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# A New North Atlantic Oscillation Index and Its Variability

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**ABSTRACT**

A new North Atlantic Oscillation (NAO) index, the NAOI, is defined as the differences of normalized sea level pressures regionally zonal-averaged over a broad range of longitudes 80°W–30°E. A comprehensive comparison of six NAO indices indicates that the new NAOI provides a more faithful representation of the spatial-temporal variability associated with the NAO on all timescales. A very high signal-to-noise ratio for the NAOI exists for all seasons, and the life cycle represented by the NAOI describes well the seasonal migration for action centers of the NAO. The NAOI captures a larger fraction of the variance of sea level pressure over the North Atlantic sector (20°–90°N, 80°W–30°E), on average 10% more than any other NAO index. There are quite different relationships between the NAOI and surface air temperature during winter and summer. A novel feature, however, is that the NAOI is significantly negative correlated with surface air temperature over the North Atlantic Ocean between 10°–25°N and 70°–30°W, whether in winter or summer. From 1873, the NAOI exhibits strong interannual and decadal variability. Its interannual variability of the twelve calendar months is obviously phase-locked with the seasonal cycle. Moreover, the annual NAOI exhibits a clearer decadal variability in amplitude than the winter NAOI. An upward trend is found in the annual NAOI between the 1870s and 1910s, while the other winter NAO indices fail to show this tendency. The annual NAOI exhibits a strongly positive epoch of 50 years between 1896 and 1950. After 1950, the variability of the annual NAOI is very similar to that of the winter NAO indices.

**Key words:** North Atlantic Oscillation (NAO) index, interannual and decadal variability, signal-to-noise ratio, seasonal phase lock

## 1. Introduction

The North Atlantic Oscillation is a large-scale seesaw in atmospheric mass between the subtropical high (the Azores High) and the polar low (the Icelandic Low) in the North Atlantic region (Walker, 1924; Walker and Bliss, 1932; van Loon and Rogers, 1978; Wallace and Gutzler, 1981; Rogers, 1984; Barnston and Livezey, 1987; Hurrell, 1995). It is the dominant mode of atmospheric circulation variability in the North Atlantic sector throughout the year, although it is most pronounced during winter (Barnston and Livezey, 1987; Rogers, 1990; WCRP, 1998; Dickson et al., 2000; Visbeck et al., 2001). Walker (1924) first discovered the oscillation and devised the first NAO index that derived from simultaneous use of time series of surface temperature at 5 stations and sea level pressure (SLP) at 4 stations (Walker and Bliss, 1932). This complex index was simplified by Rogers (1984, 1990) by using SLP anomalies from Ponta Delgados, Azores and Akureyri, Iceland. Several other simplified indices based on instrumental records have followed (Barnston and Livezey, 1987; Moses et al., 1987; Hurrell, 1995; Jones et al., 1997; Osborn et al., 1999; Gong and Wang, 2001; Cullen et al., 2002). The definitions and details of these NAO indices are listed in Table 1.

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**Table 1.** Instrument-based NAO indices

| NAO Index | Author(s) | Definition | Period | Season | Source |
|---|---|---|---|---|---|
| $NAOI_R$ | Rogers (1984) | $P_{PD} - P_A$ | 1874–2000 | Monthly | Ohio State University |
| $NAOI_H$ | Hurrell (1995) | $P_L - P_S$ | 1865–2000 | Monthly | NCAR Climate Analysis Section |
| $NAOI_J$ | Jones et al. (1997) | $P_G - P_S$ | 1821–2000 | Monthly | Climate Research Unit (CRU), University of East Anglia |
| $NAOI_M$ | Moses et al. (1987) | $P_{PD} - P_S$ | 1867–2000 | Monthly | |
| $NAOI_B$ | Barnston & Livezey (1987) | RPCs of NH mean 700-hPa heights | 1950–2000 | Monthly | Climate Prediction Center (CPC), NCEP, NOAA |
| $NAOI_V$ | van Loon & Rogers (1978) | $T_J - T_O$ | 1860–1975 | Winter | |
| $NAOI_W$ | Wallace & Gutzler (1981) | $TH_J - TH_O$ | 1949–1977 | Winter | |
| $NAOI_G$ | Gong & Wang (2001) | W: $P_{R1} - P_{R2}$ | 1873–2000 | Winter | |
| | | S: $P_{R3} - P_{R2}$ | | Summer | |
| $NAOI_C$ | Cullen et al. (2002) | Based on SST | 1856–1992 | Winter | |
| $NAOI_P$ | Portis et. al. (2001) | A mobile index | 1873–1999 | Monthly | |

The symbols in the definitions (the third column) are as follows: *P*, normalized SLP anomaly; PD, Ponta Delgada (Azores); A, Akureyri (Iceland); L, Lisbon (Portugal); S, Stykkisholmur (Iceland); G, Gibraltar; RPCs, rotated principal components; NH, Northern Hemisphere; *T*, surface air temperature; J, Jakobshavn (Greenland); O, Oslab (Norway); *TH*, 1000–700-hPa thickness; W, winter; S, summer; R1, (35°N, 10°W–10°E); R2, (65°N, 10°–30°W); R3, (45°N, 40°–60°W); SST, sea surface temperature.

The instrumental record-based NAO indices employ three types of variables: SLP (Rogers, 1984; Moses et al., 1987; Hurrell, 1995; Jones et al., 1997; Huang et al., 1998; Shabbar et al., 2001), surface air temperature (SAT) (van Loon and Rogers, 1978; Wallace and Gutzler, 1981) and sea surface temperature (SST) (Cullen et al., 2002). SLP-based NAO indices use both station data and model analysis. A station data-based NAO index is often defined as the difference of SLP between two stations located close to the "center of action" over Iceland and the Azores. The northern station is often chosen in Iceland, e.g., Akureyri (Iceland) (Rogers, 1984) or Stykkisholmur (Iceland) (Moses et al., 1987; Hurrell, 1995; Jones et al., 1997), whereas the southern station varies among Ponta Delgada (Azores) (Rogers, 1984; Moses et al., 1987), Lisbon (Portugal) (Hurrell, 1995), or Gibraltar (Jones et al., 1997). It is noticed that there are large distances between the southern stations, and the choice of station can make apparent differences in the description of circulation features related to the NAO, especially in particular seasons (Jones et al., 1997). Such a kind of index is useful for extending the record back in time (Hurrell and van Loon, 1997; Jones et al., 1997). However, it might not be the optimal representation of the spatial pattern associated with the NAO, and it also might not effectively capture the temporal variability of the NAO in all seasons (Jones et al., 1997; Hurrell, 2002) due to the fixed geographical positions of station pairs and larger noises and uncertainties from small-scale and transient circulation phenomena. Besides, Portis et al. (2001) developed a mobile NAO index that follows the seasonal migration of the NAO nodes.

The analysis-based NAO index is derived from objectively analyzed SLP (Barnston and Livezey, 1987; Rogers, 1990; Cayan, 1992), using empirical orthogonal function (EOF) analysis, rotated principal component (RPC) analysis (Rogers, 1990; Hoerling et al., 2001), or the difference of mean SLP between two regions (Gong and Wang, 2001). However, such an NAO index often requires a rather complex numerical analysis to define, and is difficult to interpret physically due to the limitations of the EOF and PC methods themselves (Richman, 1986; Ambaum et al., 2001; Dommenget and Latif, 2002).

Therefore, it is necessary to reduce noises and uncertainties in an NAO index, and to simplify and yet to optimize it (WCRP, 1998). The purpose of this study is to present a new and simplified NAO index based on the large-scale circulation structure, to study more objectively the variability of the NAO and its relationship to broad-scale atmospheric circulation and impacts on the global climate, and to shed light onto several popular NAO indices for better understanding and application. An assessment and comparison will be carried out for indices based on SLP, which capture the NAO pattern remarkably well (Wallace, 2000). A description of datasets used is given in section 2. Section 3 defines a new NAO index, the NAOI, and section 4 makes a comprehensive comparison of the NAOI with five other NAO indices (including four station-based NAO indices and one rotated principal component (RPC) type index) in terms of spatial patterns, percentage of variance explained, signal-to-noise ratio, and relationships to surface air temperature (SAT), respectively. The assessment shows that the NAOI performs better for all criteria mentioned above. Using the NAOI, section 5 contains an analysis of interannual and decadal variability of the NAO since 1873. Conclusions are given in section 6.

## 2. Data

The NAO indices used in this study are $\mathrm{NAOI}_R$ (Rogers, 1984), $\mathrm{NAOI_H}$ (Hurrell, 1995), $\mathrm{NAOI_J}$ (Jones et al., 1997; Osborn et al., 1999), $\mathrm{NAOI_M}$ (Moses et al., 1987), and $\mathrm{NAOI_B}$ (Barnston and Livezey, 1987), as listed in Table 1. The station pressure data at Ponta Delgada (Azores), Akureyri (Iceland), Lisbon (Portugal), Stykkisholmur (Iceland), and Gibraltar were originally obtained from the World Monthly Surface Station Climatology (WMSSC). It is noted that the $\mathrm{NAOI_J}$ has recently been modified, due to a minor and previously uncorrected inhomogeneity identified in the Gibraltar SLP record. The effect of this modification is most evident in the northern summer season and minimal during winter (refer to http://www.cru.uea.ac.uk/∼ timo/projpages/nao_update.htm). Besides, beginning with November 1989 and in many months since then, the Ponta Delgada data are missing and are replaced by sea level pressures at either Horta, Azores or Santa Maria, Azores - which currently seems to be the only meteorological station on the island reporting to the WMO. For details, please see the homepage of Rogers' NAO index: http://www-bprc.mps.ohio-state.edu/NAO/NAO_description.html.

Two kinds of monthly mean SLP gridded datasets are employed in this study. One is the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data on a 2.5°×2.5° mesh for the period 1948–2000 (Kalnay et al., 1996). The other is the SLP data on a 5° latitude by 10° longitude grid for the Northern Hemisphere (1873–2000) from the Climate Research Unit (CRU) at the University of East Anglia (UEA) (Jones, 1987; Basnett and Parker, 1997). This dataset is based mainly on the UK Met. Office analyses. The annual cycle was removed by subtracting the mean monthly values for the period 1958–2000.

The surface temperature dataset used in this study is from CRU (Jones et al., 2001). It is a combination of land-air temperature anomalies (Jones, 1994) and sea surface temperature anomalies (Parker etal., 1995). Jones et al. (2001) discuss the details about the merging of the two temperature anomaly datasets.

## 3. A new NAOI

The NAO is a meridional oscillation (Wallace and Gutzler, 1981; Rogers, 1984; Peixoto and Oort, 1992). Moreover, this oscillation spans a broad longitude range in the Atlantic and European sector extending from the east coast of the United States to the Mediterranean (Wallace and Gutzler, 1981). Figure 1 illustrates correlations between monthly or yearly regionally zonal-averaged SLPs over the longitudes of 80°W–30°E at every latitudes between 0°–90°N. The most important feature, whether monthly (Fig. 1a) or annual (Fig. 1b), is a statistically significant negative correlation of SLPs between the mid-latitudes and polar region, clearly indicating a north-south seesaw in air mass over the North Atlantic region. This feature is more apparent in annual data than in monthly data. The correlation pattern in the SLPs shows that there tend to be two homogeneous zones in the North Atlantic region, one centered near 35°N and the other around 65°N, and separated by a transition belt near 55°N. The strongest negative correlation coefficient is –0.73 at 35°N and 65°N and at 37.5°N and 65°N for the monthly data, and is -0.84 at 35°N and 65°N and at 37.5°N and 67.5°N for annual data, which are all statistically significant at the 99.9% confidence level.

These features suggest that there is a mass transport between the two homogenous zones. In fact, the regionally (80°W–30°E) zonal-averaged SLPs at the two latitudes represent the relative strengths of the subtropical high (the Azores High) and polar low (the Icelandic Low), which also reflect the variability of the large-scale circulation associated with the NAO. From the above discussions, a simple NAO index is defined as a pressure difference between the two latitude zones as follows:

$$NAOI = \hat{P}_{35^\circ\mathrm{N}} - \hat{P}_{65^\circ\mathrm{N}} \,, \tag{1}$$

where $P$ is the monthly SLP averaged over the longitudes of 80°W–30°E, $\hat{P}$ is the normalized value of $P$, and the subscripts in Eq. (1) denote latitudes. The normalization $\hat{P}$ for a given year $n$ and month $m$ is calculated as follows:

$$\hat{P}_{m,n} = \frac{P'_{m,n}}{S_P}, \tag{2}$$

where $P'_{m,n}$ is monthly pressure anomaly of $P_{m,n}$, a departure from the 1958–2000 base period, and $S_P$ is the total standard deviation of the monthly anomaly $P'_{m,n}$ time series, i.e.,

$$S_P = \sqrt{\frac{1}{12\cdot 43}\sum_{i=1958}^{2000}\sum_{j=1}^{12}{P'_{j,i}}^2}\,.$$

**Table 2.** Area-weighted average percentage of variance explained by NAO indices for winter (DJFM mean), summer (JJA mean), monthly, seasonal, and annual SLPs over the North Atlantic sector (20°–90°N, 80°W–30°E) for the period January 1958–December 2000

| | NAOI | $\mathrm{NAOI_R}$ | $\mathrm{NAOI_H}$ | $\mathrm{NAOI_J}$ | $\mathrm{NAOI_M}$ | $\mathrm{NAOI_B}$ |
|---|---|---|---|---|---|---|
| Winter | 48 | 42 | 40 | 37 | 42 | 39 |
| Summer | 24 | 14 | 12 | 12 | 12 | 17 |
| Monthly | 31 | 20 | 19 | 19 | 20 | 17 |
| Seasonal | 35 | 23 | 21 | 19 | 23 | 18 |
| Yearly | 43 | 29 | 29 | 20 | 28 | 28 |

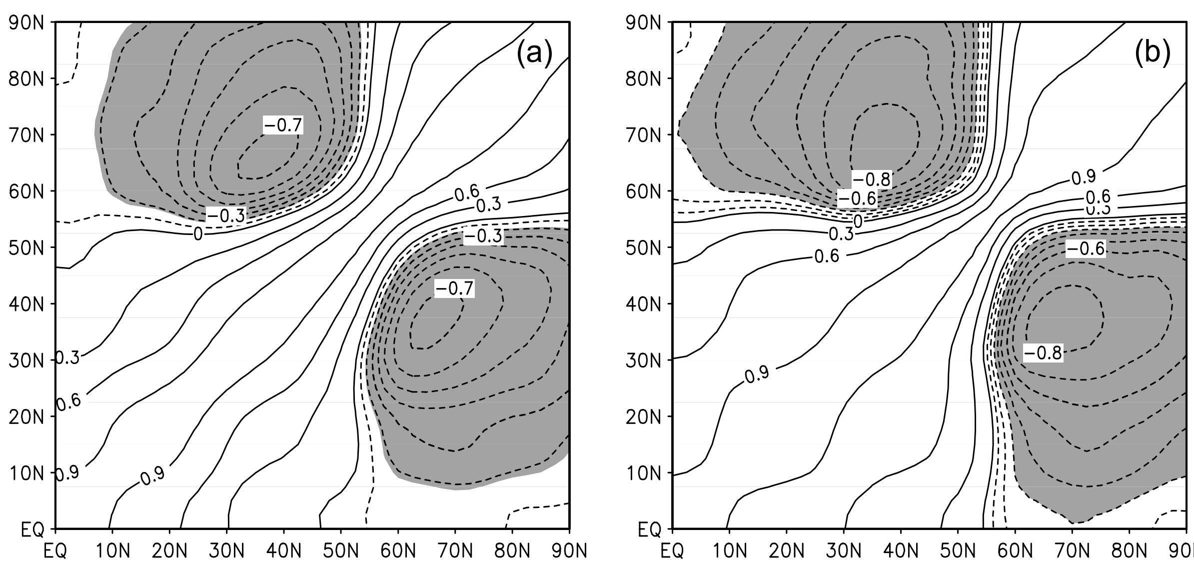


**Fig. 1.** Correlation coefficients between regional zonally-averaged SLPs over the North Atlantic region (0°–90°N, 80°W–30°E) for the period 1958–2000 for (a) monthly and (b) annual data. Critical negative values of the correlation at the 95% confidence level are shaded. The contour interval is 0.1 for negative values.

The above defined NAOI index is essentially a regional circulation index over the North Atlantic sector that measures the intensity of the westerly winds across the central North Atlantic Ocean, with an emphasis on two action centers of the NAO, as shown in Fig. 1.

## 4. Comparisons among the NAO indices

Assessing an NAO index for its representativeness, usefulness, or practicality is quite involved. It is insufficient to show the superiority of an NAO index in one way or another, because each index may be superior in a certain aspect. Osborn et al. (1999) undertook a brief comparison of NAO indices for the winter season (see their Appendix C). In order to compare objectively the capabilities of the NAO indices mentioned before, in characterizing the NAO related features, we examine each index in the following four aspects.

### 4.1 *Spatial pattern of NAO*

In order to make a comprehensive comparison of NAO indices capturing representative spatial features associated with NAO, we have computed correlations between SLPs and six NAO indices, i.e., the NAOI, $\mathrm{NAOI_R}$, $\mathrm{NAOI_H}$, $\mathrm{NAOI_J}$, $\mathrm{NAOI_M}$, and $\mathrm{NAOI_B}$ as described in Table 1, for monthly, seasonal, and yearly data, respectively. Figures 2 and 3 show the correlation coefficients between monthly and annual SLP in the Northern Hemisphere and the six NAO indices. Overall, all these correlation patterns obviously capture the main features of the NAO, i.e., a strong negative correlation between SLP in the Icelandic Low and the North Atlantic High or the Azores High (Walker and Bliss, 1932; Kutzbach, 1970; Rogers, 1990; Peixoto and Oort, 1992). However, it is evident that the

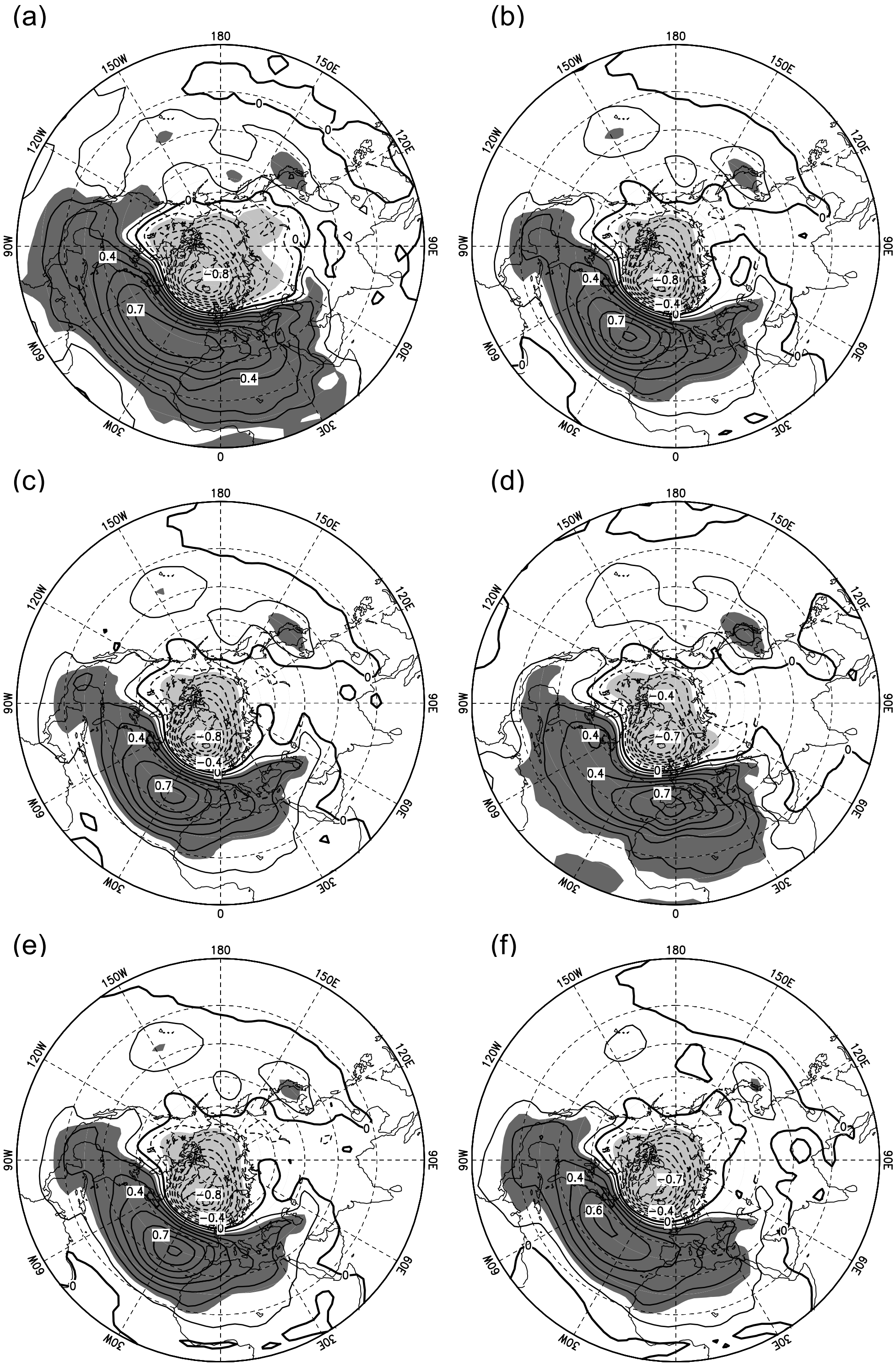


**Fig. 2.** Correlation coefficients between monthly SLP and (a) the NAOI, (b) $NAOI_R$, (c) $NAOI_H$, (d) $NAOI_J$, (e) $NAOI_M$, and (f) $NAOI_B$ indices in the Northern Hemisphere for the period 1958–2000. The shading indicates significance at the 99.9% confidence level.

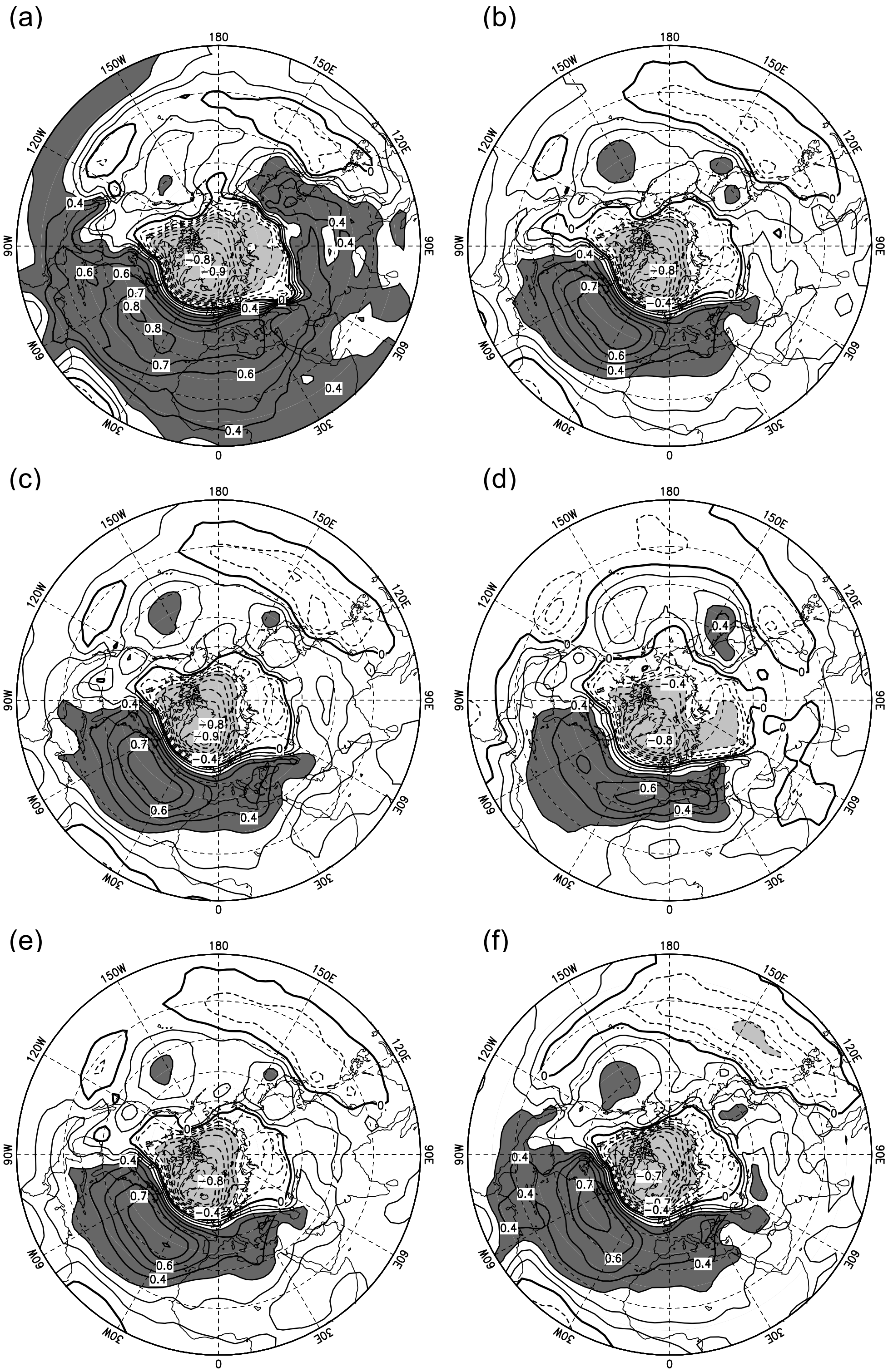


**Fig. 3.** Same as in Fig. 2, but for annual series. The shading indicates significance at the 95% confidence level.

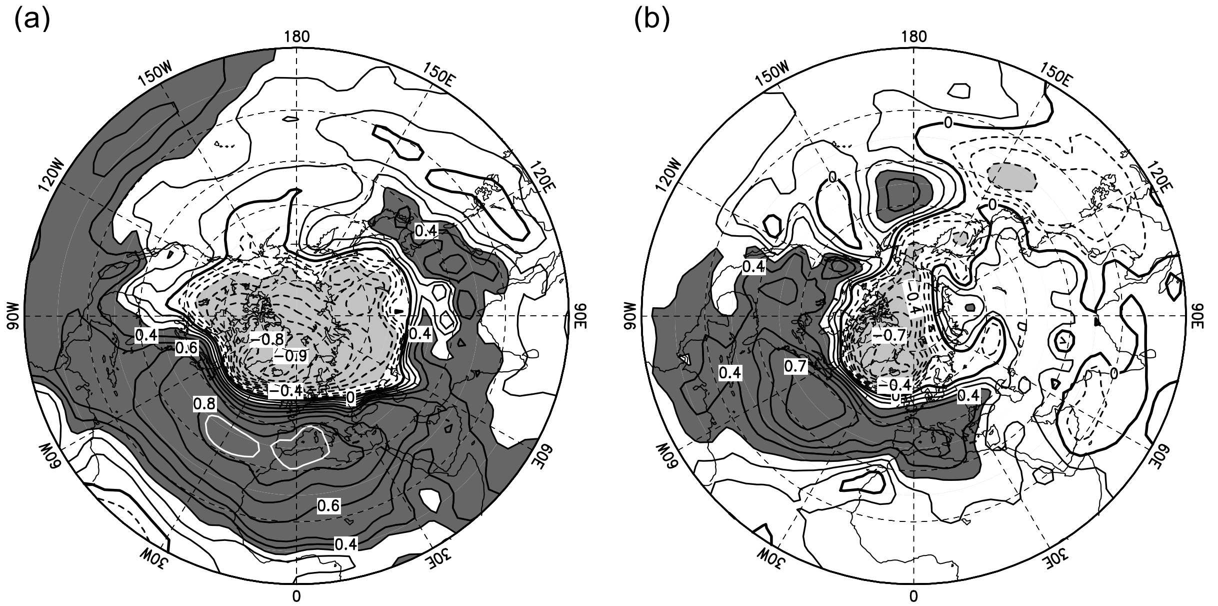


**Fig. 4.** Correlations between SLP and the NAOI for (a) winter (DJFM) and (b) summer (JJA). The period is 1958–2000. The shading shows significance at the 95% confidence level.

NAOI exhibits the strongest correlation with SLP in both the strength of correlation and the area covered by the significant correlation (Figs. 2 and 3). This suggests a remarkable capability of the NAOI to capture the spatial pattern of the NAO.

Previous studies suggest that the NAO exists throughout the year, but is most pronounced in magnitude during the northern winter, with most pronounced seasonal variations in location changes of its action centers (Barnston and Livezey, 1987; Hastenrath, 1991; Rogers, 1990; Hurrell and van Loon, 1997). However, for the station-based NAO indices, i.e., the $\mathrm{NAOI_R}$, $\mathrm{NAOI_H}$, $\mathrm{NAOI_J}$, and $\mathrm{NAOI_M}$, the associated spatial patterns describing the NAO (figures not shown) not only demonstrate action centers that are geographically fixed and do not change with season, but also intensities that are too weak in summer. Hence, these NAO indices fail to capture the seasonal variation in location of the NAO.

Figure 4 shows the correlations between the NAOI and SLPs during winter (DJFM) and summer (JJA), respectively. In winter (Fig. 4a) the NAO pattern is very strong and broadly extended. The center of negative correlation is over Iceland near 65°N and 30°–5°W with the zero line near 55°N (Fig. 4a), and the maximum values of positive correlation are over an elongated zonal band between 30°–40°N from 40°W to 20°E (refer to the area enclosed by the isoline 0.8 in Fig. 4a). The positive correlation belt contains two maxima with values larger than 0.8, over the Azores at 30°–40°N and 40°–20°W and over the western Mediterranean at 30°–40°N and 10°W–10°E, respectively. Ponta Delgada (37.8°N, 25.7°W, Azores), Lisbon (38.8°N, 9.1°W, Portugal), and Gibraltar (36.1°N, 5.2°W) are situated close to these maximal centers. Therefore, any one of the three stations is suitable for construction of an NAO index during winter. On the other hand, such a station data-based NAO index can only reflect one of the two centers, which is clearly a shortcoming. In summer (Fig. 4b), the NAO pattern is indeed weaker. The Iceland center migrates westward to near 45°–20°W. The two subtropical centers seen in winter (Fig. 4a) are merged and move westward to near 60°–35°W. The seasonal westward migration of the NAO action centers from winter through summer, as shown in Fig. 4, is similar to previous results, such as from the RPCs of Rogers (1990) and the EOFs of Hurrell and van Loon (1997) and from other investigations (Davis et al., 1997; Mähel et al., 1998; Portis et al., 2001). Thus, the NAOI as an NAO index can be applied to all seasons.

The results discussed above suggest that the NAOI provides a more faithful representation of the time-dependent behaviour of the spatial pattern in SLP over the North Atlantic sector, in comparison with other NAO indices.

**Table 3.** Signal-to-noise ratio of five NAO indices for month, winter (DJFM), summer (JJA), monthly, seasonal, and annual series (1958–2000)

| | NAOI | $NAOI_R$ | $NAOI_H$ | $NAOI_J$ | $NAOI_M$ |
|---|---|---|---|---|---|
| Jan | 3.6 | 2.2 | 2.1 | 2.3 | 2.3 |
| Feb | 2.9 | 2.6 | 2.2 | 2.2 | 2.2 |
| Mar | 3.4 | 2.0 | 1.7 | 2.5 | 2.4 |
| Apr | 1.7 | 1.5 | 1.4 | 1.4 | 1.5 |
| May | 1.6 | 1.0 | 1.0 | 1.4 | 1.4 |
| Jun | 1.7 | 0.9 | 1.0 | 1.5 | 1.5 |
| Jul | 1.3 | 0.9 | 1.1 | 1.2 | 1.2 |
| Aug | 1.4 | 1.1 | 1.2 | 1.4 | 1.4 |
| Sep | 1.5 | 1.0 | 1.1 | 1.1 | 1.3 |
| Oct | 1.7 | 1.3 | 1.3 | 1.9 | 1.9 |
| Nov | 2.2 | 1.5 | 1.5 | 1.6 | 1.5 |
| Dec | 2.9 | 2.4 | 2.4 | 2.2 | 2.2 |
| Winter | 4.4 | 2.9 | 2.2 | 3.0 | 3.0 |
| Summer | 1.5 | 0.9 | 1.0 | 1.1 | 1.1 |
| Monthly | 2.5 | 1.8 | 1.7 | 1.9 | 1.9 |
| Seasonal | 2.9 | 1.9 | 1.7 | 2.1 | 2.1 |
| Yearly | 3.4 | 1.7 | 1.4 | 2.1 | 2.0 |

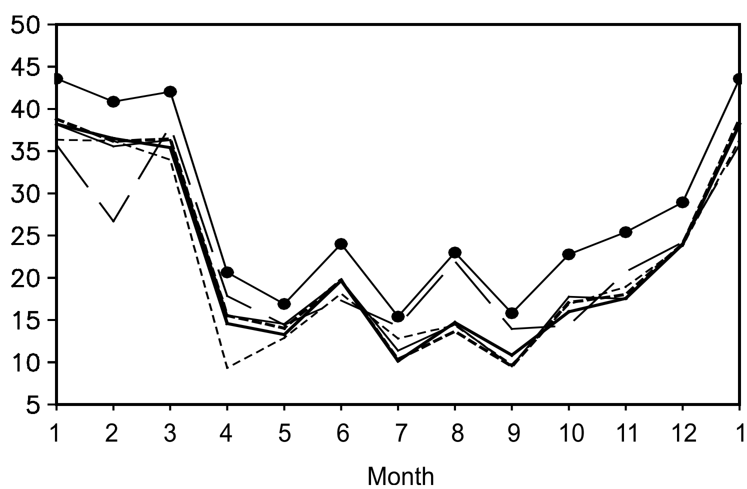


**Fig. 5.** Seasonal variation of area-weighted average percentage of variance explained by the NAOI (dotted line), $NAOI_R$ (thin solid line), $NAOI_H$ (thick solid line), $NAOI_J$ (thin short-dashed line), $NAOI_M$ (thick short-dashed line), and $NAOI_B$ (long-dashed line) for SLP over the North Atlantic sector (20°–90°N, 80°W–30°E). The period is 1958–2000.

### 4.2 *Percentage of variance explained by the NAO indices*

Analyzing the percentage of variance explained by an NAO index for SLP can give a quantitative assessment of its representativeness. Figure 5 illustrates the seasonal variation of the area-weighted average percentage of variance explained by all six NAO indices for SLP over the North Atlantic sector (20°–90°N, 80°W–30°E). A common feature shown in Fig. 5 is that the percentage of the variance explained by all NAO indices shows a sizeable annual cycle with larger values in winter (especially in January, February, and March) and smaller values in summer and both transition seasons (April, May, September, and October), which also suggests a pronounced seasonal variation of the NAO intensity itself. Besides, the sharp drop of the explained variance from March to April indicates an abrupt change of the NAO in the process of seasonal transition from winter to spring and summer. It is unclear why such an abrupt change occurs. Another noticeable characteristic in Fig. 5 is that among the six NAO indices, the variance explained by the NAOI is the largest in every calendar month.

On average for 1958–2000, the NAOI accounts for 48%, 24%, 31%, 35%, and 43% of the variances of winter, summer, monthly, seasonal, and annual SLP fields over the North Atlantic sector, respectively (Table 2). And these percentages are 6%–11%, 7%–12%, 11%–14%, 12%–17%, and 14%–23% higher than those explained by the other five NAO indices, respectively. It is obvious that the NAOI explains the largest amount of the variance of the SLP field over the North Atlantic sector in all months, seasons, and years in comparison with the other indices.

### 4.3 *Signal-to-noise ratio of the NAO indices*

The signal-to-noise ratio of an index can be considered as a measure of the effectiveness of the index. The signal-to-noise ratio from Trenberth (1984) is used here. This ratio is defined as the ratio of the standard deviations of the combined series of the two components in the NAO, and the noise, in this case, is a measure of all fluctuations where the two components in the NAO are operating in phase and therefore are not part of the large-scale coherent oscillation. A comparison of the signal-to-noise ratios of five NAO indices, the NAOI, $NAOI_R$, $NAOI_H$, $NAOI_J$, and $NAOI_M$, is given in Table 3. There is a clear seasonal variation in the signal-to-noise ratio of each of the five NAO indices with the maximum in winter and the minimum in summer. The NAOI has the best signal-to-noise ratio, significantly higher than the other four, especially in the winter season, and also for all monthly, seasonal and annual data. For winter (DJFM) and summer (JJA), the cross correlations of the two components of the NAOI are –0.9 and –0.38, and the corresponding signal-to-noise ratios are 4.4 and 1.5, respectively. The cross correlations for all monthly, seasonal, and annual data are –0.73, –0.79, and –0.84, and the corresponding signal-to-noise ratios are 2.5, 2.9, and 3.4, respectively, i.e., the signal-to-noise ratio of the NAOI increases as the timescale of the average increases. Due to the fact that the NAOI is defined as regional zonal-averages over a large range of longitude between 80°W and 30°E, the NAOI is dominated by large-scale circulation features, and is relatively insensitive to small-scale or transient processes of the circulation not related to the NAO. This is also why it has a very high signal-to-noise ratio. It is, therefore, suggested that the NAOI is the better index for describing and monitoring the monthly, seasonal, and annual variability of the NAO.

### 4.4 *Relationships to surface air temperature (SAT)*

The NAO is strongly correlated with SAT (van Loon and Rogers, 1978; Hurrell, 1996; Rogers, 1997; Jones et al., 1997; Sutton and Allen, 1997; Rodwell et al., 1999). Figures 6 and 7 display the correlation coefficients between the six NAO indices and monthly and annual SAT in the Northern Hemisphere. From the figures, it is obvious that the maximum correlations, and their covered area, are largest for the NAOI (Fig. 6a and 7a), while overall patterns are similar for all six NAO indices. The correlations are strongly positive over northern Europe extending eastward into much of Eurasia between 55°–75°N and the eastern United States, and are significantly negative over Baffin Island, the Labrador Peninsula, Greenland, and the North Atlantic Ocean between 10°–25°N and 70°–30°W (Figs. 6a and 7a).

The relationships between the NAOI and SAT are quite different from winter to summer (Fig. 8). In winter (Fig. 8a) the correlation pattern is very similar to but stronger than that in the case of the monthly series (Fig. 6a). The correlation is strongly positive over northern Europe and the eastern United States, which indicates a positive (negative) NAO phase corresponding to an intense (weak) subtropical North Atlantic High and an intense (weak) Icelandic Low with abnormally cold (warm) conditions. Over northeastern Canada, Greenland, the North Atlantic Ocean between 10°–25°N and 70°–20°W, and the region from northern Africa to the Middle East, correlations are significantly negative, indicating relatively cold (warm) conditions for the positive (negative) NAO phase. The correlation in the North Atlantic Ocean between the NAO and SAT also shows a tripole pattern, agreeing with previous studies (Bjerknes, 1964; Rodwell et al., 1999; Sutton and Allen, 1997; Grotzner et al., 1998; Czaja and Frankignoul, 2002). In summer (Fig. 8b), correlations are weak and the spatial pattern reflects prevailing small-scale characteristics. A larger region with statistically significant correlations is found over the North Atlantic Ocean between 10°–25°N and 80°–30°W. Moreover, there is still a triple pattern associated with the NAO in the North Atlantic Ocean in summer.

The correlation maps in Figs. 6, 7, and 8a show a clear signature of the temperature seesaw between

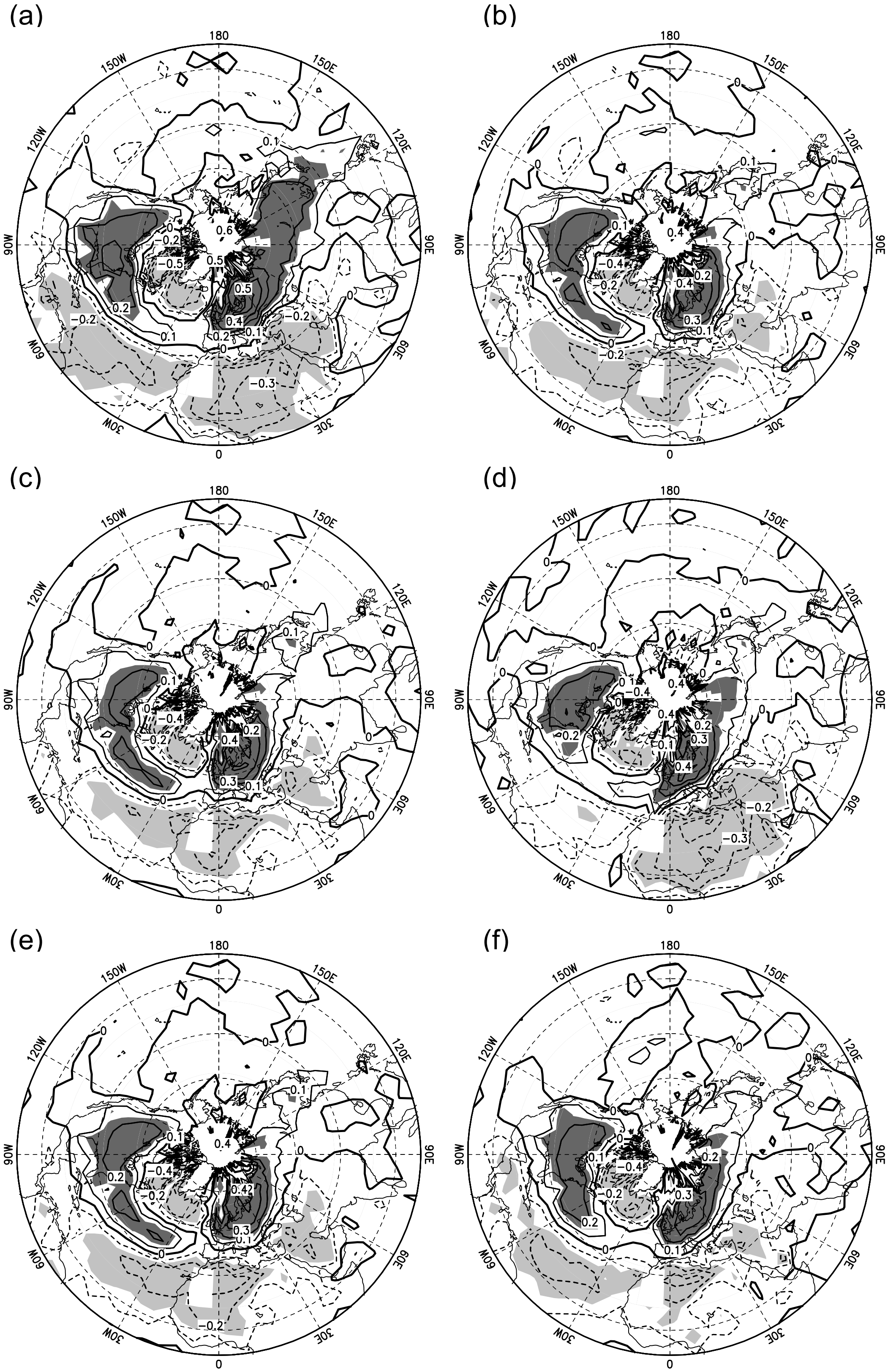


**Fig. 6.** As in Fig. 2, but for the surface air temperature.

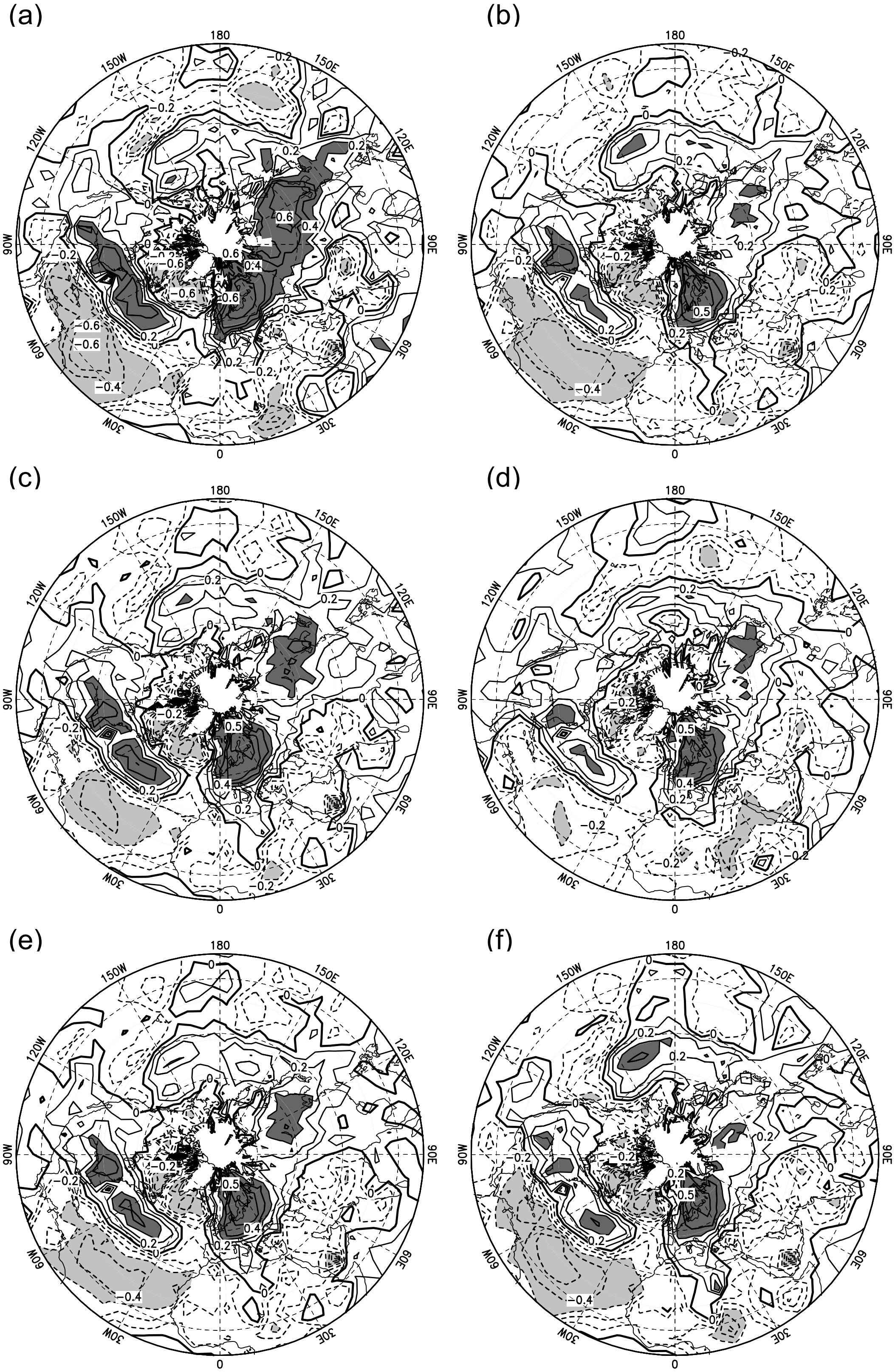


**Fig. 7.** As in Fig. 6, except using annual series.

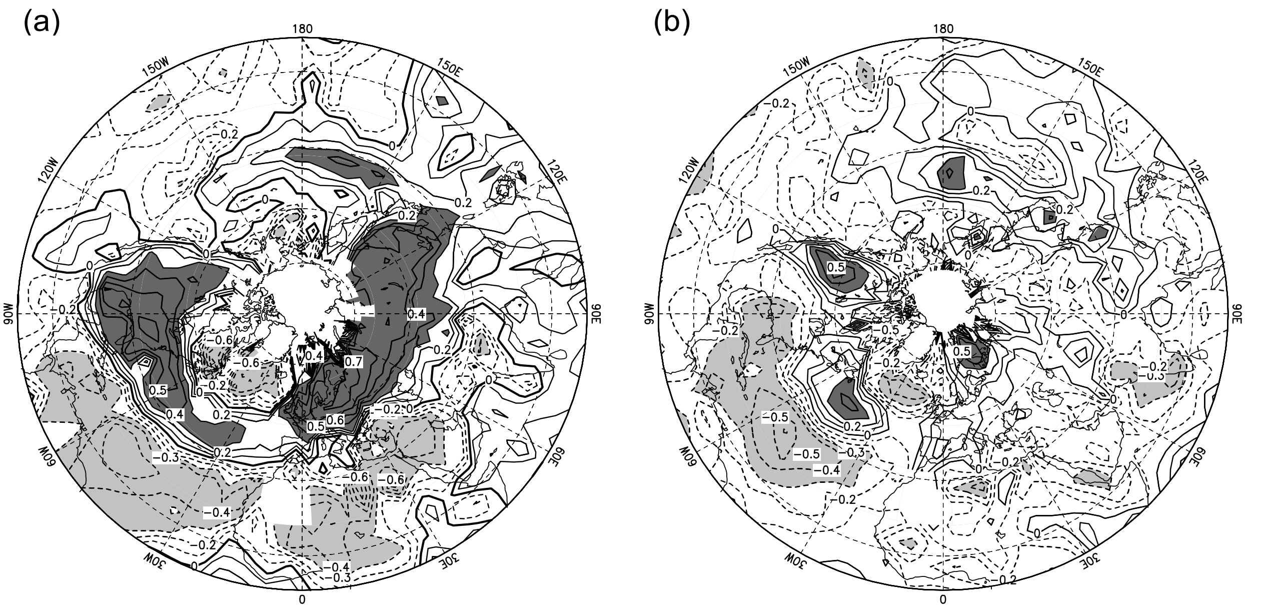


**Fig. 8.** As in Fig. 4, except for the surface air temperature.

**Table 4.** Standard deviation of the NAOI for the 128-year period 1873–2000

| Months | | | | | | | | | | | | Seasons | | | | M | S | Y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | DJFM | AM | JJA | SON | | | |
| 2.69 | 2.93 | 2.48 | 1.44 | 1.08 | 1.01 | 0.79 | 0.82 | 0.96 | 1.32 | 1.75 | 2.04 | 1.63 | 0.90 | 0.58 | 0.86 | 1.78 | 1.16 | 0.68 |

The capital letters M, S, and Y in the final columns are abbreviations for monthly, seasonal, and yearly, respectively.

Greenland and Northern Europe documented first by van Loon and Rogers (1978), including a secondary action center over the eastern United States and a broad region from the North Atlantic Ocean between 10° and 25°N across northern Africa to the Middle East. One striking and stable feature is that whether in winter or summer the correlation pattern between the NAO and the SAT exhibits a tripole pattern in the North Atlantic Ocean and the NAO is strongly negative correlated with the SAT over the North Atlantic Ocean region of 10°–25°N and 70°–30°W.

## 5. Variability of the NAOI

Using a combination of two monthly mean SLP gridded datasets, i.e., the CRU dataset for the period 1873–2000 (Jones, 1987; Basnett and Parker, 1997) and the NCEP/NCAR reanalysis for the period 1948–2000 (Kalnay et al., 1996), we construct a long-term time series of the NAOI based on the definition (1). There is very little bias introduced into the long-term NAO time series (1873–2000) although this series was computed using the statistics from the 1958–2000 NCEP reanalysis data (not shown). Computations of departure and total standard deviation are described in section 3. The time series of the NAOI since 1873 are shown in Fig. 9 for monthly, annual, and four seasons, along with their respective low-pass filtered series. Positive (negative) values of the NAOI indicate a stronger (weaker) than normal subtropical North Atlantic High, deeper (shallower) than usual Icelandic Low, and stronger (weaker) than normal westerlies over the middle latitudes.

Although the seasonal cycle has been removed from the NAOI in the calculation of the index (that is, the expected values or the first moments of twelve months of the anomalies series equal to zero), the interannual variability (i.e., the second moment) of the NAOI of each month versus month still possesses seasonal variation. In fact, the interannual variability of the NAOI is strongly phased-locked with the seasonal cycle, with a minimum in the summer months of July and August, and a maximum in the winter month of February, respectively (Table 4). The standard deviation of the

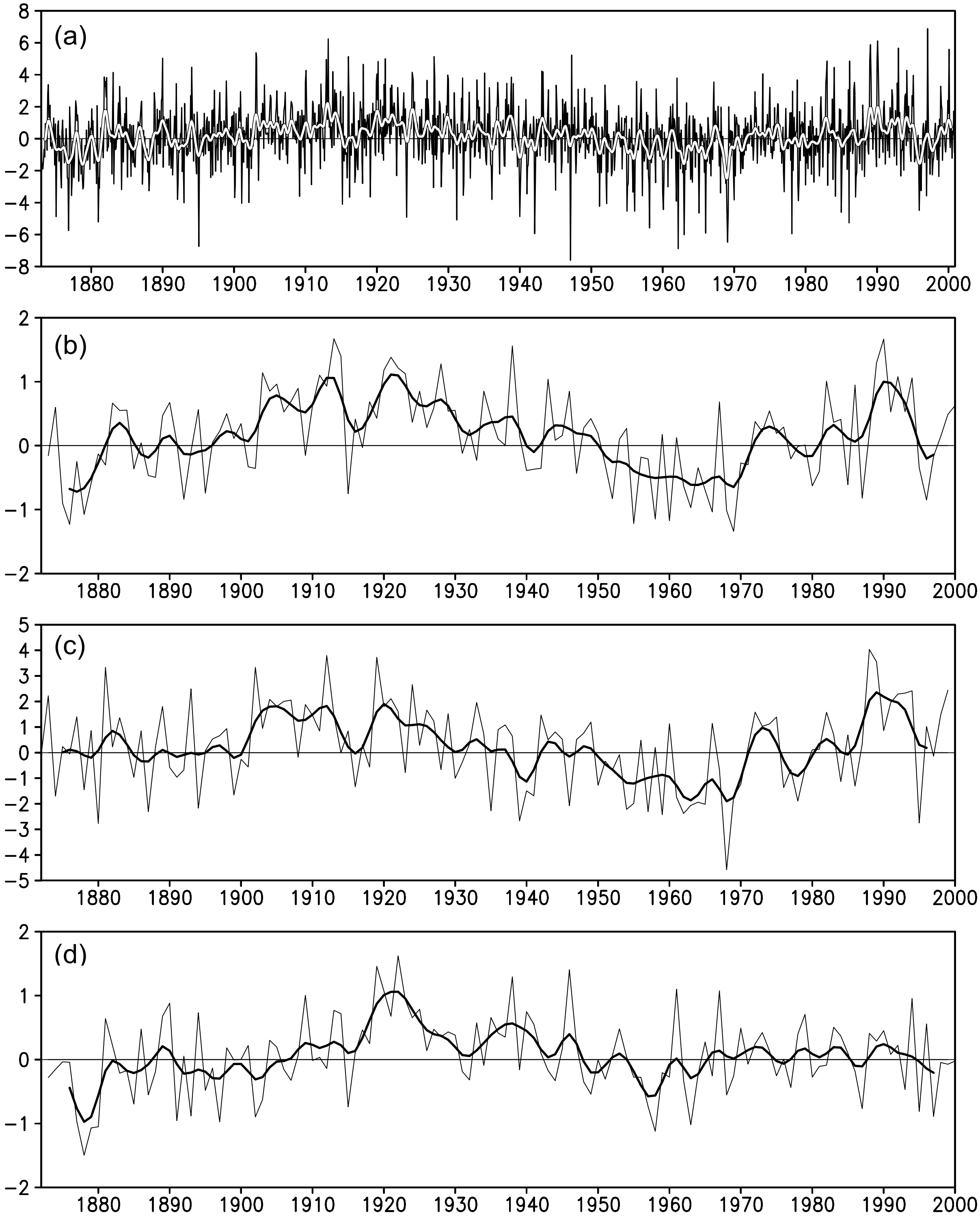


**Fig. 9.** The NAOI time series for (a) monthly (1873–2000), (b) annual (1873–2000), (c) winter (DJFM) (1872–1999), (d) summer (JJA) (1873–2000), (e) spring (AM) (1873–2000), and (f) autumn (SON) (1873–2000). The thick white line in (a) shows a 15-month Gaussian-type filtered value. The thick solid lines in (b)–(f) indicate 7-year Gaussian-type filtered values. These thick lines represent the low-pass filtered regional meridional pressure gradients over the North Atlantic sector in their respective timescales.

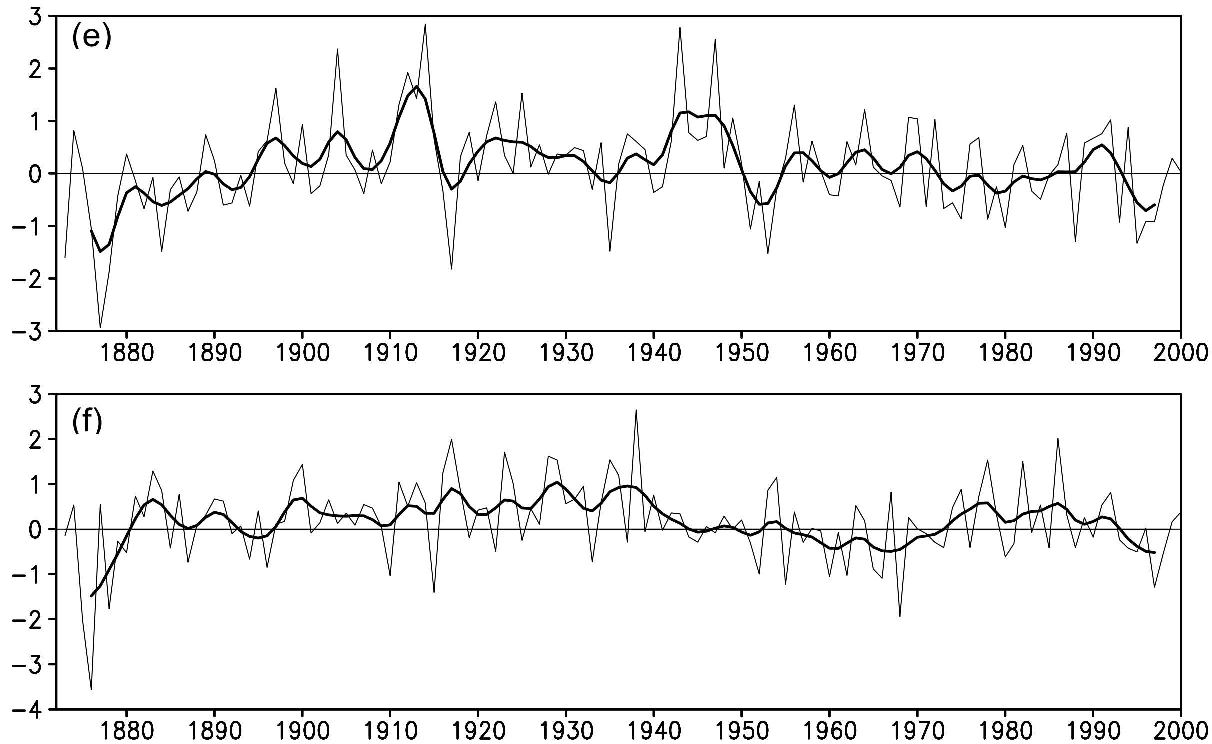


**Fig. 9.** (Continued)

NAOI in winter is about three times as large as that in summer, which implies that much of the interannual variability of the annual NAOI may primarily result from winter. For the annual NAOI since 1873, the years 1913, 1990, 1938, 1914, and 1921, show the five highest positive values, and the years 1969, 1876, 1955, 1960, and 1958 the five lowest negative values (Fig. 8b).

The annual NAOI (Fig. 9a) has gone through several noticeable epochs since 1873 in which the NAOI persists in one phase for many years. Two negative episodes with low-index extrema are from 1875–1881 and from 1951–1971, when the zonal flow across the Atlantic Ocean was weaker than normal, and two positive episodes with high-index extrema are from 1896–1950 and from the mid-1970s to the mid-1990s, when the westerlies across the Atlantic Ocean were stronger than average. This century-scale variation of annual NAOI is in accordance with the result from Portis et al. (2001). Comparison of Figs. 9b–f shows that the negative decadal epoch 1875–1881 in the annual NAOI primarily resulted from spring, summer, and autumn seasons, while the strong negative phase of 1951–1971 was primarily due to winter. The latter was also found previously in other observational and modeling studies (Hurrell, 1995; Jones et al., 1997; Rodwell et al., 1999; Osborn et al., 1999; Dickson et al., 2000; Dong and Sutton, 2002). Two negative periods of the annual NAOI (Fig. 9a) were associated with a weak Azores High and Icelandic Low during the same periods; refer to Figs. 1a and 5a of Sahsamanoglou (1990) and Fig. 1b of Rogers (1984). The two strongest positive epochs in the annual NAOI occurred in a long positive period of more than 50 years between 1896 and 1950, with the maximum value in 1913. For the early portion of the epoch (before 1930), the annual values of the NAOI were primarily contributed to by winter, while for the late portion of the epoch (after 1930), spring, summer, and autumn seasons were responsible. For the other major positive epoch from the mid-1970s to the mid-1990s, the winter season is the predominant contributor.

By examining trends in the annual NAOI values (Fig. 9b), three segments are distinguished, an upward trend from the 1870s to 1910s, a downward trend from the 1920s to 1960s, and another upward trend since the 1970s.

An apparently different feature of variability, in comparison of the annual, winter, and autumn NAOI time series with the summer and spring NAOI time series over the past 30 years, is that the summer and spring NAOI have not shown any pronounced increase or decrease in trends, i.e., lack of decadal and longer variability (Fig. 9d–e).

## 6. Conclusions

A new NAO index, the NAOI, is defined as the difference of normalized SLP regionally zonal-averaged over the North Atlantic sector. The NAOI index captures well large-scale circulation features of the NAO, and is essentially a measure of the intensity of zonal winds across the central North Atlantic between 35°N to 65°N. The cross correlations between two components of the NAOI show the existence of large-scale shifts, or meridional seesaw, of air mass between two zonally homogeneous zones, centered near 35°N and 65|*circ*N, respectively. The two components of the NAOI represent the strengths of the subtropical high and polar low in the North Atlantic region.

A systematic comparison of six NAO indices, including the NAOI, shows that the NAOI provides a much more faithful and optimal representation of the spatial-temporal variability associated with the NAO, suggesting the NAOI as a better choice for describing and monitoring variability of the broad-scale NAO and for diagnosing relationships between the NAO and global climate variations. A few key features of the NAOI are summarized as the following:

(1) Spatial variations associated with the NAO are well captured by the NAOI on multiple timescales. Unlike other NAO indices, which mostly apply to the winter season only, the NAOI can be used to characterize the NAO for all seasons. It is evident from the correlations between the NAOI and SLP that the NAOI can well describe the seasonal migration in the location of action centers associated with the NAO.

(2) The NAOI explains a large fraction of the variance of the SLP over the North Atlantic sector (20°–90°N, 80°W–30°E) on all timescales, which is significantly greater than that of other indices. Due to its implicit broad-scale property, the NAOI has a high signal-to-noise ratio, which is significantly larger than other NAO indices.

(3) The NAOI, among all six NAO indices, under examination exhibits the strongest correlation pattern with SAT, even though their spatial distributions are similar. There are quite different relationships between the NAOI and SAT during winter and summer. In winter, significant positive correlations are over northern Europe extending eastward into much of Eurasia and the eastern United States, while the strong negative correlations are over Baffin Island, the Labrador Peninsula, Greenland, the North Atlantic Ocean between 10°–25°N and 70°–20°W, and northern Africa extending eastward to the Middle East. In summer, however, only a larger area with relatively strong negative correlations exists over the North Atlantic Ocean between 10°–25°N and 80°–30°W. It is worth noting that there is a strongly negative correlation between the NAOI and the SAT over the North Atlantic Ocean between 10°–25°N and 80°–30°W in both winter and summer.

The NAOI time series exhibits strong interannual and decadal variability. While the interannual variability of the NAOI shows a clear phase lock to seasonal cycle, the decadal variation of the NAOI is stronger in the annual mean data than in the winter season average. The decadal trends of the NAOI also differ greatly from season to season, which lacks explanation.

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