Article

Chinese Science Bulletin

Atmospheric Science

August 2010 Vol.55 No.22: 2469–2472
doi: 10.1007/s11434-010-3210-8

Atmospheric oscillations over the last millennium

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Received November 11, 2009; accepted March 17, 2010

The variations of global atmospheric oscillations over the last millennium, including the North Atlantic Oscillation (NAO), the North Pacific Oscillation (NPO) highly associated with the Pacific Decadal Oscillation (PDO), the Southern Oscillation (SO) and the Antarctic Oscillation (AAO), are studied and compared in this paper based on observations and reconstructed data. The cross correlation analysis of AAO, NAO and NPO shows that there is no significant relationship on interannual variation among them. However, the consistency on decadal variability is prominent. During A.D.1920–1940 and A.D.1980–2000, the positive (strong) phase was dominant and the negative (weak) one noticeable during A.D.1940–1980. In addition, the reconstructed atmospheric oscillations series demonstrate that the positive phase existed in the early of the last millennium for NAO and in the late of the last millennium for AAO, respectively; while it occurred in the mid-late of the last millennium for PDO and ENSO.

atmospheric oscillation, climate variability, ENSO, Medieval Warm Period, Little Ice Age

Citation: Huang J B, Wang S W, Gong D Y, et al. Atmospheric oscillations over the last millennium. Chinese Sci Bull, 2010, 55: 2469–2472, doi: 10.1007/s11434-010-3210-8

Atmospheric oscillation was described as a seesaw of sea level pressure between the centers of two atmospheric actions on a wide range. The tendency of pressure of one center increases, while the pressure in another center thousands miles away decreases. During the period of 1920s–1930s, Walker proposed the concept of "world weather" and defined the North Atlantic Oscillation (NAO), North Pacific Oscillation (NPO) and the Southern Oscillation (SO) for the first time.

The understanding of atmospheric oscillations has been greatly improved from the late 20th to early 21st century [1]. First of all, it was related to the regional climate changes. It made ENSO (El Niño-Southern Oscillation), identified by Bjerknes [2], the most well-known example for linking SO with El Niño. The PNA [3] (Pacific/North America pattern) is another one, relating the atmospheric circulation over the North Pacific Ocean to the one over the North American continent. In addition, the atmospheric oscillations existed not only on the surface, but in the troposphere, even in the stratosphere, such as AO [4]. At present, it believes that these four atmospheric oscillations, covering most area of the oceans, play a key role in the regional climate changes, especially over the coastal area.

More and more scientists realize that the reconstructed or proxy data is greatly helpful to revealing the variations of atmospheric oscillation on a long term. Since the variations of the atmospheric oscillations were generally considered as the main reason directly causing the regional climate changes, to study these four oscillations over the past 1000 years can largely improve our understanding of the natural variations of the regional climate and its associated mechanism.

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1 Atmospheric oscillations in the 20th century

1.1 Data

The NAO index was defined as the differences of normalized sea level pressures between Lisbon in Portugal and Stykkishomur/Reykjavik in Iceland [5] here. The PDO index was the corresponding principal component time series of the EOF leading mode of sea surface temperature (SST) over the poleward of 20°N in Pacific [6]. The NPO index was adopted as the NPI [7], which is the averaged sea level pressure within the area of 30°N–65°N, 160°E–140°W, but inverse in order to be in phase with the PDO. Reconstructed 7-category ENSO series [8] was employed in this work. The SOI was defined as the standardized differences of normalized air pressures between Darwin and Tahiti [9], using the inverse for being consistent with ENSO. Gong and Wang [10] suggested the differences of surface pressure between 40°S and 65°S to represent the AAO intensity. So far, only two AAO series with more than one hundred years are available. One is the differences of averaged sea level pressures over 6 stations near 40°S and 60°S defined by Marshall [11]. Another was constructed by Visbeck [12] using the differences of observed sea level pressures between the subtropical in the Southern Hemisphere (South America, South Africa and Australia-New Zealand) and the Antarctic, which will be used in this study.

1.2 Atmospheric oscillations over the last 100 years

The variations of atmospheric oscillations over the past 100 years are investigated here. The cross correlations of the oscillations are computed and shown in Table 1. The NPO is closely related to the PDO with a correlation coefficient of 0.58; meanwhile a higher correlation exists between ENSO and SOI (0.81). In addition, a positive correlation exists between ENSO and NPO (0.17), and a negative correlation occurs between ENSO and AAO (–0.24). The rest of them are insignificant, which may imply their independence on interannual timescale. On the other hand, Figure 1 shows the significant consistency among these atmospheric oscillations on decadal timescale. During A.D.1920–1940 and A.D.1980–2000, they are basically in positivee (strong) phase, and in A.D.1940–1980 negative (weak) phase. It needs further investigation to reveal whether this consistence is associated with the global warming.

Given that there is no overlap of the area controlled by each atmospheric oscillation [13] (shown in Figure 2), as pointed out by Walker, the climate in one region is dominated by the atmospheric oscillation there. He also declared that the NAO and the NPO are independent of each other.

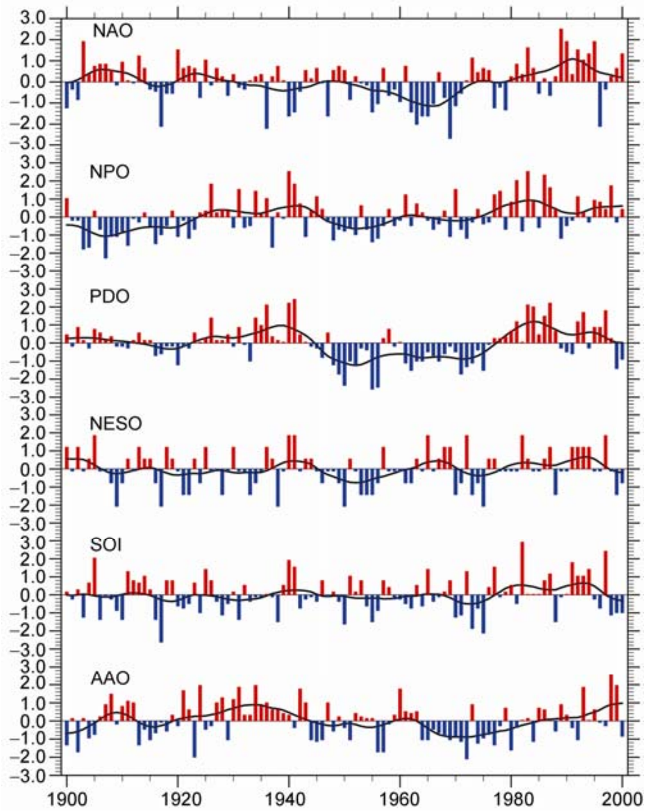

Figure 1 The normalized atmospheric oscillations series in the last 100 years (A.D.1900–2000), including NAO, NPO, PDO, ENSO, SO and AAO. The black lines are 11-point Trenberth filtering. The detailed description of data is shown in section 1.1.

Table 1 Cross correlations among atmospheric oscillations over A.D. 1900–2000a)

	NAO	NPO	PDO	ENSO	SOI	AAO
NAO	1.00	–0.11	0.00	–0.10	–0.05	0.09
NPO		1.00	0.58	0.17	0.17	–0.01
PDO			1.00	0.45	0.38	0.08
ENSO				1.00	0.81	–0.24
SOI					1.00	–0.23
AAO						1.00

a) Significant levels of 95%, 99% and 99.9% correspond to 0.197, 0.256 and 0.324, respectively.

2 Atmospheric oscillations over the last 1000 years

2.1 Data

The recent researches published a number of reconstructed atmospheric oscillations series, with a length of more than 1000 years in some of them. In this paper, four series with the length of more than 1000 years were used in this study. The NAO series was reconstructed by both tree-ring records in Morocco and stalagmite records in Scotland back to A.D.1050 [14]. The PDO index was established on the tree-ring records collected from the Northwestern of U.S.A. to Canada and the Southwestern of North America during A.D. 993–1996 [15]. In addition, the first half of the ENSO series was reconstructed according to the drought events of the Nile, and the second half was referred to El Niño series, derived from rainfall records of the South America. Diaz et

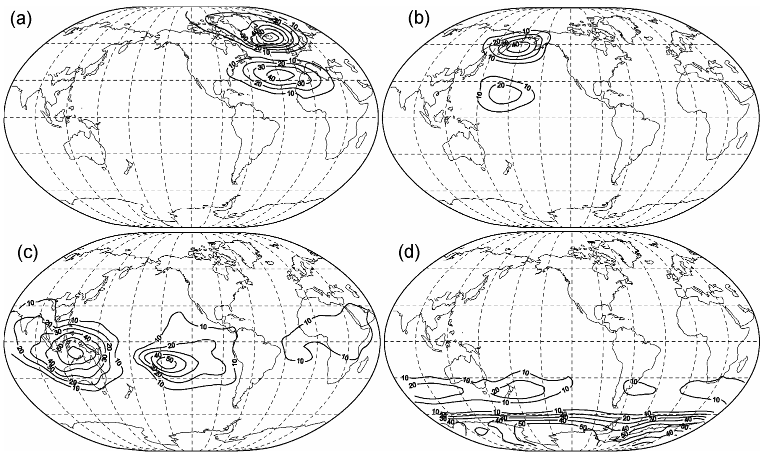

Figure 2 Variance percentage (%) explained by the atmospheric oscillations in sea level pressure during A.D.1958–1998. (a) NAO; (b) NPO; (c) SO; (d) AAO [13].

al. [16] analyzed this series using Singular Spectrum Method and synthesized the singular spectrum coefficients of two bands (25–150 a and 11–25 a) as an ENSO series. Given that there is no SOI series longer than 1000 years, Diaz's series was used to represent SOI in this study. Furthermore, the intensity of westerly winds near Antarctica is significantly correlated to rainfall over the southern South America [17,18], which means intense westerlies correspond to excessive precipitation and vice versa, so the rainfall conditions could be used to depict the variations of AAO [19]. Therefore, the value of δ^{13}C in lake sediments derived from forest steppe in Patagonia (the eastern Andes) would be used to retrieve rainfall conditions for the past 1000 years.

2.2 Atmospheric oscillations over the last 1000 years

The result from the examination of these four atmospheric oscillations over the past 1000 years (Table 2) shows that the slight correlation exists negatively between NAO and PDO and positively between ENSO and either PDO or AAO. And there is no significant sign that AAO is correlated with either PDO or NAO. Also, Figure 3 displays that the peaks of the oscillations appears in different parts of their common positive phase. The positive phase existed in the early of the last millennium for NAO and in the late of the last millennium for AAO, respectively; while it occurred in the mid-late of the last millennium for PDO and ENSO.

Table 2 Cross correlation coefficients among atmospheric oscillations over A.D.1000–2000[a)]

	NAO	PDO	ENSO	AAO
NAO	1.00	–0.22	–0.10	–0.01
PDO		1.00	0.39	0.03
ENSO			1.00	0.31
AAO				1.00

a) Significant levels of 95%, 99% and 99.9% correspond to 0.197, 0.256 and 0.324, respectively.

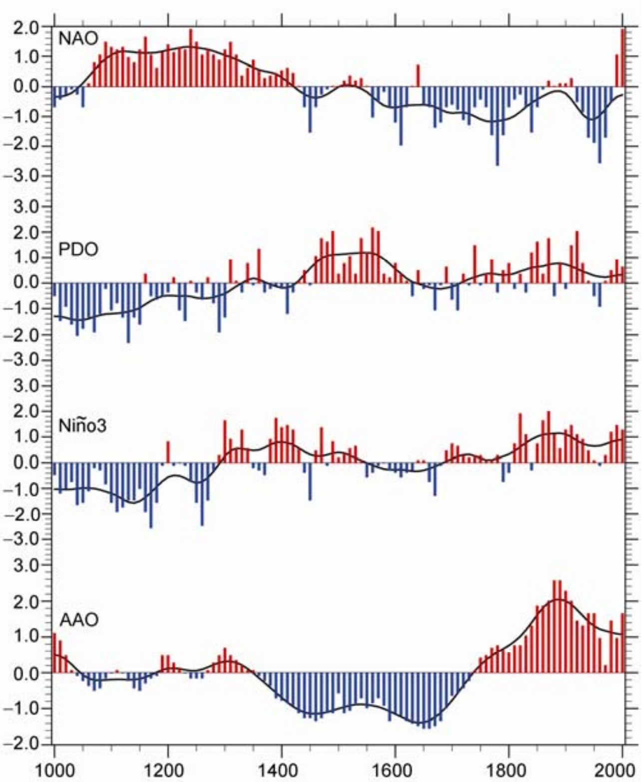

Figure 3 The normalized atmospheric oscillations series over the last 1000 years (A.D.1000–2000), including NAO, PDO, ENSO and AAO. The black lines are 11-point Trenberth filtering. The details of the data used are in section 2.1.

2.3 MWP and LIA

A.D.900–1300 is generally considered as the Medieval Warm Period (MWP) and many scientists prefer the name of the "Medieval Climate Anomaly"[14]. Figure 3 and Table 3 show that the normal AAO, strong NAO, weak PDO and ENSO in La Niño-like state happened during the MWP. During the LIA, the situation was quite opposite that both

Table 3 Atmospheric oscillations in the MWP and the LIA

No.	Atmospheric oscillations	MWP	LIA	Source
1	NAO	strong	weak	[14]
2	PDO	weak	strong	[15]
3	ENSO	La Niña-like	El Niño-like	[16]
4	AAO	normal	weak	[18]

AAO and NAO were weak, PDO was strong and ENSO was in El Niño-like state. This result again proves that La Niña-like state occurred when solar radiation enhanced in the MWP and El Niño-like appeared when solar radiation reduced [20].

3 Conclusions

First, the variations of the four atmospheric oscillations in the 20th century were analyzed using the observations at first. Then, the long-term characteristics of the four atmospheric oscillations were investigated based on the reconstructed data over the past 1000 years. The relationship among the atmospheric oscillations in different phases was discussed. Furthermore, it was examined in both Medieval Warm Period (MWP) and Little Ice Age (LIA). The conclusion is summarized as follows:

(1) The cross correlation coefficients among the four atmospheric oscillations showed clearly that the interannual variation of each atmospheric oscillation has little impact on others' in the 20th century. However, their decadal variations were significantly phase-locked. During A.D.1920–1940 and A.D.1980–2000, each of them was positively strong, and the negative phase apparent during A.D.1940–1980. Whether it is related to global warming remains unknown and needs further investigations.

(2) The NAO was out of phase to the PDO in the last thousand years. During the MWP, the NAO was strong while the PDO was weak. During the LIA, the NAO was weak while the PDO was strong.

(3) La Niña-like state prevailed in the MWP, while El Niño-like state dominated in the LIA. This phenomenon is particularly obvious in the 15th, 17th and 19th centuries.

This work was supported by R&D Special Found for Public Welfare Industry (Meteorology) (GYHY200706010) and the National Key Technology R&D Program of China (2006BAC03B03) and the National Science Foundation for Postdoctoral Scientists of China (4131482-051).

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