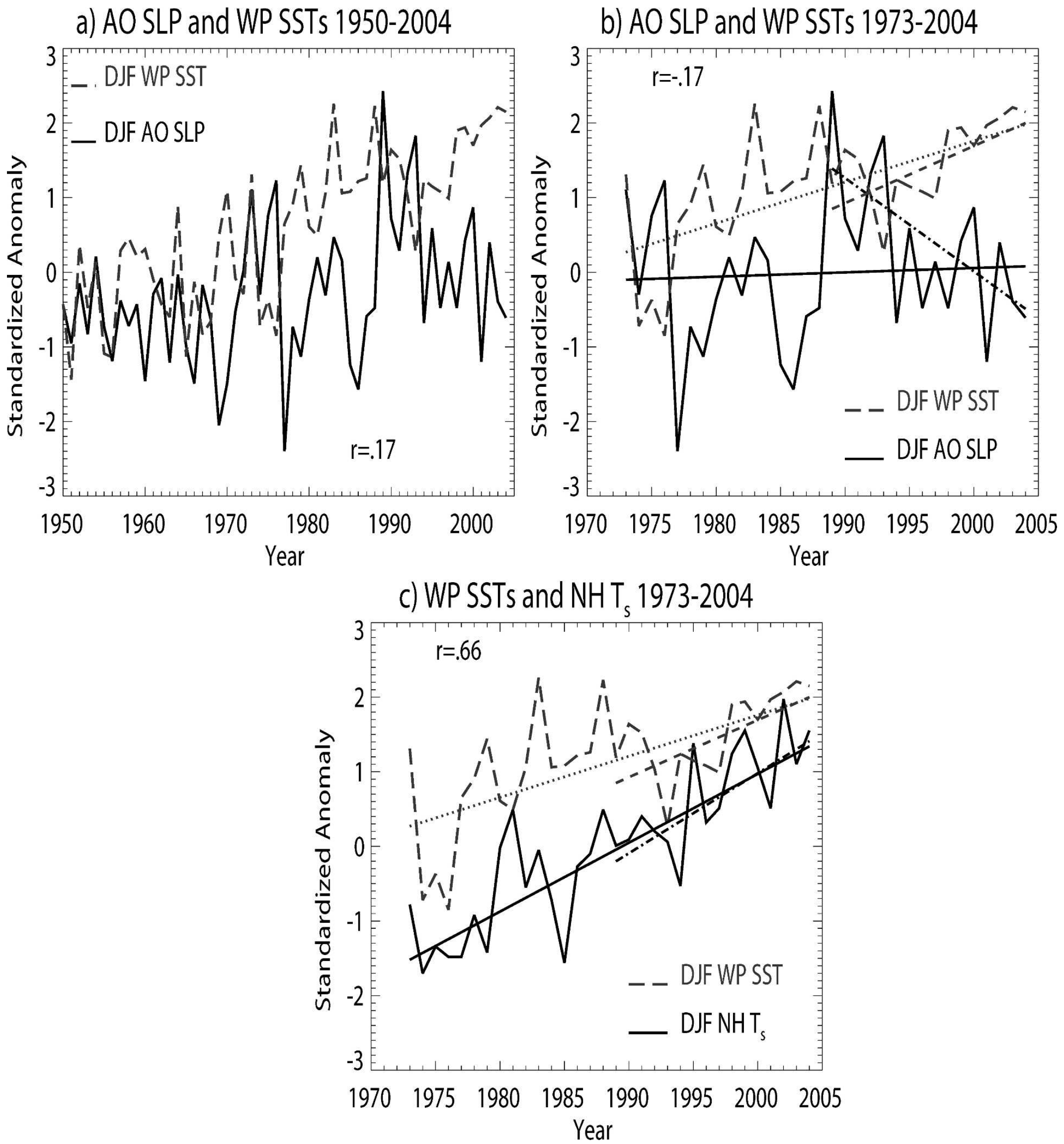


FIG. 5. (a) Plot of the normalized anomalies for the AO index and the area-weighted box average of the SST anomaly of the warm pool region bounded by 5°S–5°N, 75°–155°E for the winters 1949/50–2003/04. (b) Plot of the normalized anomalies for the AO index and time series for the SST anomaly in the warm pool region for the winters 1972/73–2003/04. Also plotted is the linear trend for the entire 32 years (dashed–three dotted line for solid curve and dotted line for dashed curve) and the most recent 16 years (dashed–dotted line for solid curve and short dash for short curve). (c) Same as (b) except for the normalized time series for the SST anomaly in the warm pool region and NH station temperatures for the winters 1972/73–2003/04. Correlation coefficient between time series is also shown.

In Fig. 5c we plot the time series from the warm pool index and NH surface temperatures where instead the trends are very similar and the correlation between the two time series is much higher than the correlation between the warm pool index and the AO. We repeated the analysis with the time series derived from the EOF analysis, and the results are nearly identical to those shown in Figs. 5a–c. While the warm pool SSTs may force variability over the Atlantic sector, the variability appears to be unrelated to the trends in the AO and NAO, in that they exhibit little trend, in distinction from the warm pool SSTs. Instead the connection between the warm pool region and global warming appears to be much stronger (Fig. 6c). Regression of the warm pool index to SLP suggests a NAO-*like* pattern (not shown), in agreement with the Hoerling et al. modeling results; however, this appears to be distinct from the actual NAO, given the divergence in the observed trends.

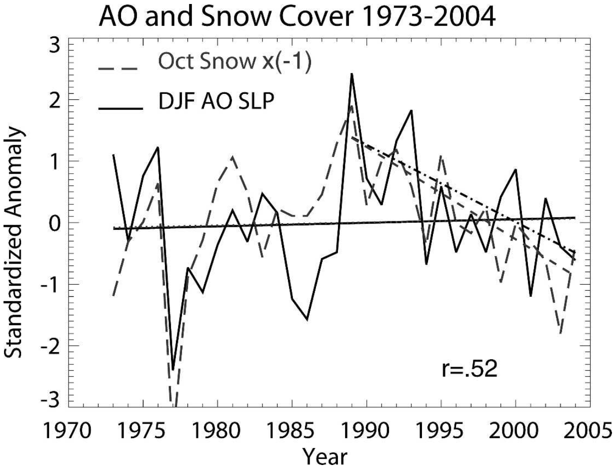


FIG. 6. As in Fig. 3b except for AO index and normalized anomalies of Oct Eurasian snow cover (multiplied by –1 for ease of comparison).

e. *Snow cover*

Unlike the previous three boundary conditions discussed, there are no GCM experiments demonstrating that snow cover has been forcing the observed trend in the AO. However, snow cover has been proposed as important in influencing the phase and strength of the winter AO (Cohen and Entekhabi 1999) and even interannual variability of the AO (Saito and Cohen 2003). We plot the AO time series and the normalized anomaly in Eurasian October snow cover in Fig. 6 (for ease of comparison we have multiplied the snow cover anomalies by –1). Over the time period of reliable measurements of snow cover, the linear trend in October Eurasian snow cover is nearly identical to that of the winter AO time series. As can be seen in Fig. 6, the two trend lines overlay each other. And over the most recent subperiod, both are in a strong negative trend (again, the snow cover index is multiplied by –1, so snow cover is *increasing*). Spearman rank correlations show that the recent strong trends for both are statistically significant. The trend in snow cover, more than the trend in the other boundary conditions presented, most closely resembles the trend in the AO, despite the fact that the snow cover index (October value) *leads* the winter AO index (December–February average) and the other boundary conditions are concurrent with the winter AO.

4. Analysis of surface temperature patterns

In addition to consideration of the indices, it is important to compare the associated spatial patterns. Figure 7a shows the trend in surface temperatures for 1950–2004, and Fig. 7b shows the surface temperature regressions to the NAO index for the same period. As noted by Hurrell (1995), there are considerable similarities between the patterns, especially over northern Eurasia, but also, to a lesser degree, over the higher latitudes of central and eastern North America. As the positive (negative) temperature anomalies associated with the positive (negative) NAO extend over a much larger area than its associated negative (positive) temperature anomalies, it is clear that trends in the NAO can affect hemispheric-scale surface temperatures with some similarity in pattern to the trend. We emphasize again that the NAO does not have a *clearly* defined linear trend whether considered in full over the last 50 years or only for 1973–2004. However, for shorter periods when the NAO is rapidly increasing, as from the early 1970s through the late 1980s, it can project onto the hemispheric average and, to some degree, onto the trend pattern.

It is important to note that, in addition to the previously noted similarities, the warming trend also exhibits important differences from the NAO/AO pattern. Comparing the AO regression (Fig. 7b) to the trend (Fig. 7a), clear differences may be seen over Alaska and northwestern North America and over North Africa and the Middle East. As discussed further below, these parts of the patterns are stable in time and have high statistical significance and so reflect important differences. In an effort to quantify the similarity of the patterns, we correlated the AO temperature pattern of variability with the temperature trend pattern for all grid points poleward of 20°N. The correlation value for the two patterns is equal to 0.40. We estimated the statistical significance of the pattern correlations using Monte Carlo simulations as in Cohen et al. (2005); the spatial correlation between the AO and temperature patterns is not significant at the 10% level.

It is useful to consider patterns both in terms of the magnitude of the signal, as in a regression or covariance plot, and in terms of the strength of the signal relative to local variance, as in a correlation plot. The trend in surface temperature divided by the local standard deviation of surface temperature is shown in Fig. 8c. This can be directly compared to the correlation of the AO to surface temperatures, shown in Fig. 8d. (The AO correlation to surface temperatures is equal to the AO regression to surface temperatures divided by the local standard deviation of surface temperature and hence provides a natural comparison.) Considering the patterns relative to the local variance, as in Figs. 8c and 8d, further highlights the differences in the NH, as well as the notable differences in global pattern, which are consistent with previous analyses of trend (e.g., Jones and Moberg 2003). As will be seen in the following analysis,

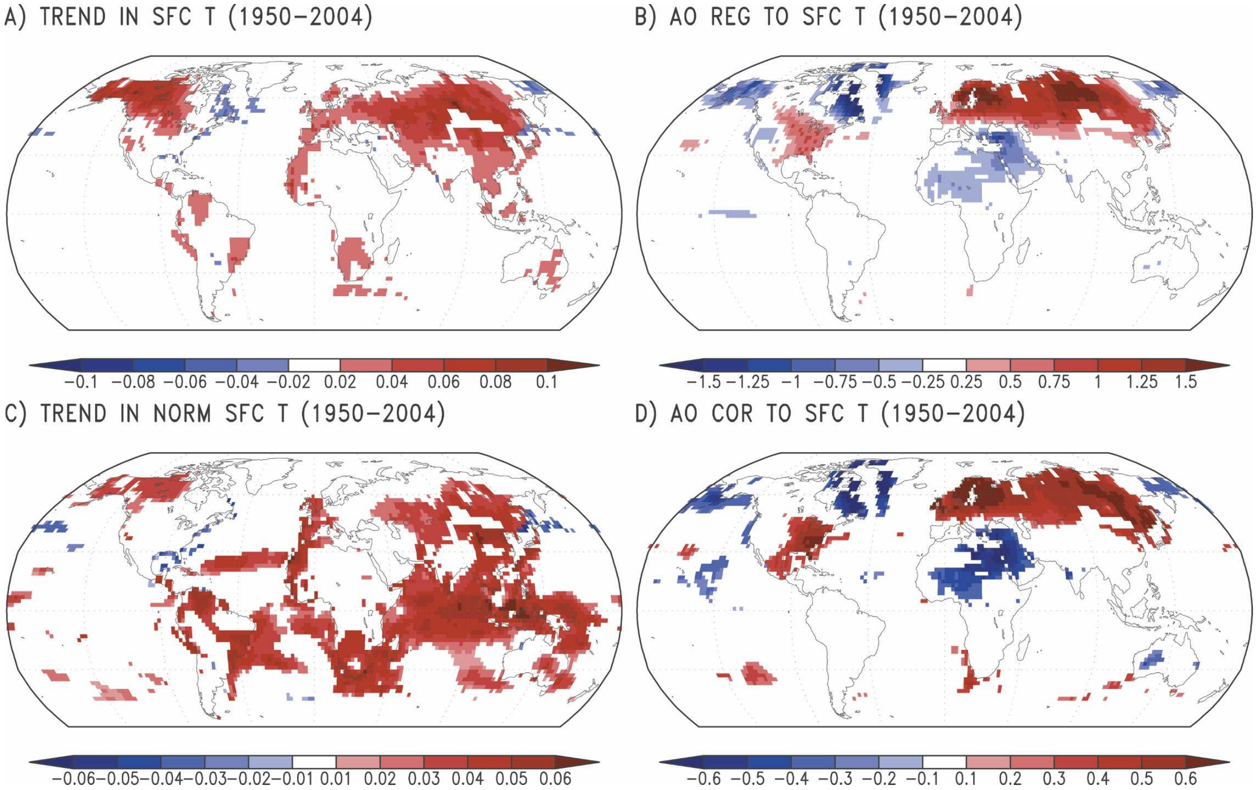


FIG. 7. (a) The raw trend in DJF surface temperatures, (b) DJF surface temperature regressions to the AO index for the same period, (c) normalized trend in DJF surface temperatures, and (d) correlation coefficients between DJF surface temperature and the AO index for the period 1950–2004. In (c) and (d) shading only shown for those regions where confidence exceeds the 95% limit.

these differences in pattern have high statistical significance and are stable in time; thus, they appear to be useful in distinguishing between the AO variability and the warming trend.

The statistical significance of these patterns is assessed through a Monte Carlo approach: 1000 sets of randomized surface temperature are generated; for each set, the AO correlation and the linear trend are calculated. The random time series were generated by maintaining the power spectrum of the observed data while randomizing the phase of each spectral component. This provides time series that are random but have the same temporal characteristics as the original signal. The field significance for both the AO correlation and the trend exceeds 99.9%; the patterns are shown in Figs. 7c,d only for those grid boxes where the local significance exceeds 95%. The main aspects of both patterns, including the areas where they are quite different, have high statistical significance. The patterns calculated from GISS and Hadley Centre surface temperatures are quite similar (not shown), and therefore the results are robust. (Note that, while the analysis and data used here are suitable for the regional and large-scale patterns of interest to the current study, as validated by the common agreement among different datasets, they are *not appropriate* for considering features at spatial scales near the 1° grid resolution.)

The stability of the patterns in time is also of interest and is critical to confidently distinguish between them. Are the key aspects of the spatial patterns stable in time and thus fundamental markers of the phenomenon or, alternatively, are certain aspects sensitive to the time period considered (as with the trend in the AO and NAO)? As a rather stringent criterion, the trend and correlation calculations were made separately on each 9-yr subperiod in the 1951–2004 period. The trend (shown in Fig. 8b) and the correlations (shown in Figs. 8c,d) are presented only for those gridboxes where the same sign was obtained in each of the subperiods; therefore the features seen in Fig. 8 were present in all of the 9-yr subperiods and are therefore stable in time. (The values shown are calculated from the full period, while the mask is calculated from the subperiods; the 9-yr length was chosen as a convenient divisor of the 54-yr record.) Although the patterns computed for each subperiod do vary, the main features are seen to be highly stable. Given this stability, the pattern of the AO and the warming trend may be distinguished with a high

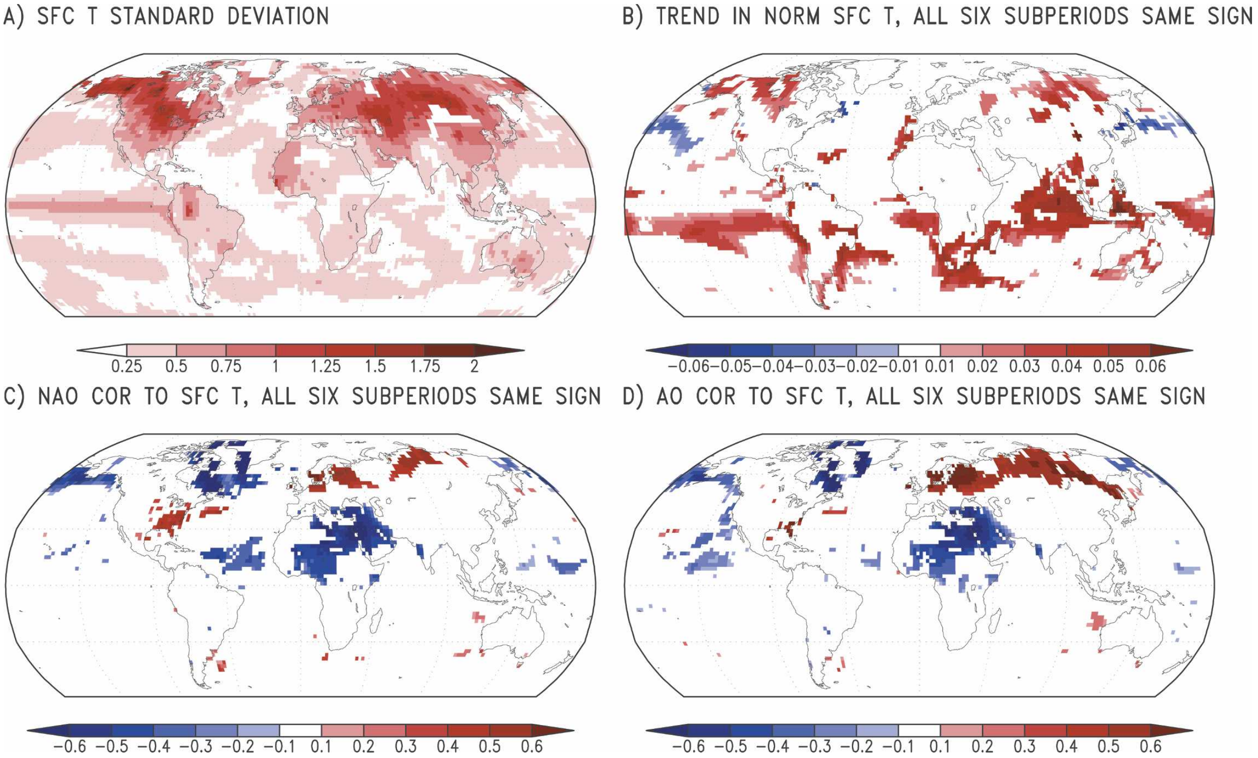


FIG. 8. (a) The standard deviation for DJF surface temperatures; (b) trend in DJF surface temperatures, shown only for those grid boxes where the sign is the same for all six subperiods during 1951–2004; (c) correlation coefficients between DJF surface temperature and the NAO index for the period 1950–2004 shown only for those grid boxes where the sign is the same for all six subperiods during 1951–2004; and (d) as in (c) but for the AO index.

degree of confidence: there is some similarity over the high and middle latitudes of Asia but not over Europe, the Middle East, and North America. The vigorous warming in the tropical and subtropical SSTs, as well as in the Southern Hemisphere, further distinguishes between the warming trend and the AO pattern. The AO may, for particular periods, force regional warming over Asia but does not appear to contribute to the majority of the trend pattern—and, again, both the patterns are stable in time. The same calculations with the NAO index instead of the AO give similar results (not shown).

The correlations for the related boundary conditions are shown in Fig. 9. The field significance has been assessed for each index based on 1000 randomly generated time series. The random time series were generated by maintaining the power spectrum of the observed index while randomizing the phase of each spectral component, as before. Statistical significance was calculated for both the NH and for only the land area of the NH. The significance of the surface temperature correlations for the warm pool index was 99.9% (NH) and 99.4% (NH land); for the North Atlantic index, 99.9% (NH) and 98.5% (NH land); for the snow index, 91.5% (NH) and 98.5% (NH land); and for the stratospheric AO index, 99.9% (NH) and 99.8% (NH land). The patterns and magnitudes of the correlations were very similar when calculated from the GISS and Hadley Centre surface temperatures (not shown), although the snow correlations in Asia are higher in both, possibly a result of real-time data limitations in the CAMS data.

The warm pool index has a very similar pattern to the warming trend. Given the similarity in both pattern and the trend of the indices, the warm pool may be identified as intimately related with the global warming trend. While the warm pool SSTs may, to some degree, force atmospheric changes in the North Atlantic that appear similar to the NAO/AO, warm pool–forced atmospheric variability is apparently not closely related to the observed NAO/AO phenomenon in either its temperature trend or pattern.

The surface temperature variations associated with North Atlantic SSTs have some relationship to the NAO/AO pattern, including over the North American and Eurasian continents as well as the Middle East, but differences as well, particularly over eastern North America and the northwest North Atlantic. As expected from the trend analysis on the time series of its

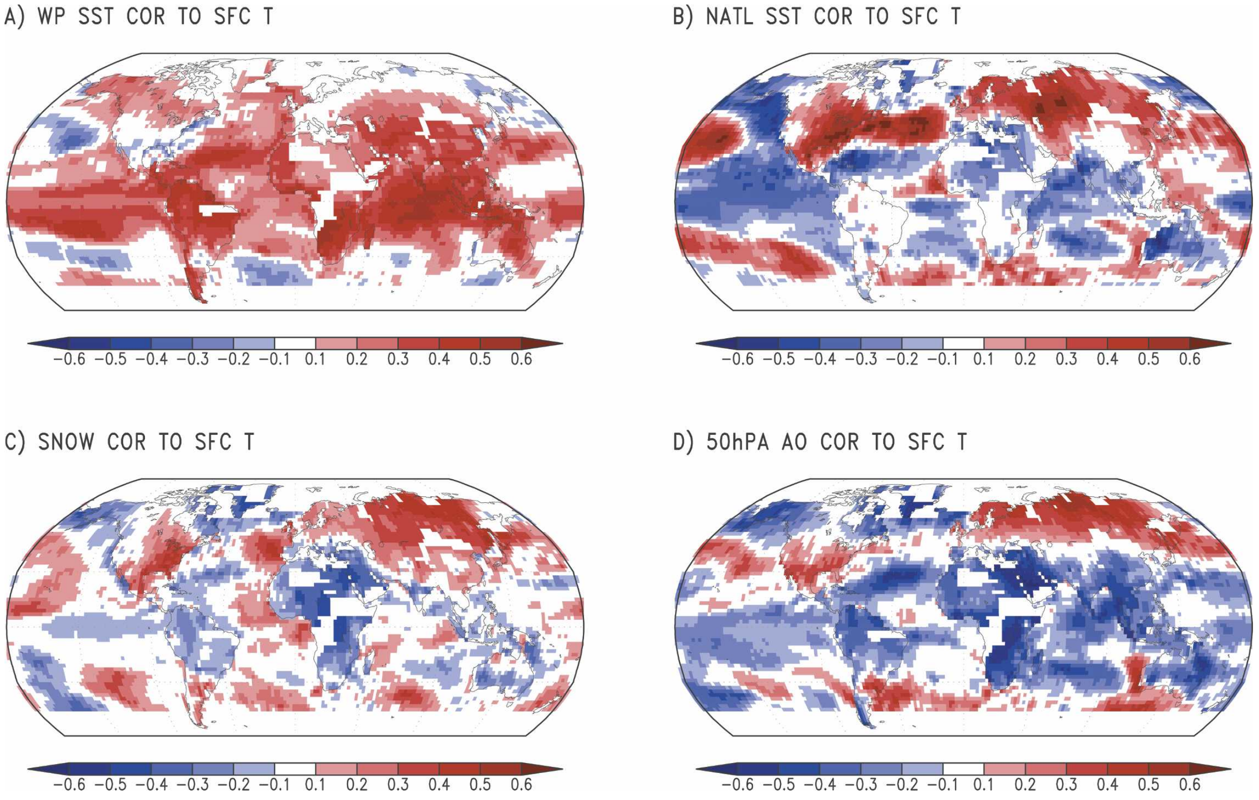


FIG. 9. Correlation of (a) time series of first EOF of warm pool SSTs, (b) time series of third EOF of North Atlantic SSTs, (c) Oct snow cover, and (d) time series of first EOF of 50 hPa with gridded DJF surface temperatures during 1972/73–2003/04.

index, there appears to be no distinguishable relationship with the warming trend pattern.

The pattern of surface temperature correlation to the Eurasian snow cover (in the preceding October) also has similarities to the NAO/AO pattern, particularly over North America, Eurasia, and the Middle East; however, the magnitudes are somewhat modest and there are differences in pattern over the North Atlantic.

Finally, the 50-hPa AO surface temperature pattern is both very similar to the tropospheric NAO/AO patterns (poleward of about 15°N) and very different (in the equatorial regions and Southern Hemisphere, where it looks very similar to the negative of the warming trend). As the 50-hPa AO has a modest negative trend while surface temperatures in those regions have a large positive trend, a negative relationship is expected; however, the magnitude is quite large. Our analysis of the trends in 50-hPa (stratospheric) temperature (Fig. 10) confirms the trend in the 50-hPa AO index: whether calculated for 1973–2004 or 1989–2004,

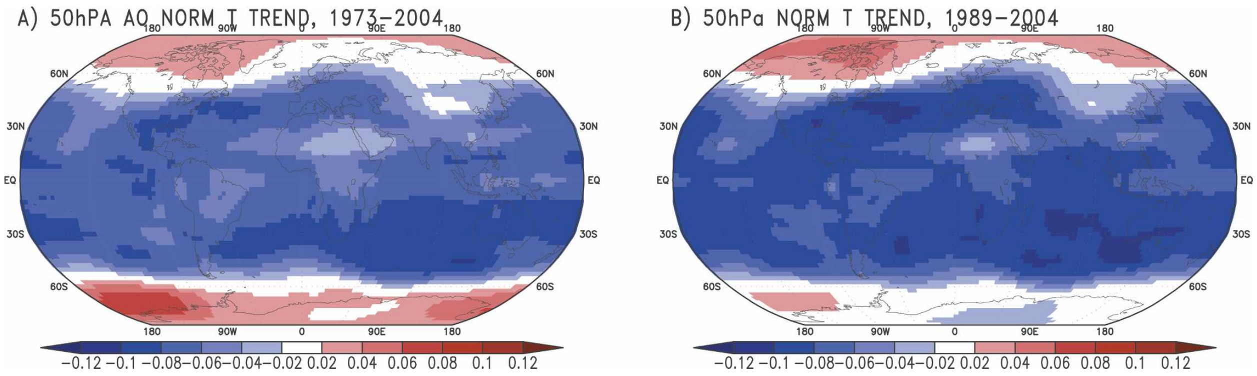


FIG. 10. Trend in normalized temperatures at 50 hPa for the period (a) 1973–2004 and (b) 1989–2004.

the poles have slightly warmed and the midlatitudes and Tropics have cooled in the reanalysis data. At 10 hPa, the warming trend in the northern polar vortex is even stronger than at 50 hPa, and the cooling trend at equatorial and southern subtropical latitudes is still present (not shown). The stratospheric trends presented here are consistent with the trend analysis reported in Lanzante et al. (2003) and in Manney et al. (2005). This is the opposite of trends in the earlier period reported by Thompson et al. (2000) and in contrast to the expected positive temperature trend in the tropical stratosphere as presented by Thompson and Lorenz (2004). Cooling in the stratosphere is an anticipated result of anthropogenically forced global warming (Clough and Iacono 1995; Pawson et al. 1998); the observed gradient in cooling is consistent with both global warming and the modest negative trend in the stratospheric AO.

5. Summary and discussion

We have analyzed the trends and patterns in DJF surface temperatures associated with the NH warming trend, the NAO, and AO for the period 1950–2004, verifying the results across a range of datasets and techniques used to generate the indices. In addition, we examined the related factors of Indo–Pacific warm pool SSTs, North Atlantic SSTs, Eurasian snow cover, and stratospheric AO. The possibility of global warming is one of the most important issues facing our society over the next century (UNEP 1999), and understanding the relationship between natural climate variability and a possible anthropogenically forced warming trend is a critical issue. We have shown that, in the context of the last 30 years, the wintertime warming trend may be clearly distinguished from the AO and NAO temperature signal in terms of the strength of the trend, the consistency of the trend, and the pattern of the trend. Although the AO and NAO showed a strong increase from the early 1970s through the mid-1990s, they have decreased rapidly since then, and their overall trends for the 1972–2004 period are weak to nonexistent and strongly dependent on the choice of start and end date. In contrast, the global warming trend over the pasty 30 years is vigorous and consistent, even in the most recent data. The AO/NAO variability may also be clearly distinguished from the global warming trend in terms of pattern. While there is similarity between the AO/NAO pattern and the warming trend in eastern North America and northern Eurasia, there are also several areas where there are differences, including Alaska and northwestern Canada, North Africa, and the Middle East, where there is a difference in sign, and large regions of the Tropics and Southern Hemisphere, where there is a robust warming trend but no AO/NAO signal. The AO/NAO and warming trend signals in all these areas are stable over the last 50 years and therefore are an appropriate basis for establishing differences between the patterns. Of particular note is the behavior over the last approximately 16 years, when the NH upward temperature trend has continued strongly while the NAO and AO indices have been decreasing. While the NAO and AO may contribute to regional warming in the NH for particular periods, differences in both trend and pattern strongly suggest that the *pattern and magnitude* of the *global warming trend* over the last 30 years are largely *independent* of the AO and NAO.

The trend analysis also highlights differences between various factors that have been related to the NAO and AO and their vigorous upward trend during the 1970s–early 1990s. Aforementioned GCM studies have attributed the anomalous positive trend in the NAO/AO to three different boundary conditions: North Atlantic SSTs, stratospheric cooling due to greenhouse gases, and strong warming of SSTs in the warm pool region of the tropical western Pacific and Indian Oceans. In the current observational analysis, the Indo–Pacific warm pool is associated with global warming both in terms of trend and pattern, with neither bearing a close relationship to the observed NAO and AO variability. North Atlantic SSTs, Eurasian snow cover, and the stratospheric AO are all more closely associated with the NAO and AO surface temperature patterns and have little to no positive trend. The North Atlantic SSTs, as represented by the third EOF, have a modest positive trend over the most recent period analyzed, divergent from the observed negative trend in the AO. From 1950 through the early 1970s the two time series were similarly divergent.

Over the last 16 years, the Eurasian snow cover is best matched with the AO and NAO, in terms of both pattern and trend. Note again that the snow index is reversed in sign so that the snow has been increasing in the recent period while the AO and NAO have been decreasing. Note also that the snow index is derived from the October snow anomalies *leading* the December–February AO and NAO averages and anomalies. A proposed physical mechanism linking fall snow cover and the winter AO in both the troposphere and the stratosphere has been presented in both observational and modeling studies (Saito et al. 2001; Cohen et al. 2002; Gong et al. 2003): increased snow cover enhances upward propagation of Eliassen–Palm (EP) flux, forcing a negative AO first in the stratosphere and then in the troposphere. One interesting question is whether there is a physical connection between the rising temperatures, increasing snow cover, and negative AO over this recent period. We advance the following hypotheses: 1) Warming temperatures are thought to be responsible for the observed decrease in extent and thinning of Arctic sea ice (Parkinson et al. 1999; Vinnikov et al. 1999; Rothrock et al. 1999: Bitz and Roe 2004). 2) As more open water becomes available in the late summer and early fall, a previously frozen moisture source becomes available, providing greater low-level moisture and resulting in increased Siberian snow cover. 3) An increase in snow cover leads to greater frequency of a negative AO through the dynamic pathway previously postulated. We are in the process of examining these proposed linkages.

The stratospheric AO is well matched in trend to the tropospheric AO but has differences in its relationship to surface temperature. Our analysis showed that the stratospheric AO is more highly correlated to surface temperatures in the Tropics than the NAO and AO. The stratospheric temperatures have a near-global-scale cooling trend in the Tropics and midlatitudes, with weak positive trends in the northern polar cap region. The weak positive trends over the Arctic, a reversal of the positive trend widely reported in the late 1990s, are consistent with the near-neutral trend in the AO. The large-scale stratospheric cooling in the Tropics and midlatitudes is consistent with thermal considerations of the stratospheric response to tropospheric warming (Clough and Iacono 1995; Pawson et al. 1998). Such a link to the tropospheric warming trend might also explain the connection to tropical surface temperatures.

In a dynamical context, the global warming trend analyzed here appears to be consistent with theoretical expectations linking the observed increase in anthropogenic greenhouse gases to surface warming, with natural low frequency variability in the climate system likely playing some role as well. Dynamical theory for low frequency behavior of the NAO/AO is much less advanced.

Shindell et al. (1999) showed that a set of models with a highly resolved stratosphere responded to anthropogenic greenhouse gases with a continuous upward trend in the modeled AO index and surface warming, consistent with both the warming trend and the AO increases observed at the time. Based on these results, they suggested that the observed trend in the AO was due to anthropogenic greenhouse forcing and that stratospheric dynamics were a key part of the relationship. While the predicted future behavior of the NAO/AO is outside the scope of the current observational analysis, observational analysis of DJF 1973–2004 shows that the rapid upswing of the NAO/AO during the first half of the period has almost completely reversed itself, while the warming trend has continued unabated throughout the whole period. Therefore, when considering the recent data, the currently observed AO variability no longer seems to be well captured by the strongly increasing AO produced in the model runs with a highly resolved stratosphere. An interesting question is whether aspects of the stratosphere–troposphere coupling hypothesized by Shindell et al. are active during the recent period when the NAO/AO has trended downward. For example, they suggest that greenhouse gases cool the stratospheric polar regions relative to midlatitudes and the Tropics, refracting propagating tropospheric planetary waves equatorward, resulting in a positive AO. However, it is possible that greenhouse gases might cool the midlatitudes and Tropics relative to the polar regions, therefore refracting planetary waves poleward and favoring a negative AO. Further investigation of the connection between increased greenhouse gases and stratospheric temperatures appears to be warranted.

Hoerling et al. (2001) have suggested that the positive trend in Indo–West Pacific SSTs has forced a corresponding positive trend in the NAO/AO. The current observational analysis shows that the Indo–West Pacific SSTs exhibit a robust positive trend throughout the period while the NAO/AO, in contrast, have exhibited decadal swings with a positive trend in the 1970s through the early 1990s and a subsequent negative trend in the recent period, with no overall trend. However, preliminary analysis has suggested that the Indo–West Pacific SST trend *is* associated with NAO-*like* trends in the atmosphere—trends that are similar in pattern but do not project onto the standard definitions of the AO and NAO. These relationships need to be explored further.

Rodwell et al. (1999) have suggested that trends in North Atlantic SSTs force a positive trend in the NAO; however, in the current analysis, the observed NAO variability does not exhibit a clear positive trend. Furthermore, the North Atlantic SST trend (Figs. 8c and 9b) does not appear to be a close match with the forcing pattern used by Rodwell et al., suggesting that further study of these relationships would be useful.

Finally, Cohen and Entekhabi (1999) have suggested that boundary forcing associated with fall snow cover in Eurasia forces subsequent wintertime variability in the AO. The observational variability analyzed here supports this linkage: fall snow cover is linked with subsequent winter AO variability throughout the period of interest ($r = 0.52$: Fig. 7). Additionally, the decadal swings in the AO are well captured in the snow data, with no mismatch where trends are present in one index and not the other. As noted in the previous discussion, we also hypothesize that there is a related dynamical relationship between the recent downward trend in the AO and global warming due to the role of snow cover.

Although our observational analysis shows that the strong positive trend in the AO observed during the 1970s and 1980s has completely reversed over the most recent period, in clear distinction from the global warming trend, the dynamics of the reversal are not clear. It would be of further interest to pursue more in-depth observational analysis and targeted modeling experiments aimed at understanding the dynamical mechanisms underlying the strong reversal in the AO trend, both in the troposphere and the stratosphere, and its divergence from the trend in surface temperatures. It is our intention to pursue these lines of inquiry in future research.

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