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Influence of Arctic Oscillation on winter climate over China

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Abstract: In this study the relationship between the Arctic Oscillation (AO) and climate in China in boreal winter are investigated. Correlation analysis for the last 41 years shows that the winter temperature and precipitation in China change in phase with AO. High positive correlation (>0.4) between temperature and AO appears in the northern China. High correlation coefficients between precipitation and AO cover the southern China (close to the South China Sea) and the central China (between 30°-40°N and east of ~100°E), with the values varying between +0.3 and +0.4. It is found that during the past several decades the precipitation was strongly affected by AO, but for the temperature the Siberian High plays a more important role. At the interdecadal time scale the AO has significant influence on both temperature and precipitation. Multivariate regression analysis demonstrates that AO and the Siberian High related variance in temperature and precipitation is 35% and 11% respectively. For precipitation, however the portion is rather low, implying that some other factors may be responsible for the changes in precipitation, in addition to AO and the Siberian High.
Key words: Arctic Oscillation; climate; China
CLC number: P461; P467

1 Introduction

It is noteworthy that there is significant association between the surface climate over northern continents and atmospheric circulation (Hurrell, 1995, 1996; Gong and Ho, 2002a). Thompson and Wallace (1998) pointed out that the leading empirical orthogonal function of the wintertime northern hemisphere sea level pressure field resembles the North Atlantic Oscillation but with more zonally symmetric appearance. This annular-like mode in the northern extratropical circulation, which has an equivalent barotropic structure from the surface to the lower stratosphere, is called the "Annular Mode" or "Arctic Oscillation (AO)" (Thompson and Wallace 1998). This mode is found to exist in both hemispheres (Thompson and Wallace 2000; Gong and Wang, 1998, 1999a). The North Atlantic Oscillation is usually regarded as the regional manifestation of the AO. In fact, they are largely the same things, and the North Atlantic Oscillation is part of the AO (Wallace, 2000; Kerr, 1999). Fluctuations in the AO create a seesaw pattern in which atmospheric pressure at the northern polar and middle latitudes alternates between positive and negative phases.

It is found that AO strongly coupled to surface air temperature fluctuations over the Eurasian continent (Thompson and Wallace, 1998, 2001; Thompson *et al*., 2000, 2002). The positive phase brings wetter weather to Alaska, Scotland and Scandinavia, and drier conditions to California, Spain, and the Middle East (Cutlip, 2000). Some regional climate changes associated with AO are highlighted, for example, Cavazos (2000) reported that the wintertime extreme precipitation events in Balkans are modulated by changes in the circulation associated with the AO. Wang and Ikeda (2000) demonstrated the significant relationship between the sea-ice cover

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in the Arctic and subpolar regions and the AO. The surface air temperature changes over the Arctic Ocean are strongly related to the AO too, which accounts for more than half of the surface air temperature trends over Alaska, Eurasia and the eastern Arctic Ocean during the last about two decades (Rigor *et al*., 2000). Variability for some regional circulation systems such as Aleutian Low also shows an apparent relation to AO (Overland *et al*., 1999). The remarkable connections between AO and East Asian climate were addressed recently too (e.g., Gong *et al*., 2001, 2002; Gong and Ho 2002a, 2002b).

In this study we focus on the investigation of AO's influence on the climate changes over the domain of China in wintertime. In Section 2 the data used here are described. The influence of AO on the surface air temperature and precipitation in China are investigated in Section 3. Then, long-term variations in AO, temperature and precipitation and their co-variability are discussed in Section 4. Concluding remarks are presented in Section 5.

2 Data

The main surface climate data set for this study consist of the monthly precipitation and surface temperature data of 160 stations in China from 1951 to 1999 compiled by the China Meteorological Administration (CMA). Twenty-six stations' data are unavailable from 1951 to 1953 (or 1954). Monthly mean sea level pressure (SLP) data in the Northern Hemisphere are taken from National Centers for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set (Kalnay *et al*., 1996). Here we extracted the sub-data set on the $5^o \times 5^o$ box from the original $2.5^o \times 2.5^o$ grids for the SLP and 500 hPa heights on the purpose of reducing data downloading time and quickening the calculation task.

The Arctic Oscillation indices used here are kindly provided by Dr. David Thompson (http://horizon.atmos.colostate.edu/ao/). One longer time series began in January 1899 and ended in April 1997, which is derived from the empirical orthogonal function analysis of the northern hemisphere sea level pressure field observations (Thompson and Wallace, 1998). This longer AO index is hereafter referred to as AO1. Another monthly AO records are available over the period 1958-1999, which is derived from the NCEP/NCAR Reanalysis SLP field. This shorter AO index is hereafter referred to as AO2. These two AOs correlate at 0.99 for the period 1958-1997 for all the four seasons. Regarding of the concerning season, all the above-mentioned data are rearranged by averaging (temperature, sea level pressure and 500 hPa geopotential heights) or summing (precipitation) the data of three wintertime months (i.e., December, January and February).

3 Influence of AO on the climate in China

3.1 Temperature and precipitation

Figure 1(a) shows the correlation coefficients between AO index (AO2) and temperatures over China for wintertime (1958/59-1998/99). Apparently, the possitive relationship exists everywhere in China, except in the small regions over the southeastern Tibetan Plateau where the correlation coefficients vary from 0 to -0.2. The most significant areas cover the northern territory of China north of 30^o-40^oN, namely the north-west, the north-east, and the coastal regions, where the correlation coefficients are above 0.3. This means that 16-36% of variance are associated with the AO. Thompson and Wallace (1998; 2000) have regressed northern hemispheric surface air temperature anomalies onto the standardized AO for January, February and March. They found that the positive phase of the winter AO is associated with positive surface air temperature anomalies throughout high latitudes of Eurasia. Regression coefficients vary from about 0.25 to 0.5K per standard deviation of AO index over the northern China. The results presented in Figure 1 is consistent with those previous findings but with more regional details.

Figure 1(b) shows the correlation coefficients between AO index (AO2) and precipitation for

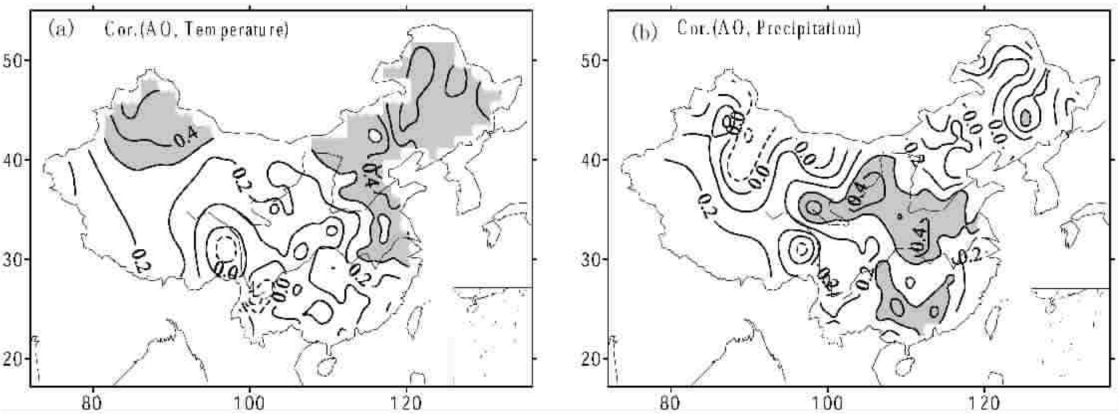


Figure 1 Correlation between AO index (AO2) and temperature (a) and precipitation (b) for winter (1958/59-98/99). Areas above 95% significance level are shaded. Negative contours are shown as dashed lines

the same period. It is interesting to note that the positive phase of AO also associates with positive precipitation anomalies generally, only exception appears in the small region of the north-west. The most significant relationship arises from two regions with the values ranging between about 0.3 and 0.4: one very large area covers the central China between 30° and 40°N (east of about 100°E), and the other small area is located in the south of China, closing to the South China Sea. This means that about 10-15% of the winter precipitation variance can be explained by AO. The averaged precipitation over the entire mainland China also correlates with AO at 0.47, this value is above the 95% confidence level.

It is interesting to note that both regional averages of temperature and precipitation correlate to AO more significantly than that for single station. This might be due to the fact that station records of temperature and precipitation are often affected by a variety of local-to-regional factors. Regional average could smooth out these small-spatial-scale factors and/or observational errors notably, and retain the large-scale signals. Hence would result in a higher correlation, of course, only if there are really physical relationships.

3.2 AO and the Siberian High

A plenty of evidence indicated that the most important regional factor affecting winter climate in China is the Siberian High (for example, Tu, 1936; Wang, 1962; Zhu *et al.*, 1997). Gong and Wang (1999b) pointed out that the Siberian High can account for about 43.6% variance of the winter temperature in China in average. Figure 2 shows the correlation between the 160-station averaged temperature and the simultaneous SLP for winter (1951/52-1998/99). It is obvious that

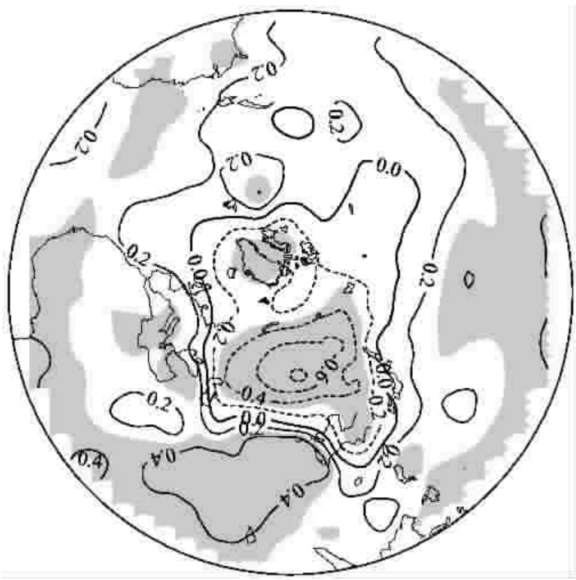
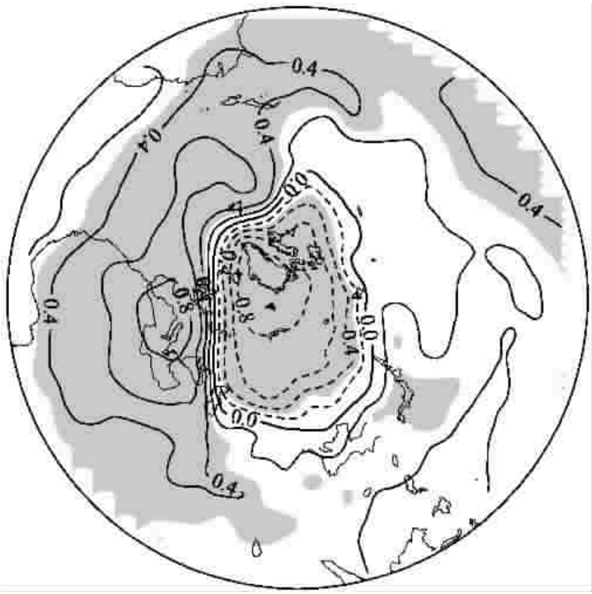


Figure 2 Correlation between 160-station averaged temperature in China and sea level pressure over the Northern Hemisphere in winter (1951/52-98/99). Areas above 95% significance level are shaded. Negative contours are shown as dashed lines

the winter temperature in China is strongly connected to the SLP variation over the high latitudes of Eurasia continent. Significant negative correlation coefficients center at Siberia with values of lower than -0.6. Some previous studies (Thompson and Wallace, 1998; Thompson *et al*., 2000) found that the positive phase of AO is associated with the lower SLP over the polar region and most regions of Eurasia continent, when the AO becomes one standard deviation higher, the SLP over Siberia is 1-3 hPa lower than normal. Figure 3 shows the correlation of AO and SLP. It suggests that there is an out-of-phase relationship between AO and Siberian SLP variation again. Those maybe imply that there are dynamical connection between AO and the Siberian High (Gong *et al*., 2001).



Fgiure 3 Correlation coefficient between AO and winter sea level pressure over the Northern Hemisphere (1958-98/99). Areas above 95% significance level are shaded. Negative contours are shown as dashed lines

Figure 4 shows the time series of the AO, the intensity of the Siberian High and the mean temperature of 160-station in winter, the intensity of the Siberian High is defined as the weighted mean of SLP with the value above 1028 hPa over the middle to higher Asia continent (30°-70°N, 60°-130°E). This index provides a measure of the anomaly of atmospheric mass over the area occupied by the atmospheric center (Gong and Wang, 1999b). To facilitate comparison, all the intensity of Siberian High, AO and average temperature in China are normalized with respect to 1961-1990. The changes in AO and the Siberian High show strong connection to the temperature (Figure 4). There are the similar trends in AO and temperature, and out-of-phase variations between temperature and the Siberian High. The out-of-phase relationship between AO and the intensity of Siberian High is also clear. The intensity of Siberian High correlates to AO at -0.51, this is significant at the 95% confidence level. More detailed correlation statistics are briefly

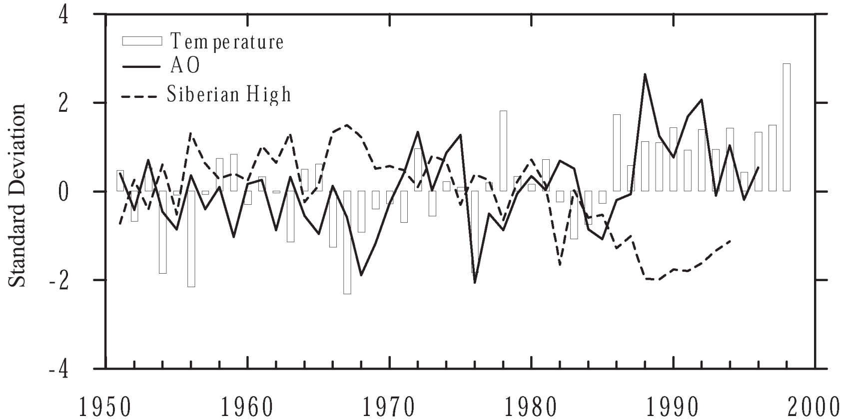


Figure 4 Time series of AO (AO1), the intensity of Siberian High and the mean surface air temperature of 160-station in China during wintertime. To facilitate comparison all series are standardized regarding to 1961-1990

summarized in Table 1.

The partial correlation coefficient measures the "real" correlation between two variables after the influence of other variables has been eliminated. The partial correlation between a and b ($R_{ab.c}$), excluding the influence of c, is computed using the following formula (Panofsky and Brier, 1968):

$$R_{ab\cdot c} = \frac{R_{ab} - R_{ac}R_{bc}}{\sqrt{(1 - R_{ac}R_{ac})\,(1 - R_{bc}R_{bc})}}$$

where $R_{(a,b)}$ indicates the correlation coefficient between factor a and b, $R_{ab.c}$ is the partial correlation between factor a and b. It is interesting to note that when the contribution of Siberian High is excluded, the partial correlation between AO and average temperature in China is only 0.14, this is much below the 95% confidence level. But when the AO's influence is excluded, the partial correlation between the intensity of Siberian High and the temperature remains -0.58, implying that the regional Siberian High plays very important roles in temperature in China. However, the condition for winter precipitation seems in different ways, when the contribution of Siberian High is excluded, the partial correlation between AO and average precipitation of 160 stations is 0.36. But when the AO's influence is excluded, the partial correlation between the intensity of Siberian High and precipitation is only -0.16.

Table 1 Correlation statistics for the AO (AO1), the intensity of Siberian High and wintertime climate in China. The considered epoch is 1958/59-1994/95. Correlation coefficients above the significant at the 95% confidence level are bold

	AO	Siberian High
Temperature:		
Correlation	+0.43	-0.67
Partial Correlation	+0.14	-0.58
Precipitation		
Correlation	+0.47	-0.36
Partial Correlation	+0.36	-0.16
Cor. (AO, Siberian High) = -0.51		

The above-mentioned AO related changes in temperature and precipitation would be compared and confirmed by calculating the AO associated variations in atmospheric circulation in middle troposphere. The changes in 500 hPa heights corresponding to the AO, temperature and precipitation are analyzed. The patterns in 500 hPa related to AO and precipitation are virtually similar to some degree (Figure 5). Associated with the more precipitation and positive AO, 500 hPa geopotential heights tend to be above normal at higher latitudes of East Asia and Southern Europe, and lower than normal in central Asia. But the spatial pattern associated with temperature is totally different. That suggests that there might be different mechanisms responsible for AO-temperature and AO-precipitation connections.

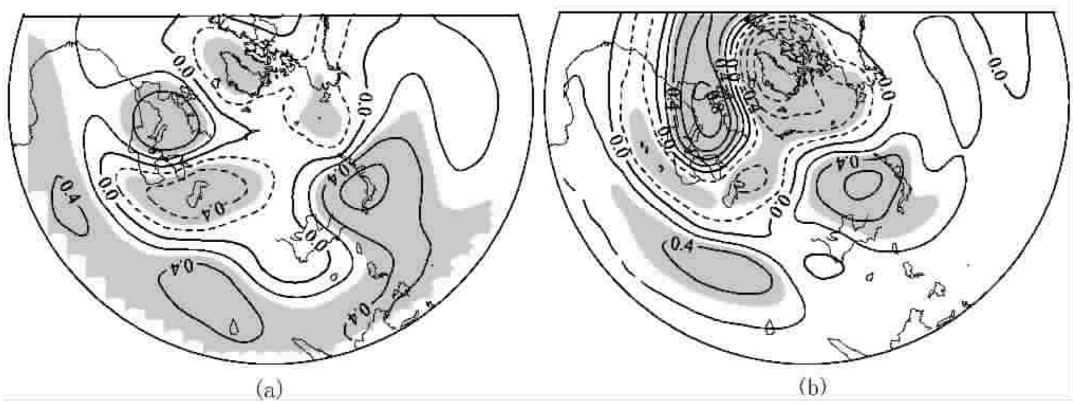


Figure 5 Correlation coefficients between China mean precipitation and winter 500 hPa geopotential heights (1951/52-1998/99) (a). Correlation between AO and winter 500 hPa geopotential heights (1958/59-1998/99) (b). Areas above 95% significance level are shaded

4 Long–term climate variations

4.1 Interdecadal fluctuation

In this section the long-term variations of AO, the Siberian High and the connections to climate in China are analyzed by employing the low-pass filtering. The long time series of winter precipitation and temperature in China is shown in Figure 6. Precipitation is the mean of 33 stations over the eastern China. All stations are located to east of 100°E (Wang *et al.*, 2000). This 33 stations' mean series correlates to the 160 stations' mean at 0.99 in the period 1951-1999. Temperature is the mean of Shanghai and Beijing. Because there are good spatial consistency in the temperature changes over China in winter as revealed by the empirical orthogonal function analysis (for example, Wang *et al.*, 1999), so that several typical stations

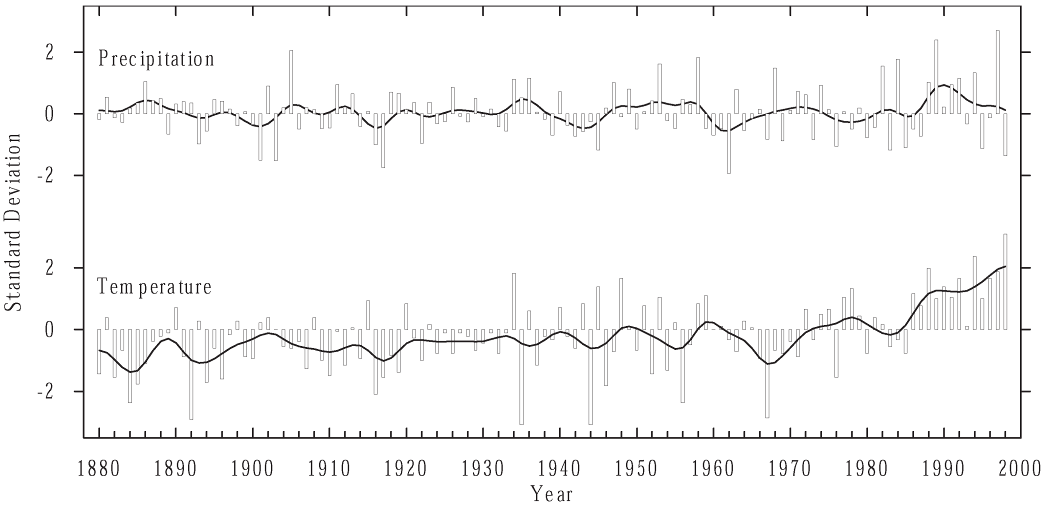


Figure 6 Long-term variation of winter precipitation and temperature. Precipitation is the mean of 33 stations over the eastern China (east of 100°E). Data taken from Wang *et al.*, 2000. Temperature is the mean of Shanghai and Beijing, this 2-station-mean series correlate to the 160-station-mean at 0.92 in the period 1951-1998. Both time series are normalized. Low frequent variations filtered by 10-40 yr band-pass filter are shown as smooth lines

may be enough for analysis. Here we chose only Beijing and Shanghai, this 2-station-mean series correlates to the 160-station-mean at 0.92 in the period 1951-1998.

Some previous studies demonstrated that there are interdecadal variations in climate in China as well as the Siberian High. For example, Gong and Wang (1999b) indicated the variation in the Siberian High on 30-40 yr time scale is clear. In order to compare the correlation between the climate and atmospheric indices on the interdecadal scale, a 10-40yr band-pass filter is employed (Huang, 1990). The filtered low frequent components for these series are shown in Figure 7. To facilitate comparison, all series are normalized before filtering. Here only shows the period 1899-1994 due to the limit of data availability.

In the above analysis for the period of 1958/59-1994/95, it is found that there are good relationships between AO and precipitation, as well as between the Siberian High and temperature. As shown in Figure 7, these relationships still exist, but the correlation coefficients suggest that on the interdecadal time scale the AO plays a significant role in both temperature and precipitation. Table 2 shows both the correlation and partial correlation coefficients. The partial correlation coefficients are displayed in parentheses. Obviously, the correlation between the AO and precipitation is the highest in all correlation coefficients (with the value of 0.72),

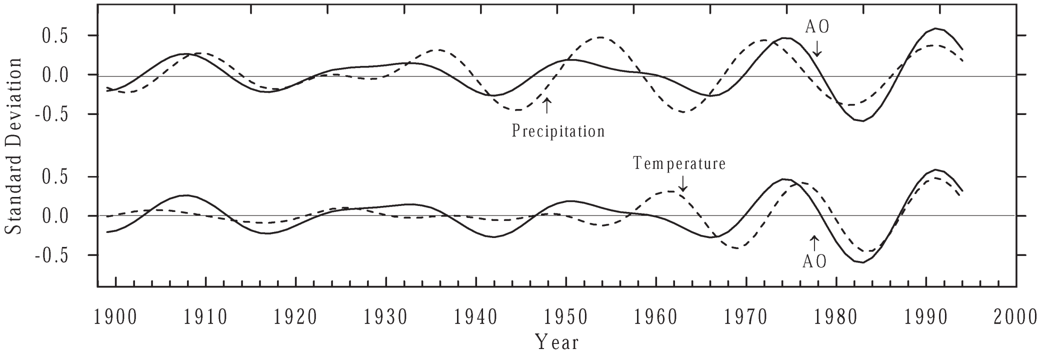


Figure 7 The filtered results of interdecadal components for AO (AO1), temperature and precipitation on the time scale of 10-40 yr. Filter used here is taken from Huang (1990)

and the partial correlation between AO and precipitation is also the highest in all partial correlation coefficients (with the value of 0.70). This implies that the planetary scale AO has more significant influences on the climate changes in China on the interdecadal time scale than the Siberian High. This is different from that on the interannual time scale as demonstrated in Section 3.

4.2 Regression analysis

The indices of AO and the intensity of Siberian High are regressed onto the winter temperature and precipitation respectively. In order to compare, all series are cut into the same period of 1899-1994. The multivariate regression details are summarized in Table 3. The regression model, taking account of both AO and the Siberian High, can explain 35% of the temperature, and 11% of precipitation variance, respectively.

Table 2 Mutual correlation coefficients. Values in the lower portion of matrix are calculated using the interdecadal components as shown in Figure 7. The partial correlation coefficients are shown in parentheses. All data cover the period of 1899/00-1994/95

	Temperature	Precipitation	AO	Siberian High
Temperature	1.00			
Precipitation	0.12	1.00		
AO	0.68 (0.66)	0.72 (0.70)	1.00	
Siberian High	-0.25 (-0.11)	-0.35 (-0.25)	-0.25	1.00

Table 3 Summary statistics from the multivariate regression using the AO and intensity of Siberian High as the independent variable and temperature and precipitation as dependent variables

Temperature	Values	Error	t-value	Probability>|t|
Siberian High	-0.3258	0.07079	-4.60218	<0.0001
AO	0.25076	0.08428	2.97528	0.00373
	R = 0.57	R^2 = 0.35	Y intercept is 0.28701	
Precipitation				
Siberian High	-1.28061	1.69078	-0.75741	0.45072
AO	5.48867	2.01293	2.72671	0.00765
	R = 0.32	R^2 = 0.11	Y intercept is 0.39402	

Figure 8 presents the changes in temperature and precipitation associated with AO and the Siberian High. They are calculated using the multivariate regression model shown in Table 3. It is obvious that the fluctuation in temperature related to AO and the Siberian High is prominent, for example, the warm periods during the 1940-1950s and 1980s, and the colder condition in the 1960s agree well with the observations. But the temperature variance explained by AO and the Siberian High is very low before the 1930s. The scarcity of sea level pressure data in the early periods may be responsible for that. For precipitation, the upward trends since the late 1970s are also consistent with the observations. However, the precipitation variance related to AO and the Siberian High is only 11%, much lower than that for temperature. This means some other factors must play an important role and should be taken into account (Shi 1996; Zhu *et al.*, 1997; Gong and Ho, 2002a).

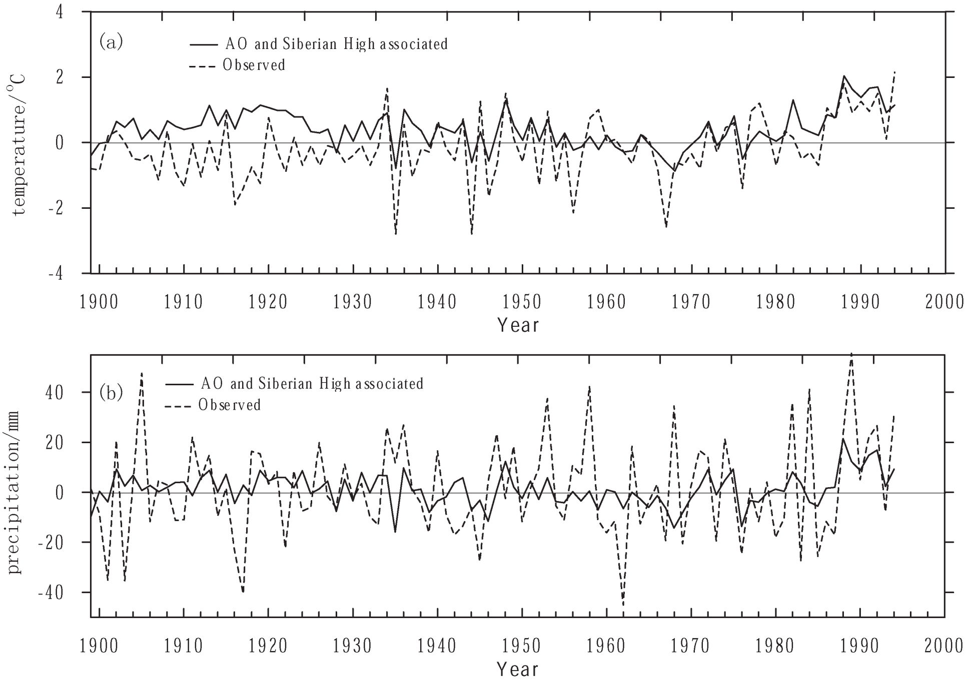


Figure 8 Temperature (a) and precipitation (b) changes associated with AO (AO1) and the Siberian High. The observations are also shown as dashed lines

5 Concluding remarks

From the above studies, we can conclude that both AO and the Siberian High influence the climate in China strongly. During the high-AO years, the temperature and precipitation increase over most of China in winter. However, there are differences on the interannual and the interdecadal time scales. On the interannual time scale, the Siberian High has more important impact on temperature in China than AO does. The partial correlation coefficient between temperature and the Siberian High is -0.58, much higher than that of between temperature and AO (only 0.14). On the other hand, the AO shows more significant influence on precipitation in China than the Siberian High, the partial correlation coefficient between precipitation and AO is 0.36, whereas the value between precipitation and the Siberian High drops to -0.16.

On the interdecadal time scale, the AO shows significant influences on both temperature and precipitation. The partial correlation coefficient between AO and temperature is 0.66, and between AO and precipitation is 0.70, but the values for Siberian High drop to -0.11 and -0.25 respectively (Table 2). During the period of 1899/00-1994/95 AO and the Siberian High together can explain 35% of the temperature and 11% of the precipitation variance.

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