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Monthly Changes in the Influence of the Arctic Oscillation on Surface Air Temperature over China

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ABSTRACT

Partial Least Squares Regression (PLSR) is used to study monthly changes in the influence of the Arctic Oscillation (AO) on spring, summer and autumn air temperature over China with the January 500 hPa geopotential height data from 1951 to 2004 and monthly temperature data from January to November at 160 stations in China. Several AO indices have been defined with the 500-hPa geopotential data and the index defined as the first principal component of the normalized geopotential data is best to be used to study the influence of the AO on SAT (surface air temperature) in China. There are three modes through which the AO in winter influences SAT in China. The influence of the AO on SAT in China changes monthly and is stronger in spring and summer than in autumn. The main influenced regions are Northeast China and the Changjiang River drainage area.

Key words: arctic oscillation, temperature field, monthly changes, partial least squares regression

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1. Introduction

In recent years, many meteorologists have paid great attention to the Arctic Oscillation (AO). The AO is defined as the leading mode of the empirical orthogonal function analysis on normalized sea-level pressure (Thompson and Wallace, 1998; Wang and Ikeda, 2000). It represents the seesaw-like spatial distribution of the pressure field between the mid-latitudes and the North Pole area. The positive phase of the AO is that the pressure strengthens at mid-latitudes while the pressure in the North Pole area weakens. The reverse is the negative phase of the AO. The AO exists not only in levels near the surface but also upward into the stratosphere. The spatial distribution of the AO near the surface shows two centers in the mid-latitudes: one in the North Atlantic Ocean, and another weaker center in the North Pacific Ocean. In the middle atmosphere, the mid-latitude part of the AO is more annular in distributes. Thompson et al. (2002) indicated that in the Northern Hemisphere the AO can account for 25%–30% of variance in the troposphere and 50% of variance in the stratosphere.

The AO exists not only in the surface but also in the stratosphere. Observations show that positive/negative AO anomalies always occur in the upper stratosphere and propagate downward. When these large-amplitude anomalies propagate from the stratosphere into the troposphere they may cause atmospheric circulation variations in the troposphere and have important effects on synoptic systems in the troposphere (Thompson and Wallace, 1998; Baldwin and Dunkerton, 1999). Some scholars consider the signature of the AO anomaly in the stratosphere to be a precursor for the prediction of weather changes in the troposphere (Thompson et al., 2002; Wallace, 2000).

Because the AO is an important signature for reflecting atmospheric circulation in the mid-high latitudes, research on the influence of the AO on climate elements over China, especially on surface meteorological elements is concerned. Gong et al. (2001) and Gong and Wang (2003) studied the influence of the AO on winter climate over East Asia and China. The influences of the wintertime AO can be reflected by the interdecadal variation of summer monsoon rainfall in East Asia (Ju et al., 2005), plus the AO has signals in the East Asian summer monsoon (Gong and Ho, 2003). It can also be reflected by the East Asian winter

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monsoon, as well as by sea-ice extent (Wu and Wang, 2002a,b). Some scientists have studied the relationships between the AO index and meteorological and climatic elements in China (Gong et al., 2004; Gong and Ho, 2004).

The studies referred to above are mostly about simultaneous correlations between climate elements and the AO. There has been little research carried out on how the AO affects temperature in different months in China and how these effects change monthly. On the other hand, the studies referred to above mostly use the singular point or correlation field analysis method, which only calculates correlations between the AO index and climate elements at these stations. They do not represent the connection between the whole temperature field and the AO index and cannot measure the responses of certain regions to AO anomalies. In this article, partial least squares regression (PLSR) is used to study the characteristics of monthly changes, and the amplitude and distribution patterns of the influences of the AO on the temperature field in China. Because the AO is most obvious in winter, the influences of the January AO on temperature in spring, summer and autumn in China are emphasized.

The AO index, which represents the amplitude of the oscillation generally, is defined as the first mode of the principal component of sea level pressure in the ultra-tropical region of the Northern Hemisphere. Although the AO has a deep vertical structure from the surface to the stratosphere (Hartmann et al., 2000), its' effects on climate elements in China mainly come from atmospheric circulations in the troposphere.

January is the representative month of winter. Therefore, in this article the January middle-troposphere atmospheric circulation is chosen as representative, i.e. the geopotential field at the 500-hPa level in January is used to calculate the AO index.

2. Datasets and analysis techniques

Geopotential data at the 500-hPa level in January and monthly temperature data from January to November at 160 stations in China from 1951 to 2004 were used (provided by the National Climate Center of China Meteorological Administration).

Regression analysis can be used to study the relationship between all variables at the temperature field and the AO index. However, the regression equation will be ill-defined and unstable in the calculation process because the time series of the temperature at nearby stations have similar variations and are closely correlated. There is a lot of overlapping of information in the variable dataset and such overlapping will amplify the degree of one certain character in the systemic analysis. Thus, partial least squares (PLS) analysis is used to improve this status.

Partial least square regression (PLSR) is useful in constructing regression model when variables are highly correlated, and such a model can ensure more reliable and more integrated results than traditional multi-variable regression analysis. This method is effective in dealing with high correlations among variables and the difficulty of constructing the model when the number of samples is smaller than that of variables. (Stone and and Brooks, 1990; Frank and Friedman, 1993).

PLS is different from other traditional regression analysis methods. The independent variables and dependent variables are standardized first to compose the standardized variables matrices $\boldsymbol{E}_0, \boldsymbol{F}_0$, and then the principal component analysis is implemented with the standardized independent variables matrix to extract the principal component corresponding to the largest eigenvalue and the corresponding loading vectors. The principal component from PLSR is most correlated with dependent variables. Regression analysis is executed based on the principal component and dependent variables, then the remaining matrices are calculated respectively. Such analogous analysis is implemented on the remaining matrices, and so on. The final results are as follows:

$$\begin{cases} \boldsymbol{E}_0 = t_1 p_1' + t_2 p_2' + \cdots + t_s p_s' \ , \\ \boldsymbol{F}_0 = t_1 r_1' + t_2 r_2' + \cdots + t_s r_s' + F_s \ , \end{cases} \tag{1}$$

where t_i represents the stepwise principal component extracted from the independent variables matrix, p_i represents the loading vectors of the independent variables, r_i is the projected vector of the dependent variables onto the principal component axis and the symbol ($'$) represents the transposition. Because the relationship between the independent variables and the dependent variables is transferred by the principal component $-t_i$, the independent variables' loading reflects the importance of the contributions independent variables in the PLSR process, and the contribution of the independent variables for the transferred regression relation between the independent variables and dependent variables. The loading and the principal component compose the simulation of the independent variables matrix. The explained covariance percentage of the regression equation can reflect how close the relation between all the independent variables and the dependent variables is.

In this article, the AO index is the dependent variable and the temperature field is the independent variable. Therefore, the values in the loading vector of the independent variables can reflect the intensity of the AO on the temperature field. Because the corresponding principal components are the major variables con-

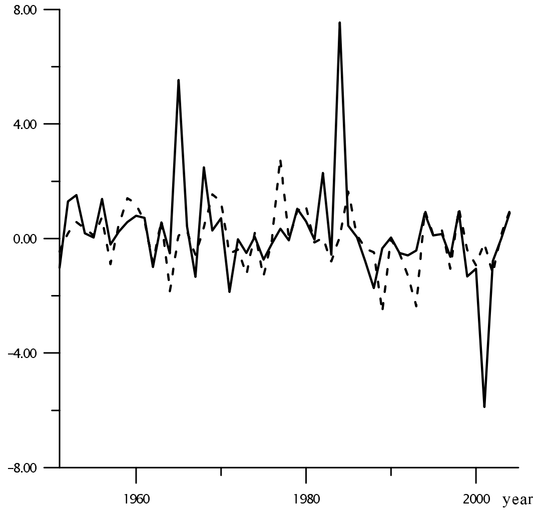

Fig. 1. Time series of AO1 and AO2 (1951–2004). Dashed (solid) line represents AO1 (AO2).

structing the regression equation of the AO index, the explained covariance of the estimated regression equation can reflect how close the relationship is between the whole temperature field and the AO index.

3. Indices of the AO

An index is usually used as a signature of a synoptic system in atmospheric circulation. For example, Li and Wang (2003) proposed a new North Atlantic Oscillation (NAO) index and compared several indices defined with different methods. The rotated principal component analysis was used to make some indices of the NAO (Rogers, 1990; Hoerling et al., 2001). Actually, the NAO and the AO are almost indistinguishable (Dickson et al., 2000). Thus there are also some AO indices defined with different calculation methods for describing the variation of the AO in this article.

In consideration of the difference of the fluctuation amplitude of geopotential height at different latitudes, girded geopotential height variables have been first normalized. Next, the principal factor analysis is executed based on the normalized data to obtain the first principal factor as the AO index, referred to as AO1. The corresponding loading field showing the spatial distribution characteristics of the AO at 500-hPa can also be obtained.

In order to give prominence to the main representation of the AO, the principal factor obtained above is rotated for obtaining another AO index.

According to the maximum covariance principle, the first two factors were rotated to obtain another two factors. The loading of the first rotated factor can also represent the spatial distribution of the AO

Table 1. Correlation matrix of the three AO indices.

	AO1	AO2	AO3
AO1	1.000	0.311	0.991
AO2	–	1.000	0.307
AO3	–	–	1.000

at 500-hPa (not shown), and thus it is also defined as the AO index, for short, AO2. Figure 1 shows a comparison of the first factor before rotation (dashed line) and after rotation (real line). It is clear that there are obvious differences in the inter-annual variability between AO1 and AO2.

Variations in geopotential height at high latitudes are large. To emphasize the changes in height at high latitude, the height anomaly field at 500-hPa is used to perform EOF analysis. The third AO index is defined as the first time function corresponding to the first eigenvalue of the cross-product matrix of the height anomaly variables, for short, AO3. Its explained covariance (31%) is the largest among the three indices. The correlation matrix of the three indices is shown in Table 1.

For comparison, the correlation coefficients between the traditional AO index, which is defined as the first component of the principal component analysis on sea level pressure, and the three AO indices mentioned above were calculated. They are −0.926, −0.246, and −0.912, respectively, meaning that AO1 seems to represent the best AO signature. Because the signs in the oscillation center in these AO modes are contrary to that in the traditional AO mode, there is the negative correlation between the traditional index and the indices in this paper.

4. Impacts of the AO in winter on temperature in China

In order to study the response of temperature in China to the AO, PLS analysis is used. The AO index is the dependent variable and temperatures at 160 stations in January are independent variables. The first principal component represents the prime connection between the temperature field and the AO index (see Eq. (1)). The explained covariance (that is, the imitated coefficient) can measure the degree of response of the whole temperature field to the AO. The degrees of response of the January temperature field in China to the three indices are 30%, 7%, and 28%, respectively (Table 2).

Because the response of the January temperature to the AO is most significant, the present discussion will concentrate on the January temperature response to the AO.

Table 2. Explained covariance of the regression equations constructed with the temperature field from January to November and the three AO indices. G1, G2, and G3 refer to those corresponding to AO1, AO2, and AO3, respectively.

Month	1	2	3	4	5	6	7	8	9	10	11
G1 (%)	30	6	7	12	23	21	17	19	16	11	7
G2 (%)	7	4	4	10	12	14	16	17	10	9	15
G3 (%)	28	6	6	13	22	25	16	19	15	11	6

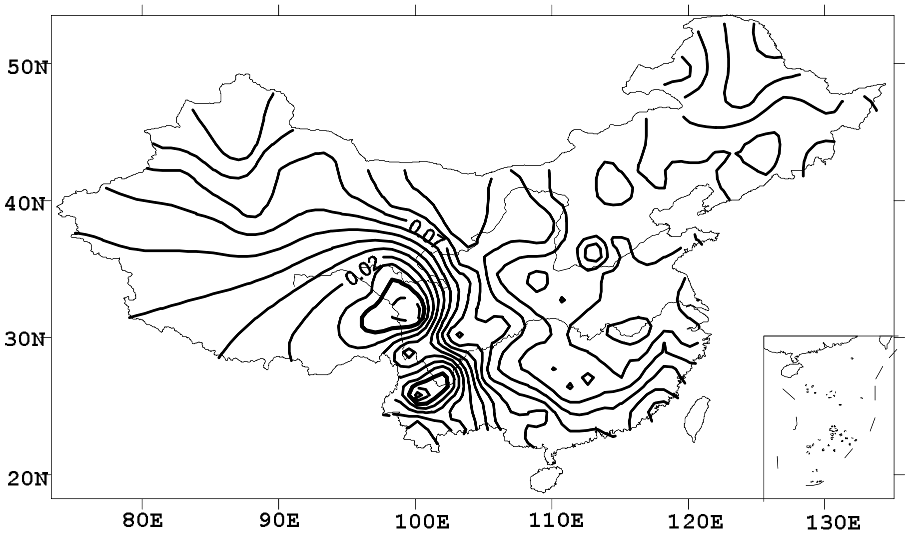

Fig. 2. First response mode to the AO of January temperature. Solid lines represent positive isolines.

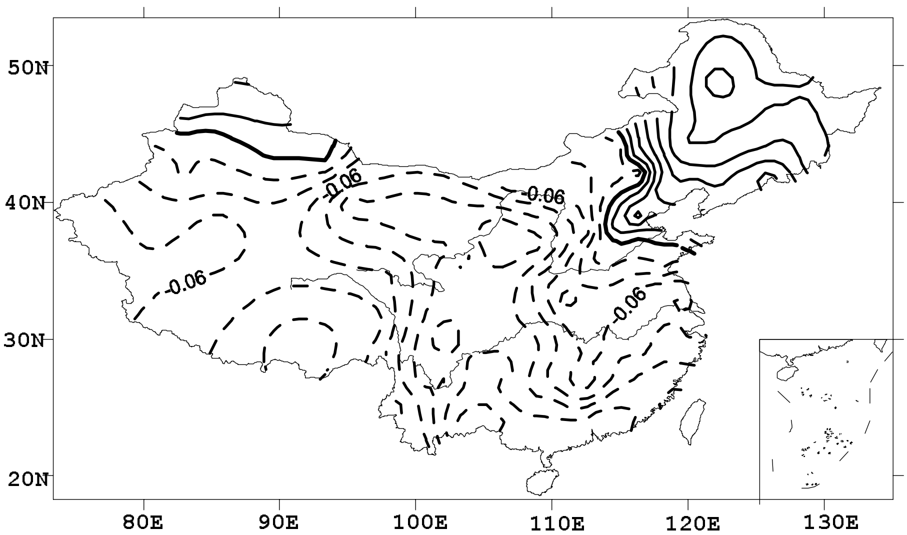

Fig. 3. Second response mode to the AO of January temperature. Dashed (solid) lines represent negative (positive) isolines.

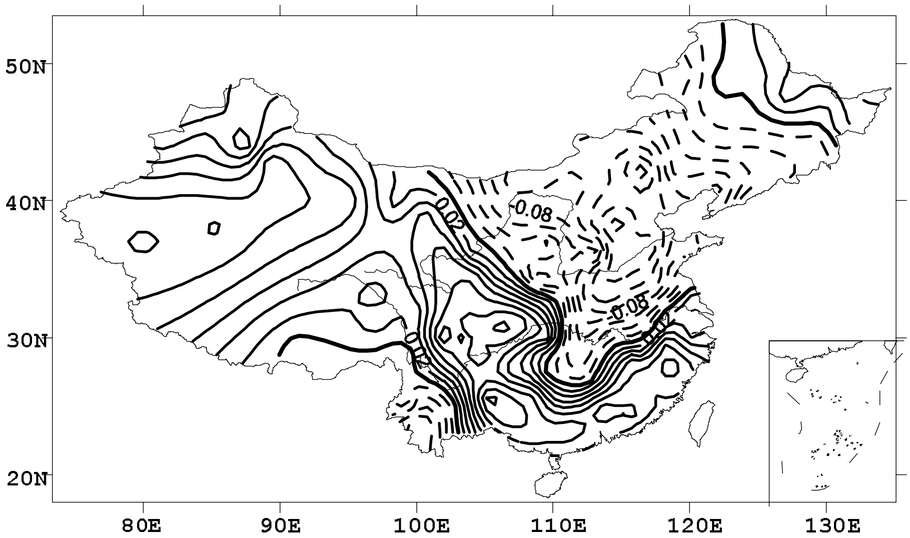

Fig. 4. Third response mode to the AO of January temperature. Dashed (solid) lines represent negative (positive) isolines.

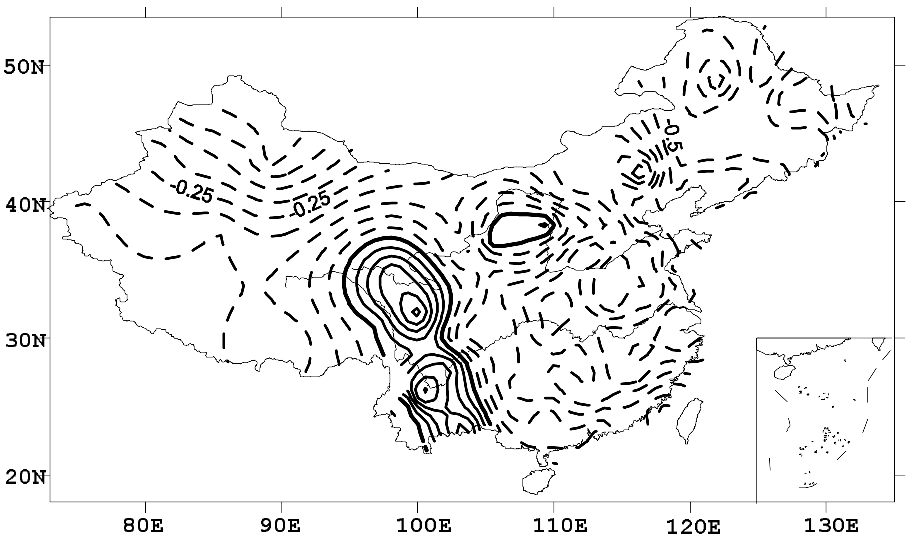

Fig. 5. Correlation field between the AO1 index and January temperatures in China. Dashed (solid) lines represent negative (positive) isolines.

PLSR is been implemented on the January temperature field and the AO index. The total explained covariance of the first three principal components in the regression equation with AO1 are 30%, 52% and 71%, respectively. Their accumulated explained covariance is more than 70%. Therefore, only the loading distribution of the three principal components is discussed.

The first principal component, which represents the closest relation between the temperature field and the AO index, can represent the main response mode of the whole temperature field to the AO. Thus, the loading vector field, that is the first mode, is called the first response mode to the AO and is also the main response mode to the temperature field. The distribution of the response is shown in Fig. 2. Figure 2 demonstrates that the regions where deep responses exist are mostly in the coastal provinces of East China and in the southern most areas of South China. Because the first principal component of the independent variables field has a negative correlation (−0.08) with AO1, the temperature anomalies where the sign is positive in Fig. 2 are negative when the AO1 index is positively anomalous. In years when the AO index anomaly is positive, temperature anomalies in the coastal provinces of East China are negative. For example, in 1977, strong negative temperature anomalies appeared in eastern China while a strong positive AO1 index anomaly was apparent, and vice versa.

The loading vector field of the temperature variables corresponding to the second principal component is defined as the second response mode of the January temperature field to the AO. The distribution of such a response is shown in Fig. 3. The sign of the response in Northeast China is opposite to that in most other regions in China. Because the second principal component of the independent variables has a negative correlation with the AO index, temperature anomalies in most regions in China where the sign is negative in the figure. Such mode represents another response mode of the temperature field in China to the AO.

The loading vector field of the temperature variables corresponding to the third principal component is defined as the third response mode of the January temperature field to the AO. The distribution of such a response is shown in Fig. 4. In Fig. 4, the signs of the response loading are distributed as $+, -, +, -$, respectively corresponding to the areas of northern Northeast China, North China, the lower reaches of the Changjiang River and Southwest China. Because the third principal component of the independent variables has a negative correlation with the AO1 index, such a response mode is still a negative response mode.

Because the principal components of the temperature field obtained step by step in the PLS progress are independent of each other, the three response modes of the temperature field to the AO index are independent of each other. They can represent three different distributing characters of temperature responses to the AO.

There are few similar characteristics when comparing the three response modes with the correlation field between the AO1 index and temperature. The correlation field shows a linear relation between the temperature fields at all the stations and the AO1 index, negatively correlated in most regions in China. The most correlated area (at the 5% significance level, the absolute value of the correlation coefficient is larger than 0.30) is in Northeast China (see Fig. 5), whereas the strongest response area in Fig. 2, which shows the primary response mode of the temperature field to the AO index, is in East China.

The aforementioned response modes reflect the effects of the AO in the mid-troposphere on surface climate momentums. Wu and Wang (2002a) discussed the relationship between the winter AO and Siberian anticyclones. Obviously, the cold air from Siberian anticyclones can influence temperature in East Asia and North China. In years of a strong (weak) AO, East Asian winter wind is weak (strong), Siberian anticyclones are weak (strong), the Asian surface northeast wind is diminishing (enhancing), and the East Asian trough in the upper atmosphere is diminishing (enhancing). The cold air coming from a Siberian high affects not only Northeast China and North China but also East China (the mode shown in Fig. 2). Because of the different paths of movement of the cold air, it only affects Northeast China and North China when it is weak (the mode shown in Fig. 3), and can affect North China and central China when it is strong and deflecting west. The representation of the correlation field (Fig. 5) cannot explain these different influences as the results of the different paths of the cold airflow. Therefore, the aforementioned three-response modes can better explain the relationships than the simple correlation field.

5. Influence of the AO in winter on spring, summer and autumn temperature in China

In order to study the influence of the AO in winter on spring, summer and autumn temperature in China, PLS analysis is used. The AO index defined in the present paper is the dependent variable and the temperatures at 160 stations from February to November are the independent variables. The regression equations are constructed based on the monthly first principal component, which represents the prime connection between the temperature field and the AO index. The explained covariance of the equations (that is the imitated rate) can measure the response intensity of the whole temperature field every month to the AO. Table 2 shows the explained covariance of the regression equations constructed with the temperature field from January to November and the three AO indices defined in the paper, respectively. G1, G2 and G3 refer to those corresponding to AO1, AO2 and AO3, respectively.

It is obvious from Table 2 that the response of temperature in China to the three winter AO indices is weaker in months other than January. Such a response varies monthly. The explained covariance of the temperature fields respond to the AO comparatively better with AO1. Thus, AO1 is used as being representative of the AO to study the monthly variability of the influence on the temperature fields.

Table 2 also shows that stronger responses to the AO appear in May, June and August. This state demonstrates that the AO effects are larger in spring and summer, while smaller in autumn. This is very similar to the conclusions of the influence of the AO on precipitation in China (Gong et al., 2002).

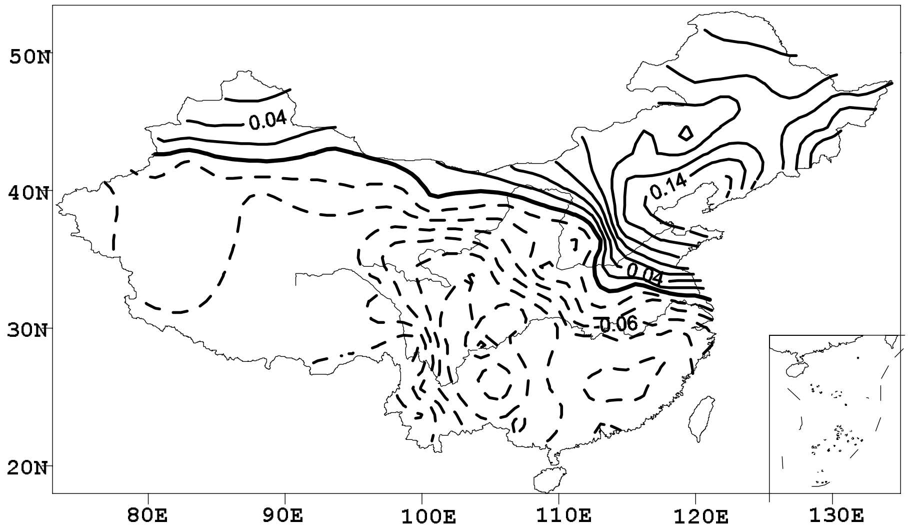

Fig. 6. Primary response mode (the first mode) to the AO of the temperature field in May. Dashed (solid) lines represent negative (positive) isolines.

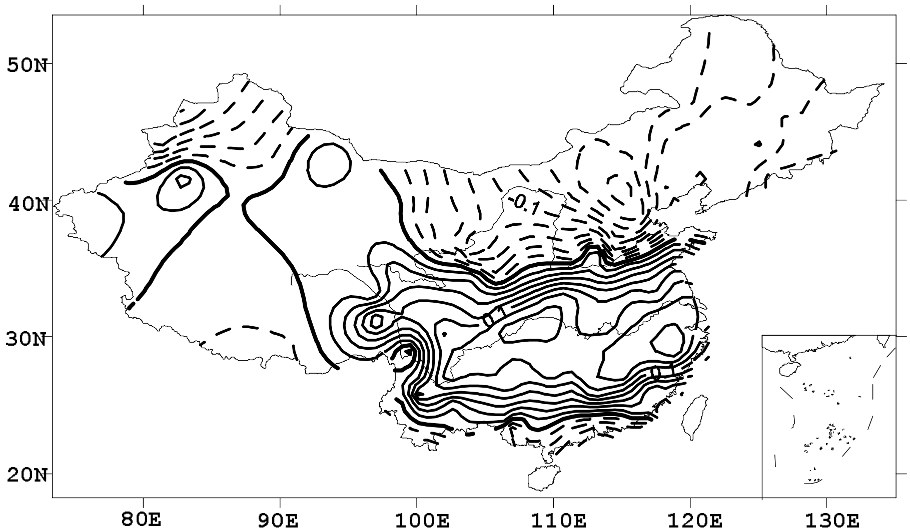

Fig. 7. Primary response mode (the first mode) to the AO of the temperature field in August. Dashed (solid) lines represent negative (positive) isolines.

The response of spring temperature briefly appears in May. Figure 6 shows the primary response mode (the first mode) to the AO of the temperature field in May.

It shows that the regions with a large positive response are in Northeast China and North China. The regions with a negative response are in Southwest China. The degree of positive response is larger than that of negative response. This means that the AO in winter affects the spring temperature field briefly in North China and South China. Because the first principal component of the independent variables is negatively correlated with AO1, the temperature anomalies where the sign is positive in Fig. 2 are negative when the AO1 index is positively anomalous. Such a response pattern may bear a close correlation with the cyclones in Northeast China in late spring. This means that the atmospheric circulation in late spring may be correlated with that in winter.

The response of summer temperature in China to the AO briefly presents in August. Figure 7 shows the primary response mode (the first mode) to the AO of the temperature field in August.

The regions with a larger positive response are in the Changjiang River and Huaihe River areas and the negative response area is in North China. The degree of positive response is larger than that of negative response. This means that the AO in winter affects the summer temperature field briefly in the Changjiang River regions. Because the first principal component of the independent variables has a positive correlation with the AO1 index (0.11), such a response mode is positive, opposite to the spring mode. This means the temperature anomalies where the sign is positive in Fig. 2 are positive when the AO1 index is positively anomalous. Such a response is obviously similar to the characteristic modes of the empirical orthogonal function on the precipitation field in summer over China (see Gong et al., 2002). Therefore, the atmospheric circulation and temperature in summer may also have a close relationship with atmospheric circulation in winter.

6. Discussion and conclusions

Research was carried out on the monthly variability of the effects of the AO on temperature in spring, summer and autumn in China, with January geopotential data at the 500-hPa level from 1951 to 2004 and monthly mean temperature data at 160 stations in China from January to November. The main results are as follows:

(1) Several oscillation indices of the AO at the mid troposphere are obtained with the geopotential data at the 500-hPa level from 1951 to 2004. The index defined as the first principal factor of the normalized geopotential data is better for studying the influences of the AO on the temperature field in China.

(2) There are three main modes of influence of the AO on temperature in China in the corresponding period and the regions with significant influences are the east inshore areas, Northeast China and North China, respectively.

(3) The influence of the AO in winter on the temperature fields in China in different months varies monthly. Deeply influenced periods are in May, June and August. The most significantly influenced region in spring is Northeast China and in summer the drainage area of the Changjiang River.

It should be emphasized that although the influence of the AO on spring, summer and autumn temperature in China reflects the effects of atmospheric circulation in winter, such an influence is not the only factor affecting monthly changes in temperatures in China. The primary mode of influence only explains 30% of variance in the temperature field. In other strongly influenced months, this reduces to around 20%. However, the ability to explain also illuminates that the AO influence on temperature changes in China is an important factor and cannot be ignored among all the factors. The temperature response to the AO should be considered as part of short term climatic predictions in China.

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