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Interannual and interdecadal variations in the North Atlantic Oscillation spatial shift

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The spatial shift of the North Atlantic Oscillation (NAO) is analyzed by using the Twentieth Century Reanalysis version 2 dataset and identifying NAO action centers directly on winter mean sea-level pressure (SLP) anomaly maps. The spatial shift of the NAO is characterized by four NAO spatial shift indices: the zonal and meridional shifts of the NAO southern and northern action centers. It is found that the zonal and meridional shift trends of the NAO action centers move along a path of southwest-northwest direction. Spectral analysis shows that the four NAO spatial shift indices have periodicity of 2–6 years and the NAO index has periodicity of 2–3 years in terms of high-frequency variations. On a decadal time scale, the NAO spatial shift indices are closely (positively) related to the NAO index, which is in agreement with previous studies of the relationship between the NAO index and the spatial shift of the NAO pattern. However, there is no relationship between the NAO index and the meridional shift of the northern action center on an interannual time scale. The significant relationship between the NAO index and the interannual variability of NAO spatial shift indices is very likely to be associated with synoptic-scale Rossby wave breaking, which generates surface pressure anomalies and thus affects the phase and pattern of the NAO. The correlations of winter westerly winds over 90°W–0° and the NAO index and the NAO spatial shift indices have a '+ – + –' structure from the Equator to the North Pole. Although there is close correlation between the NAO spatial shift indices and the strength of the zonal winds in the North Atlantic region, the effect of the zonal winds on the NAO spatial shift differs at different latitudes. Hence, the role of the zonal winds is probably a result of the NAO spatial shifts.

North Atlantic Oscillation, spatial shift, interannual variation, interdecadal variation, zonal winds

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The North Atlantic Oscillation (NAO) is a large-scale seesaw in atmospheric mass between the subtropical high (Azores high) and the subpolar low (Icelandic low) in the North Atlantic Ocean. The NAO is the dominate mode of winter climate variability in the North Atlantic region, ranging from central North America to Europe and far into northern Asia, and even covering the whole Northern Hemisphere [1–6] .

The influence of the NAO on the climate of the North Atlantic and surrounding areas depends on the temporal variation in the NAO spatial structure [7]. Hilmer and Jung [8] found an eastward shift of the NAO action centers when comparing the period 1978–1997 with the period 1958–1977. Accompanied by this shift in the NAO pattern, NAO-related climate variability, such as the Siberian wintertime temperature, sea ice export through Fram Strait, North Atlantic storm activity and net surface heat fluxes, in the North Atlantic region have clearly changed [7–11].

Previous studies have suggested that the eastward shift of NAO in the late 1970s is probably due to increased greenhouse gas concentrations [12], a higher NAO index [13–15], increased North Atlantic storm activity [9,12], stronger mean westerly winds in the North Atlantic region [16,17] and the eastward shift of the Atlantic storm-track eddy

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[18,19], among which the higher NAO index is widely considered to be the most important because it is associated with increasing North Atlantic storm activity [9], stronger mean westerly winds in the North Atlantic region [16] and the eastward shift of the Atlantic storm-track eddy [18,19]. In addition to the zonal shift, Wu et al. [20] found that the active centers of the NAO shift southward (northward) when the NAO index is in a negative-anomaly (positive-anomaly) phase.

Previous research on the NAO spatial shift has been mostly limited to interdecadal variations in the period 1958–1997. However, the interannual variation in a longer time series has barely been investigated. In addition, the location of the NAO action centers has been indirectly obtained using mathematical methods, such as empirical orthogonal function (EOF) analysis [13], regression analysis [7], cluster analysis [14] and the self-organizing map method [15]. Realistically, atmospheric oscillation is described as a seesaw of sea-level pressure between the centers of two atmospheric actions on winter mean sea-level pressure anomaly maps [21], and the positions of action centers derived from mathematical methods are thus not exactly the position of the NAO. In addition, it is difficult to obtain the interannual variation in the NAO spatial shift. The purpose of this study is to clarify the spatial-shift mechanism of the NAO by identifying the action centers directly on winter mean sea-level pressure anomaly maps.

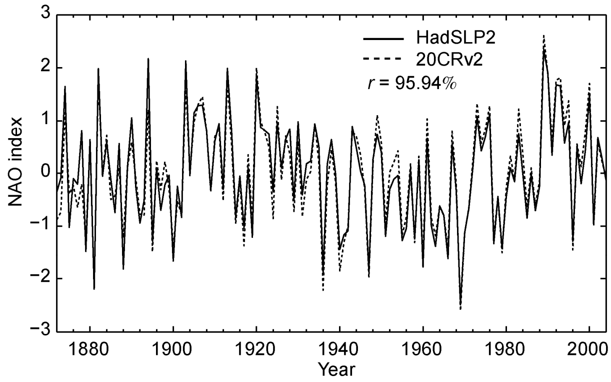

Figure 1 NAO index based on HadSLP2 (solid line) and 20CRv2 (dashed line) during 1872–2004 (principal component of the first EOF).

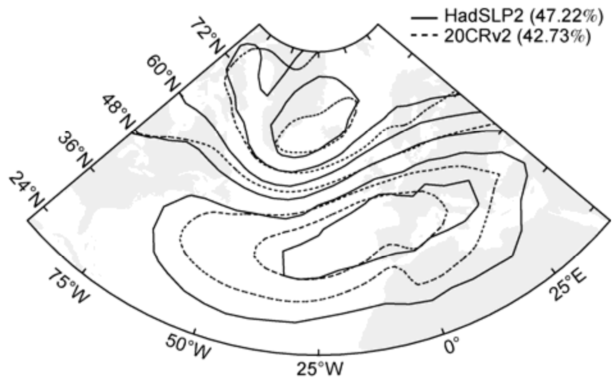

Figure 2 NAO spatial pattern based on HadSLP2 (solid lines) and 20CRv2 (dashed lines) during 1872–2004 (first EOF mode).

1 Data and methods

The basic dataset used in this study is the Twentieth Century Reanalysis V2 (20CRv2) dataset from NOAA/OAR/ESRL PSD [22–24]. Variables analyzed include the monthly mean sea-level pressure (SLP) and zonal winds from the year 1871 to 2008. The data are on a 2.0°×2.0° latitude-longitude grid, with 24 pressure levels for zonal winds. To check the reliability of this dataset, an estimation for the NAO is made here. The NAO index based on 20CRv2 agrees extremely well with HadSLP2 observations, with a correlation coefficient of 95.94% (Figure 1). Meanwhile, their spatial patterns are a close match (Figure 2). Hence, this long-term dataset has high reliability. In addition, the location of the NAO action centers can be acquired more accurately from 20CRv2, which has higher spatial resolution.

The NAO index used in this study is defined as the principal-component time series of the leading EOF of winter (December through March) SLP anomalies over the Atlantic sector (20°–80°N, 90°W–40°E). Because the NAO has the two action centers of the subtropical high (Azores high) and the subpolar low (Icelandic low), four indices need to be defined to characterize the NAO spatial shift. The four indices are the northern-center meridional shift index (NMS index), northern-center zonal shift index (NZS index), southern-center meridional shift index (SMS index) and southern-center zonal shift index (SZS index). The NMS/SMS index is defined as the latitudinal anomalies of the position of the northern (Icelandic low)/southern (Azores high) center in each year relative to the averaged annual mean during the period 1872–2008, while the NZS/SZS index is defined as the longitudinal anomalies during the period 1872–2008. The position of the northern (Icelandic low)/southern (Azores high) center can be deduced from the annual mean winter SLP field.

A 7-year Gaussian filter is used to investigate the interdecadal variations. Spectral analysis employing the multi-taper method (MTM) [25] is carried out to extract periodic signals.

2 Spatial shift in the NAO

The NAO index and NAO spatial shift indices for the period 1872–2008 are shown in Figure 3. Both the NAO index and NAO spatial shift indices exhibit interannual and interdecadal variability. Table 1 lists the correlations among the NAO spatial shift indices and with the NAO index. The NAO spatial shift indices are closely related to the NAO

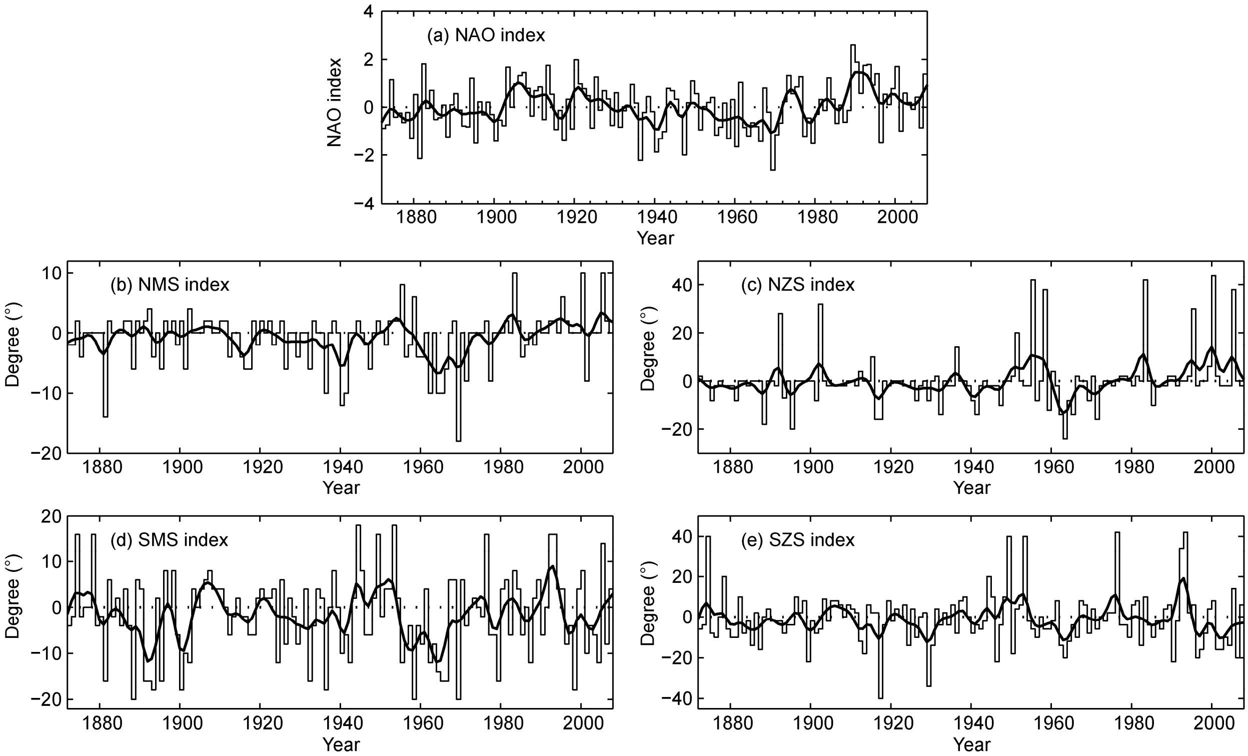

Figure 3 (a) NAO index; (b) NMS index; (c) NZS index; (d) SMS index; (e) SZS index. The thick black lines indicate 7-year Gaussian-type filtered values.

Table 1 Correlations among the NAO spatial shift indices and with the NAO index a)

	NMS index	NZS index	SMS index	SZS index
NAO index	0.5644*** (0.5576***) b)	0.1542 (0.2355)	0.6690*** (0.7491***)	0.4289*** (0.5287***)
NMS index	–	0.6155*** (0.6362***)	0.5085*** (0.5620***)	0.3512*** (0.3460*)
NZS index	–	–	0.1404 (0.1589)	0.1773* (0.2238)
SMS index	–	–	–	0.7122*** (0.7847***)

a) *, **, *** indicate statistical significance at the 95%, 99% and 99.9% levels respectively according to a Student's *t*-test. b) Numbers in parentheses are correlation coefficients calculated for the period 1958–1997.

index (except the NZS index) with correlation coefficients of 0.5644, 0.6690 and 0.4289 at the 99.9% significance level, showing the spatial shift trends are in accordance with the NAO index except the zonal shift of the northern center. The high correlation between the NMS index and NZS index (0.6155) and that between the SMS index and the SZS index (0.7122) suggest a preferable southwest-northeast path for the NAO. In addition, there is positive correlation between the NAO index and the meridional shift, indicating that the NAO shifts to the north (south) during the positive (negative) phase of the NAO.

The correlations between the NAO index and NAO spatial shift indices for the periods 1958–1997 and 1872–2008 have much less variation, showing that the significant relationship between the NAO index and NAO spatial shift indices during 1958–1997 is not a special case for the past 137 years (1872–2008), but it is surely a period of relatively large magnitudes of variation in the NAO spatial shift. The NAO index reached its highest value in the early 1950s before following a declining trend and reaching a minimum around 1970, whereas the NAO action centers shifted from the northeast to their southwesternmost positions in a period from the early 1950s to around 1964. The NAO index began an oscillating rise after 1970 and into the early 1990s, whereas the southern center shifted afterwards to its northeasternmost position. However, the northern center did not shift to its northeasternmost until the early 2000s. An eastward shift of the NAO during 1978–1997 as compared to 1958–1977 was reported by Hilmer and Jung [8]. In our analysis of the period 1958–1997, a northward shift of the NAO is also seen (Figure 3).

The oscillation amplitude of the NZS index is smaller than that for the other three NAO spatial shift indices, especially before the 1950s. However, the northern center has had a persistent eastward trend since 1964 while the southern center was located relatively westward during the 1980s, resulting in the northern center having a more distinct eastward shift than the southern center [18].

The MTM of spectral analysis is employed to determine the series of the NAO index and spatial shift indices. Figure 4 shows that the significant periodicities of the NAO index and spatial shift indices are less than 10 years. There are quasi-cycles of 2–3 and 8–9 years in the NAO index and 4 years in the NAO spatial shift indices (except the NZS index). There is also a significant quasi-cycle of 5–6 years in the zonal shift indices. In addition, there are quasi-cycles of 2–3 years in the NAO spatial shift indices, as seen for the high-frequency variations in the NAO index.

3 Possible mechanism for the spatial shift of the NAO

The spatial shift of the NAO is considered to be closely related to the variability of the NAO index [13–15,20]. As shown in Table 2, there are positive correlations between the NAO index and the NAO spatial shift indices on the interdecadal time scale with a significant confidence level. This is especially the case for the correlations between the NAO index and the meridional shift of the action centers (NMS index and SMS index), with high correlation coefficients of 0.6184 and 0.6066 respectively. The correlations are much stronger for the period 1958–1997 than for the period 1872–2008.

Peterson et al. [13] found that there is nonlinear dependence of the spatial pattern of the NAO on the NAO index (i.e. the eastward (westward) shift of the NAO pattern corresponding to the high (low) NAO index), suggesting that on interdecadal time scales, the eastward shift of the NAO pattern might be attributed to the transition from a negative (during 1958–1977) to positive NAO phase (during 1978–1997). However, the zonal shift of the northern center on interannual time scales is not obviously related to the variation in the NAO index.

Although the NAO exhibits significant variability on both interannual and interdecadal time scales, several recent studies have investigated the mechanisms for the NAO on a synoptic scale. Feldstein [26] found a complete life cycle of

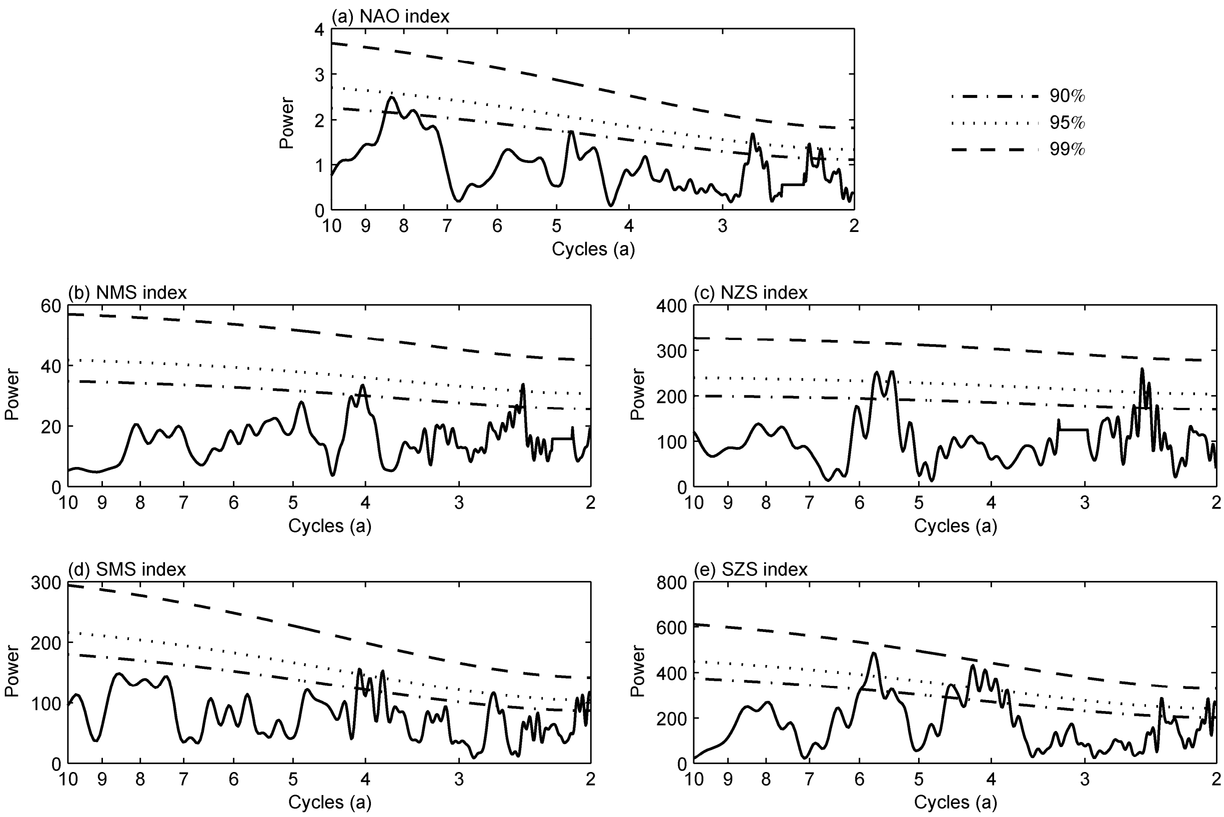

Figure 4 MTM power spectra of (a) the NAO index, (b) NMS index, (c) NZS index, (d) SMS index and (e) SZS index. The dotted-dashed lines, dotted lines and dashed lines in the figures indicate 90%, 95%, and 99% significance levels respectively relative to the estimated red-noise background.

Table 2 Correlations between the NAO index and NAO spatial shift indices smoothed by a 7-year Gaussian-type filter a)

	NMS index	NZS index	SMS index	SZS index
NAO index	0.6184*** (0.7190***) b)	0.2850** (0.4193**)	0.6066*** (0.8090***)	0.3622*** (0.6064***)

a) **, *** indicate statistical significance at the 99% and 99.9% levels respectively using a Student's *t*-test. b) Numbers in parentheses are correlation coefficients calculated for the period 1958–1997.

growth and decay in the NAO variability within a period of approximately two weeks and suggested that the NAO is driven by both high-frequency (period of less than 10 days) and low-frequency (period of more than 10 days) transient eddy fluxes. The intrinsic time scale is closely related to synoptic-scale Rossby wave breaking (RWB) over the North Atlantic, with anticyclone Rossby wave breaking (AWB) leading to a positive NAO event and cyclonic Rossby wave breaking (CWB) leading to a negative event [27–31]. In addition to the phase of the NAO, the RWB also plays a role in determining the NAO spatial pattern. The NAO exhibits a southwest-northeast tilt during AWB events and a NW-SE tilt during CWB events [28]. Kunz et al. [32] noted that the southern center of the NAO undergoes a northeastward shift and the northern center undergoes a northward shift during AWB events as compared to CWB events in a composite analysis (Figure 5 in [32]), which is closely related to the effect of the NAO index on the NAO pattern.

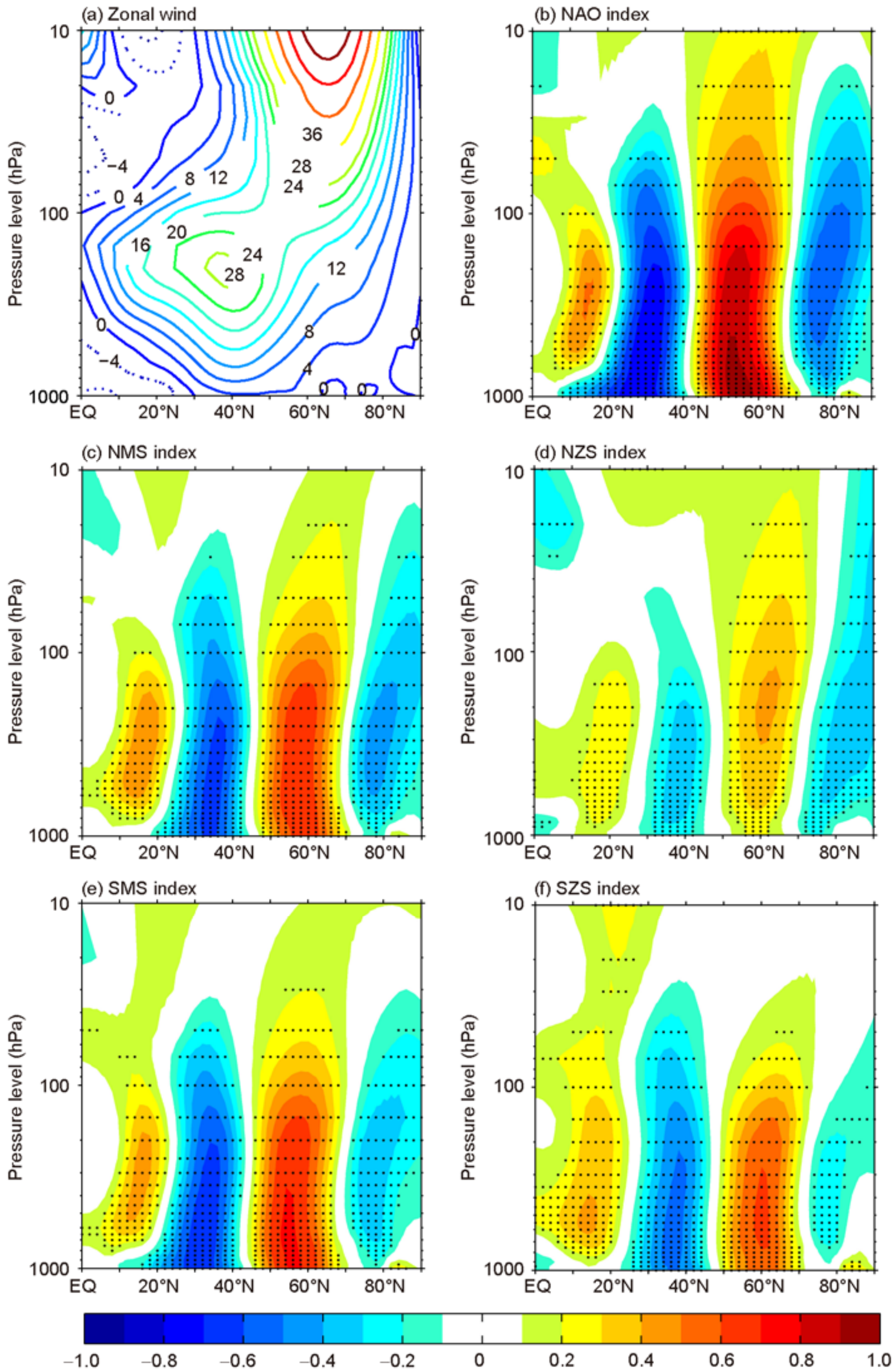

Figure 5 (a) Winter mean zonal winds averaged over 90°W–0° (contour line units: m/s) and correlations with (b) the NAO index, (c) NMS index, (d) NZS index, (e) SMS index and (f) SZS index. Values for the 95% confidence level are shaded.

Therefore, the influence of the NAO index on the interannual variability of NAO spatial shift indices is very likely to be associated with RWB, which generates surface pressure anomalies and thus affects the phase and pattern of the NAO [33].

Luo and Gong [16] attributed the eastward shift of the NAO action centers in the late 1970s to an increase in the strength of the mean westerly winds during boreal winter over the North Atlantic region (90°W–0°, 50°–70°N). Is the westerly wind a cause or only a result of the eastward shift of the NAO action centers? Figure 5 shows the winter mean westerly winds over 90°W–0° and the correlations with the NAO index and NAO spatial shift indices. It is found in Figure 5(a) that there are prevailing westerlies over the entire region (90°W–0°) apart from small low-latitude and high-latitude areas. The map of correlation of mean westerly winds to the NAO index has a '+ – + –' meridional quadrupolar pattern from the Equator to the North Pole [34]. There is similar '+ – + –' meridional quadrupolar pattern for the map of correlation between the NAO spatial shift indices and mean westerly winds, but the correlations are weaker than those of the NAO index. As shown in Figure 5(d) and (f), there are indeed positive correlations among the NAO zonal shift indices and the mean westerly winds over the North Atlantic region (50°–70°N). However, further investigation into how the middle-high latitude (50°–70°N) zonal winds drive the southern center to the east and why the low-middle latitude (30°–50°N) zonal winds drive the action centers to the west is needed. Meanwhile, similar correlations between the NAO shift indices and westerlies and between the NAO shift indices and the NAO index imply that the relationship between the zonal winds and the NAO spatial shift indices is probably an outward manifestation of the effect of the NAO index on the NAO spatial shift.

4 Conclusions

Four NAO spatial shift indices were obtained using Twentieth Century Reanalysis (V2) monthly mean data for the period 1871–2008 from NOAA/OAR/ESRL PSD and identifying the NAO action centers directly on winter mean sea-level pressure anomaly maps. The NAO index and the spatial shift of the NAO patterns were then analyzed to investigate the possible mechanism for the spatial shift. The conclusions are summarized as follows.

(1) NAO spatial shift indices had interannual and interdecadal variabilities, which are closely related to the NAO index except the NZS index. In addition, the zonal shift trends are in accordance with the meridional shift for both action centers, showing a preferable path of southwest-northeast.

(2) MTM analysis shows that the four NAO spatial shift indices had quasi-cycles of 2–6 years and the NAO index had quasi-cycles of 2–3 years in terms of high-frequency variations.

(3) On a decadal time scale, the NAO spatial shift indices are closely (positively) related to the NAO index, which is in agreement with previous studies on the relationship between the NAO index and the spatial shift of the NAO pattern. However, there is no relationship between the NAO index and the meridional shift of the northern action center (NMS) on an interannual time scale. The significant relationship between the NAO index and the interannual variability of NAO spatial shift indices is very likely to be associated with synoptic-scale RWB, which generates surface pressure anomalies and thus affects the phase and pattern of the NAO.

(4) The correlations of winter westerly winds over 90°W–0° and the NAO index and the NAO spatial shift indices have a '+ – + –' structure from the Equator to the North Pole. Although there is close correlation between the NAO spatial shift indices and the strength of the zonal winds in the North Atlantic region, the effect of the zonal winds on the NAO spatial shift differs at different latitudes. Hence, the role of the zonal wind is probably the outward manifestation of the influence of the NAO index on the NAO spatial shift.

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