

Using the physical decomposition method to study the effects of Arctic factors on wintertime temperatures in the Northern Hemisphere and China

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Abstract The physical decomposition method separates atmospheric variables into four parts, correlating each with solar radiation, land–sea distribution, and inter-annual and seasonal internal forcing, strengthening the anomaly signal and increasing the correlation between variables. This method was applied to the reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), to study the effects of Arctic factors (Arctic oscillation (AO) and Arctic polar vortex) on wintertime temperatures in the Northern Hemisphere and China. It was found that AO effects on zonal average temperature disturbance could persist for 1 month. In the AO negative phase in wintertime, the temperatures are lower in the mid–high latitudes than in normal years, but higher in low latitudes. When the polar vortex area is bigger, the zonal average temperature is lower at 50°N. Influenced mainly by meridional circulation enhancement, cold air flows from high to low latitudes; thus, the temperatures in Continental Europe and the North American continent exhibit an antiphase seesaw relationship. When the AO is in negative phase and the Arctic polar vortex larger, the temperature is lower in Siberia, but higher in Greenland and the Bering Strait. Influenced by westerly troughs and ridges, the polar air disperses mainly along the tracks of atmospheric activity centers. The AO index can be considered a predictor of wintertime temperature in China. When the AO is in negative phase or the Asian polar vortex is intensified, temperatures in Northeast China and Inner Mongolia are lower, because under the influence of the Siberia High and northeast cold vortex, the cold air flows southwards.

Keywords Physical decomposition, AO index, polar vortex intensity index, polar vortex area index

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1 Introduction

Extremely low temperatures frequently occur in wintertime in the Northern Hemisphere, mainly in North America, Europe, and East Asia, which can lead to unusual increase in the amount of snowfall^[1-4]. For example, in the winter of 2009–2010, much of the Northern Hemisphere experienced extremely low temperatures^[5], and in January 2014, many

parts of North America were affected by the most extreme cold temperatures of the past two decades (<http://www.weather.gov/>).

The Arctic is one of the biggest cold sources within the global climate system. By influencing atmospheric circulation in the mid–high latitudes, it can affect the distribution of air temperature and precipitation throughout the Northern Hemisphere. The Arctic Oscillation (AO) is the most important large-scale atmospheric circulation mode in the mid–high latitudes in the Northern Hemisphere

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wintertime, controlling the antiphase variation in the nature of the atmosphere between the polar and mid-latitude areas. When the AO is in its positive phase, atmospheric pressure is lower in the polar area, but higher in the mid-latitudes. Statistical analysis shows that when the AO is in its negative phase, blocking activity happens frequently. The collapse of a blocking high allows cold air into the mid-latitudes, such that temperatures in the mid-latitudes decrease^[6]. Many studies have indicated that the main reason for the very low temperatures that occurred in northwestern Europe and the Mid-Atlantic States of the United States in the winter of 2009–2010 was the influence of the negative phase of the AO^[7–9]. There have also been studies on the influence of the AO on wintertime temperatures in China. For example, Wu and Wang^[10] suggested that the AO might affect the East Asian winter monsoon, because when the AO is in positive phase, temperature is relatively higher in eastern China. Gong and Wang^[11] and Gong et al.^[12] highlighted that during the 20th century, the AO was mostly positively correlated with wintertime temperature and precipitation in China, and negatively correlated with wintertime daily temperature variance. He and He^[13] considered that when the AO attains a high value, the Siberian High and East Asian trough both weaken, reducing the occurrence and strength of cold air outbreaks and consequently, North China experiences a warm winter, which is quite consistent with Gong's conclusions.

The polar vortex is a deep system that moves around the polar area. It embodies the characteristics of atmospheric activity at high latitudes, and it is one of the most important systems in atmospheric circulation. For example, the main reason for the cold wave in America in January 2014 was that the Arctic Vortex had adopted a more wave-like shape instead of the more typical oval around the North Pole, which led to outbreaks of colder air moving into the mid-latitudes and milder temperatures in the Arctic (<http://www.climate.gov/news-features/event-tracker>). In fact, in the 1980s, Chinese meteorological scholars proposed schemes for describing the physical parameters of the area, intensity, and location of the polar vortex. They believed that these parameters better reflected the state of the polar vortex circulation, and that they have a close correlation with changes in the weather and climate in China; one aspect of this “correlation” is the effect of these parameters on temperature^[14–17]. Therefore, it is necessary to consider the effects of the polar vortex when studying the impact of the Arctic atmosphere on wintertime temperatures in the Northern Hemisphere and China. Since 2006, the AO index has been decreasing obviously, and the polar vortex area index in the Northern Hemisphere and Asia has been rising. This marks a helpful inter-decadal background against which to study the frequent occurrence of extremely low wintertime temperatures in the Eurasian continent^[18].

The methods adopted in the above studies were mostly climatic anomaly analyses, which consider the effects of Arctic factors on westerly trough and ridge activities in the high latitudes and their further influence on temperature. Traditionally, the system state is considered as the sum of the climate condition \bar{S} and the weather disturbance condition S' during a certain period, i.e., $S = \bar{S} + S'$, in which $\bar{S} \gg S'$. However, there is a human factor involved in this method. For example, the World Meteorological Organization suggested formerly that the climate state should be considered as the annual mean of the 1971–2000 period; however, this has subsequently been changed to the 1981–2010 period. This paper discusses the use of the physical decomposition method, proposed by the Qian research group^[19–21], in studying the effects of Arctic factors on the westerly trough and ridge activities and wintertime low temperatures in the mid-high latitudes in the Northern Hemisphere. It first introduces the statistics used and the specific processes of the physical decomposition method, and then uses this method to decompose the geopotential temperature and height fields to obtain the climate anomaly field. The main content involves the study of the effects of the Arctic factors both on zonal temperature variation and on how they influence temperature in the Northern Hemisphere, and in China in particular. The final section of the paper presents a summary and discussion.

2 Data and methods

The data used in this paper include the monthly mean NCEP/NCAR reanalysis data^[22] with a resolution of $2.5^\circ \times 2.5^\circ$, AO index (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml), Arctic polar vortex area index (PVA) and intensity index (PVI), and Asian polar vortex area index (PVA_I) and intensity index (PVI_I) (sources from the Climate Diagnostics and Prediction Division of National Climate Center, China). The methods used involve rotated empirical orthogonal function (REOF) decomposition, correlation analysis, and physical decomposition.

The method used for the calculation of the PVA is similar to that of Reference [14]. First, we establish a monthly southern boundary characteristic contour, as shown in Table 1, based on the 500-hPa geopotential height field in the Northern Hemisphere from 1950–2002. Based on the southern boundary characteristic contour, the PVA and PVI are given by:

$$PVA = \frac{R^2 \pi}{72} \sum_{i=1}^n (1 - \sin \varphi_i) \quad (1)$$

$$PVI = \rho R^2 \Delta \varphi \Delta \lambda \sum_i \sum_j [H_0(M) - H_{ij}] \cos \varphi_i \quad (2)$$

Table 1 Monthly southern boundary characteristic contour of 500-hPa polar vortex in Northern Hemisphere

Month	1	2	3	4	5	6	7	8	9	10	11	12
Contour/gpm	5 500	5 520	5 540	5 560	5 620	5 700	5 720	5 720	5 680	5 620	5 580	5 520

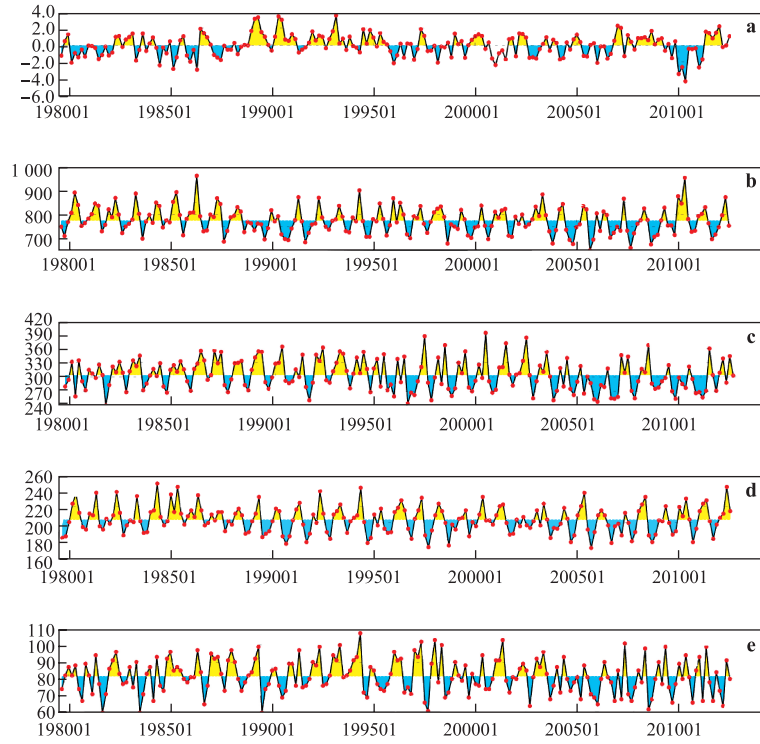


Figure 1 Time series of indices: **a**, AO index; **b**, PVA ; **c**, PVI ; **d**, PVA_I ; **e**, PVI_I .

Where φ_i is the latitude where the southern boundary contour intersects the longitude, R is the radius of the Earth (6 371 km), ρ is air density, $\rho R^2 \approx 1$, $\Delta\varphi = \Delta\lambda = \pi/72$, and $H_0(M)$ is the value of the polar vortex southern boundary characteristic contour. Furthermore, we can obtain the PVA_I by limiting the longitude to between 60 °E and 150 °E. The time focus in this paper is the wintertime, i.e., from October to March of the following year. Figure 1 shows the time series of AO, PVA , PVI , PVA_I and PVI_I in wintertime (reference line is mean value, except for AO it is 0).

The physical decomposition method was proposed by Qian's research group, who separated atmospheric variables into four parts, correlating the variation of each with solar radiation, sea–land distribution, and interannual and seasonal internal forcing. Taking the NCEP reanalysis data of the temperature field as an example, the specific decomposition formula is:

$$T(\lambda, \varphi, t)_Y = [\bar{T}_t(\varphi)] + T_t^*(\lambda, \varphi) + [T(\varphi, t)]'_Y + [T(\lambda, \varphi, t)]''_Y \quad (3)$$

On the left-hand side of Eq. (3), the variable $T(\lambda, \varphi, t)_Y'$ represents the temperature field varying with longitude (λ) and latitude (φ) in the t -th month from the first time level of the Y -th year. The specific data used are $\lambda = 144^\circ$, $\varphi = 73^\circ$, and t refers to the 408 months from January 1979 to December 2012.

On the right-hand side of Eq. (3), the first monomial $[\bar{T}_t(\varphi)]$ refers to the temperature, which varies only with latitude (φ) after the climate mean and zonal mean in the t -th month (from January to December) of the N -th year ($N = 34$). The mathematical expression is:

$$[\bar{T}_t(\varphi)] = \sum_{\tau=1}^n \sum_{\lambda=1}^p T_t(\lambda, \varphi, \tau) / (N \times P) \quad (4)$$

The constituent $[\bar{T}_t(\varphi)]$ is the climate variable field determined by the seasonal variation of solar radiation, τ is the t -th month from the 1st year to the N -th year, and λ is the number of grid sites on isometric latitude from the 1st site to the final site P ($P = 144$).

On the right-hand side of Eq. (3), the second monomial is the month-by-month space variable field, obtained using the 1st N -th year average space lattice site temperature to minus the latitude average seasonal variation of solar radiation $[\bar{T}_t(\varphi)]$, relative to the t -th month. This is the month-by-month temperature space distribution field of the seasonal regulation of the sea–land distribution.

$$T_t^*(\lambda, \varphi) = \sum_{\lambda=1}^p T_t(\lambda, \varphi, \tau) / N - [\bar{T}_t(\varphi)] \quad (5)$$

In the third monomial, the separation method of the planetary-scale zonal average disturbance is based on using the zonal average of the reanalysis monthly data to minus the month-by-month zonal average, i.e., it represents the planetary-scale temperature disturbance of the zonal average in the t -th month of the Y -th year. This component is the phase of the planetary-scale temperature disturbance circulation in the t -th month, and it is related to the variation of the tropical ocean or polar decadal, interannual, and seasonal internal thermal forcing.

$$[T(\varphi, t)]'_Y = \sum_{\lambda=1}^p T(\lambda, \varphi, t)_Y / P - [\bar{T}_t(\varphi)] \quad (6)$$

In the fourth monomial, the synoptic-scale transient disturbance component is the synoptic-scale transient disturbance component of the t -th month in the Y -th year. The mathematic expression is:

$$T(\lambda, \varphi, t)_Y^* = T(\lambda, \varphi, t)_Y - [\bar{T}(\varphi)] - T_i^*(\lambda, \varphi) - [T(\varphi, t)]_Y^* \quad (7)$$

It must be clarified that this calculation method was used originally to analyze weather-scale anomalies for which the statistics used were based on “days”; however, this paper discusses variations of interannual scale and thus the units are “months”. Therefore, the fourth monomial can be understood as the climate-scale disturbance caused by interactions between the multi-scale terrains, thermal forcing, and the non-linear interactions of atmospheric internal fluctuations.

By means of the above methods, the geopotential height field is also decomposed, producing the 500-hPa geopotential height with four components (Z500_1, Z500_2, Z500_3, Z500_4) and the 1000-hPa geopotential temperature with four components (T1000_1, T1000_2, T1000_3, T1000_4). The objective of this paper is to study the effects of Arctic factors on wintertime temperatures in the Northern Hemisphere with particular focus on China, and to explore the reasons for these effects.

3 Effects of Arctic factors on Northern Hemisphere wintertime temperatures

3.1 Effects of Arctic factors on zonal temperature variation

The third monomial of the physical decomposition is the planetary-scale zonal average disturbance in the atmosphere. We performed a lead-lag correlation analysis on the AO index, PVI , PVA , and T1000_3, and advanced these indices by 0–3 months. A correlation coefficient of more than 0.23 can be considered passing the significance test when $\alpha=0.001$. Figure 2a shows that the wintertime AO index is positively correlated with the average temperature disturbance of 45°N–60°N, but negatively correlated with the temperature disturbance in lower latitudes. This illustrates that when the AO is in its negative phase in wintertime, the temperature in the mid-latitudes is lower than in the same period of normal years, but higher in latitudes south of 30°N, and that the effect of the AO can persist for 1 month. Figures 2c and 2e shows that the correlation between PVI and the average temperature disturbance in the mid–high latitudes is not obvious, and that PVA is negatively correlated with it at 50°N. This suggests that when the polar vortex area is more extensive, the weather within this domain is colder than average.

We also performed an analysis on the AO index, PVI , PVA , and Z500-3. It can be seen in Figure 2b that the correlation between the AO index and height field is the best (correlation coefficients up to 0.8). When the AO is in its negative phase, there is low pressure at 500 hPa in the mid-latitudes and high pressure at higher latitudes. Furthermore, the zonal wind is weakened in high latitudes

and the meridional circulation is enhanced by the pressure rise in the Arctic. This favors the flow of cold air from the high latitudes to the mid-latitudes, which is represented in Figure 2a. Figure 2f presents the distribution of the correlation coefficients of the PVA and potential height zonal average disturbance, showing that they are correlated negatively in the mid-latitudes and positively in high latitudes. Therefore, when the PVA is more extensive, there is low pressure at 500 hPa in the mid-latitudes, but high pressure at higher latitudes. This causes lower temperatures in the mid-latitudes, similar to the effects of the negative phase of the AO. The correlation between the PVI and average temperature disturbance in the mid–high latitudes is not obvious and therefore we have chosen not to analyze Figure 2d.

Figure 2 illustrates only the zonal average conditions, i.e., it only shows that when the AO is in its negative phase or when the polar vortex area is more extensive, the temperature in the mid–high latitudes is lower. It is not possible to establish in which area the effect of the cold air is greatest or how the cold air influences the mid–high latitudes. Therefore, we come to the analysis of the fourth monomial of the physical decomposition.

3.2 Mechanisms of the effects of Arctic factors on Northern Hemisphere wintertime temperatures

The fourth element of the physical decomposition is the disturbance on an inter-monthly scale. We decomposed T1000_4 and Z500_4 using REOF. During the EOF process, the spatial distribution of the eigenvector varies when the study areas or the sizes of samples are different; however, such limitations can be overcome by REOF^[23]. To discuss the effects of Arctic factors on the mid–high latitudes in the Northern Hemisphere, we performed a correlation analysis between the decomposed time coefficient and the AO index, PVA , and PVI . The data presented in Table 2 indicate that the correlations between the AO index and the second mode decomposed with Z500_4 and the first mode decomposed with T1000_4 are the highest (correlation coefficients of -0.62 and 0.71 , respectively). The correlations between PVA and the second mode decomposed with Z4 and the first mode with T4 are 0.23 and -0.29 , respectively. The correlation coefficients between PVI and the fourth mode decomposed with Z4 and the fourth mode with T4 are 0.28 and 0.32 , respectively (the critical value for the correlation coefficient to pass the significance test is 0.23 when $\alpha=0.001$). The correlation between the zonal average temperature disturbance and PVI is not as obvious as for PVA and the AO index (Figure 2), and the best correlation with REOF is neither the first nor the second modes, but the fourth mode. Therefore, we only analyze the influence of the PVA and the AO index.

To highlight the advantages of physical decomposition, we also calculated the correlation between the Arctic factors and the time series decomposed by traditional anomaly REOF (data omitted). We found that the correlation coefficient between the AO index and the first mode decomposed

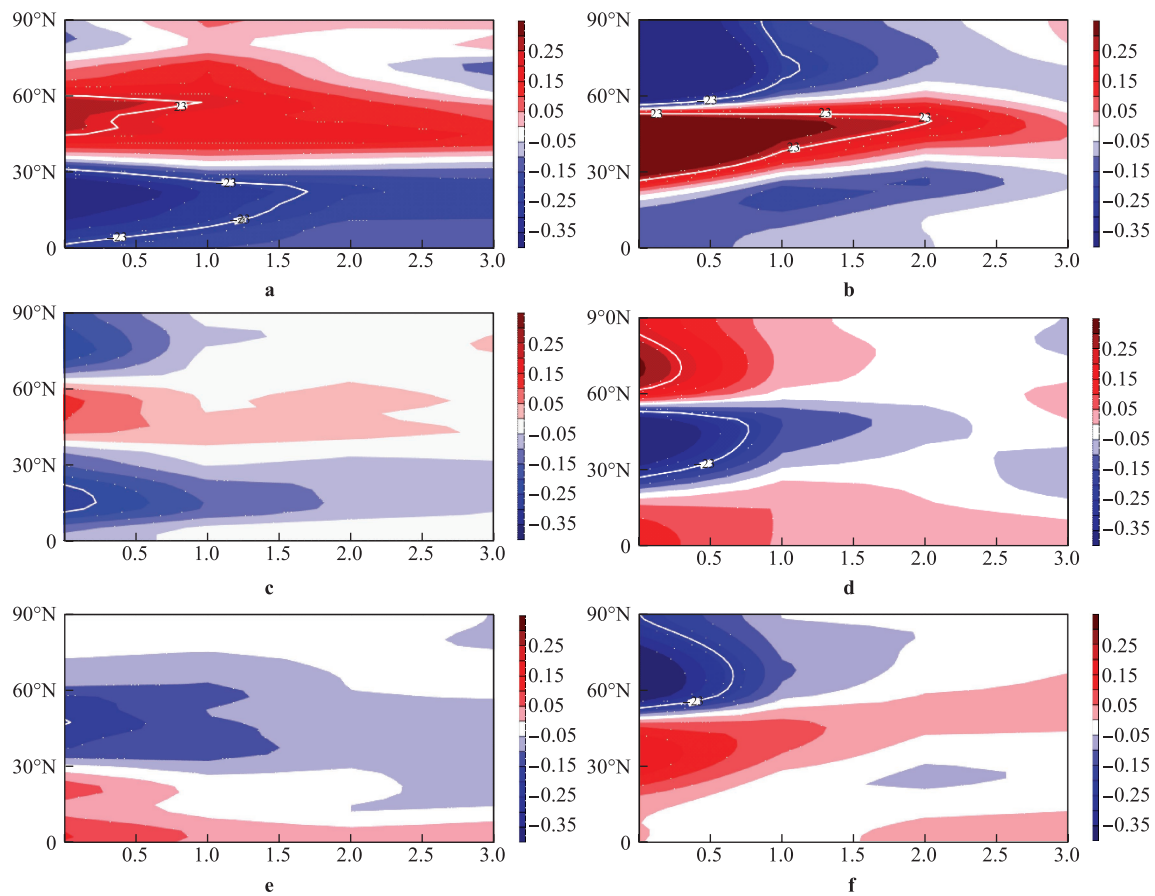


Figure 2 Distribution of correlation between Arctic factors and zonal average disturbance. The x-axis represents the monthly advance of the index, y-axis represents latitude, and the area of significant correlation is delineated by a white line. **a**, correlation between the AO index and T1000_3; **b**, correlation between the AO index and Z500_3; **c**, correlation between *PVI* and T1000_3; **d**, correlation between *PVI* and Z500_3; **e**, correlation between *PVA* and T1000_3; **f**, correlation between *PVA* and Z500_3.

by climate anomaly was -0.52 , which is far below that found between the AO index and the first mode following the physical decomposition disturbance field (0.71). The correlation between *PVA* and the first mode of the anomaly field is 0.27 and between *PVA* and the first mode of the physical decomposition disturbance field it is -0.29 . The correlation is marginally lower than the physical decomposition method, i.e., the physical decomposition method amplifies the correlation, which helps our analysis.

The correlation indicates that the modes of best correlation between the AO index and *PVA* are the second mode of the height field and the first mode of the temperature field (Table 2). Taking temperature as an example, the first mode, shown in Figure 3a, represents the antiphase of temperature between the Eurasian continent and the Bering Sea–Canada–Greenland region. The relationship between these two areas is like a seesaw. If the AO is in positive phase and the polar vortex area is reduced in size, the European–Siberian region becomes the strong warm center, the Greenland and Bering Strait regions become strong cold centers, and there is a weak warm center over

eastern parts of the United States. However, the situation is reversed if the AO is in negative phase and the polar vortex area is more extensive. This has been proven by Liu et al.^[4] using a numerical model; when pressure increases in the high latitudes in winter (AO in negative phase), Greenland and Northeast Canada are warmer, whereas northern North America, Europe, Siberia, and East Asia are colder.

Table 2 Correlation coefficients between time series and the AO index, *PVA*, and *PVI*

Index Mode	AO		<i>PVA</i>		<i>PVI</i>	
	Z500_4	T1000_4	Z500_4	T1000_4	Z500_4	T1000_4
1	-0.14	0.71	0.15	-0.29	0.16	0.17
2	-0.62	-0.18	0.23	0.06	-0.12	0.07
3	-0.09	0.35	-0.09	-0.20	-0.07	0.07
4	0.36	0.60	-0.10	-0.13	0.28	0.32
5	-0.07	-0.17	-0.07	0.01	-0.11	-0.09
6	-0.22	-0.46	0.07	0.23	0.04	-0.17

Note: Significant numbers are shown by gray highlighting.

The same analysis has been performed on the second mode of the height field, which has the best correlation with the AO index and *PVA* (Figure 3b). When the AO is in negative phase and the polar vortex area is more extensive, there is a strong low-pressure center near the Aleutian Islands, a strong high-pressure center in Canada, and two weaker high-pressure centers extending from Italy to Mongolia and centered on the Azores, respectively. If the atmospheric long wave is a cold-trough and warm-ridge structure, i.e., cold advection behind the trough (ahead of the ridge) and warm advection before the trough (behind the ridge), cold air will move southwards (120°E–150°E) between the areas of high pressure over Mongolia–Siberia and low pressure in the region of the Aleutian Islands, making Siberia and East Asia colder (Figure 3). In addition, warm advection between the Aleutian low-pressure and Canadian high-pressure areas can make Alaska warmer; the Canadian high pressure and weak low pressure around Baffin Bay can lead to a colder eastern North America; and warm advection between the weak low

pressure of Baffin Bay and high pressure near the Azores can cause Greenland to be warmer. This is in line with the warm–cold areas shown in Figure 3a, indicating that the system in Figure 3b is the main source for cold and warm air.

According to the decomposition figure of REOF, within the modes having the highest correlation coefficient with the AO index and *PVA*, the high and low-pressure centers are similar to the atmospheric activity centers (Figure 3b). Based on the study of Qian et al.,^[20] the physically decomposed second component (Z500_2) shows that there are seasonal high- and low-pressure systems all over the world, i.e., the so-called atmospheric activity centers (Figure 4). It was discussed earlier that because of the effect of westerly troughs and ridges, the cold and warm air are mainly derived from active centers. In other words, the cold polar air spreads along the quasi-stationary activity centers to the mid-latitudes when the AO is in negative phase or when the polar vortex area is more extensive.

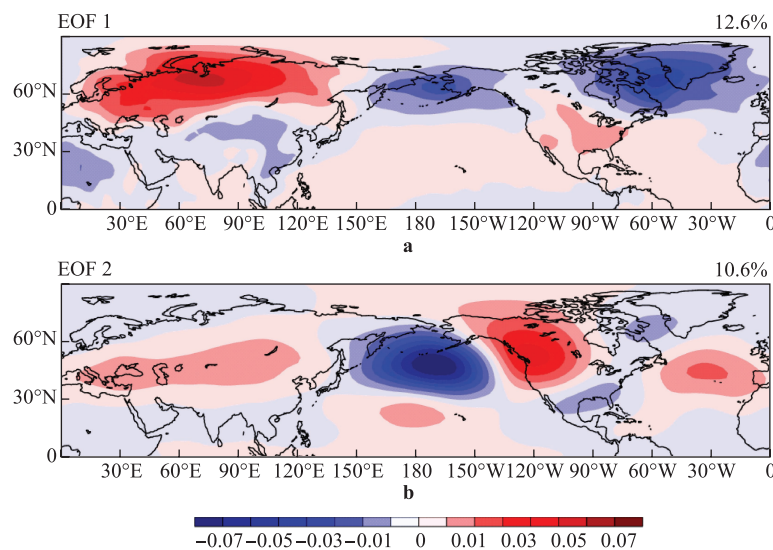


Figure 3 Rotated empirical orthogonal function (REOF) mode that has the best correlation with the AO index and *PVA*: **a**, first mode of T1000_4; **b**, second mode of Z500_4.

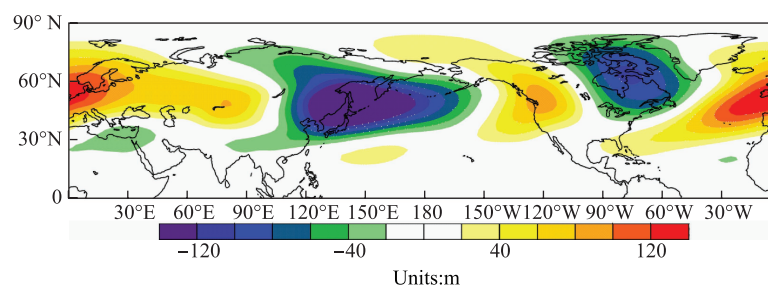


Figure 4 Physically decomposed second component of 500-hPa height field in Northern Hemisphere.

4 Effects of Arctic factors on winter temperature in China and their Predictive Effects

In Section 3, the effects of the AO on China are mainly presented as the fourth mode (correlation coefficient is 0.6). If the AO is in negative phase, it is possible to see extreme low temperatures in Northeast China (figure omitted). In this section, we focus on the effects of the Arctic factors on winter temperatures in China, and use REOF to decompose the fourth components of the 1000-hPa temperature field and 500-hPa height field from 60°–150°E (Figure 5). It must be noted that we used the PVA_I and PVI_I for the China analysis. We analyzed its correlation with the AO index, PVI_I , and PVA_I , and the coefficients are shown in Table 3.

Table 3 Correlation coefficients between time series and the AO index, PVA_I , and PVI_I

Index Mode	AO		PVA_I		PVI_I	
	Z500_4	T1000_4	Z500_4	T1000_4	Z500_4	T1000_4
1	0.25	-0.46	-0.04	0.08	-0.49	0.36
2	-0.35	0.15	0.16	-0.36	0.01	-0.01
3	-0.49	-0.55	-0.19	0.24	0.23	0.05
4	-0.31	0.12	-0.10	-0.04	0.30	-0.17

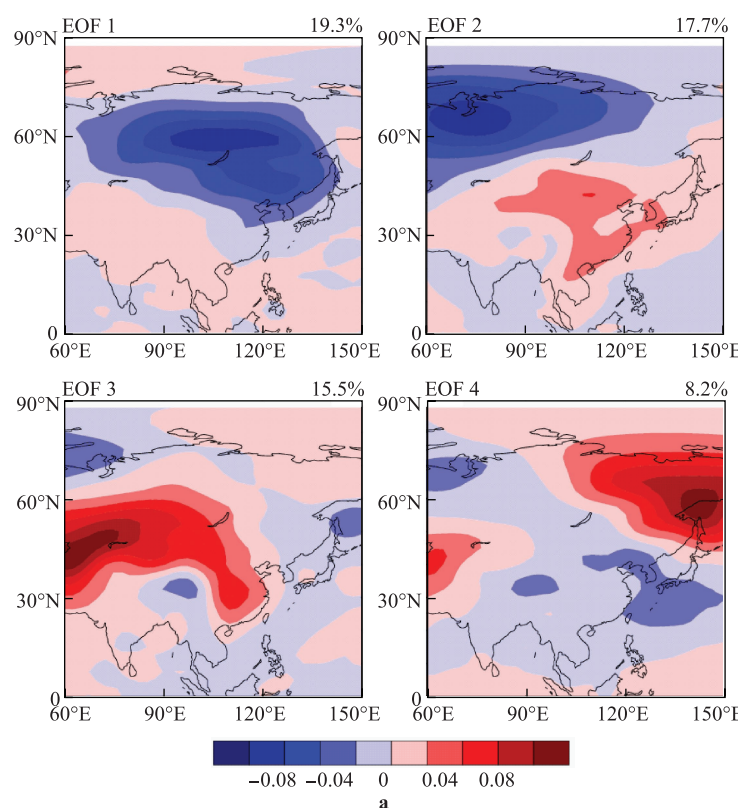
Note: Significant numbers are shown by gray highlighting.

Figure 5a shows that the variance contributions of the

four modes are 19.3%, 17.7%, 15.5%, and 8.2%, respectively. Although the third mode of the temperature anomaly has the best correlation with the AO index, the first mode has the greatest influence on China. According to the correlation coefficients shown in Table 3 and Figure 5a, Northeast China and Inner Mongolia will be colder (best correlation is the first mode) if the AO is in negative phase or if the Asian polar vortex is strong. This is in accordance with the study of Gong and Wang^[11]. They showed that the temperature in most of China is positively correlated with the variation of the AO and that it is more obvious in northern regions, i.e., northern Xinjiang, Northeast China, North China, and Shandong. Inner Mongolia, North China and South China are colder when the Asian polar vortex is more extensive, indicating that a larger polar vortex area pushes the cold air further southwards (best correlation is the second mode).

The third mode has the highest correlation with the AO index in the 500-hPa height field (Figure 5b). When the AO is in negative phase, the Ural Mountains blocking the high and cold vortex over northeastern China interact. The cold vortex rotates in a counterclockwise direction, distributing cold air further southwards, making northern China colder. The PVI_I has the greatest correlation with the first mode. When the intensity is stronger, northern China is under the influence of low pressure, which also makes it colder compared with the same time in other years.

In addition to simultaneous correlation, we also analyzed the leading correlation. We advanced the AO index, PVA_I , and PVI_I by 1–3 months and performed the correlation analysis between them and the time series of each



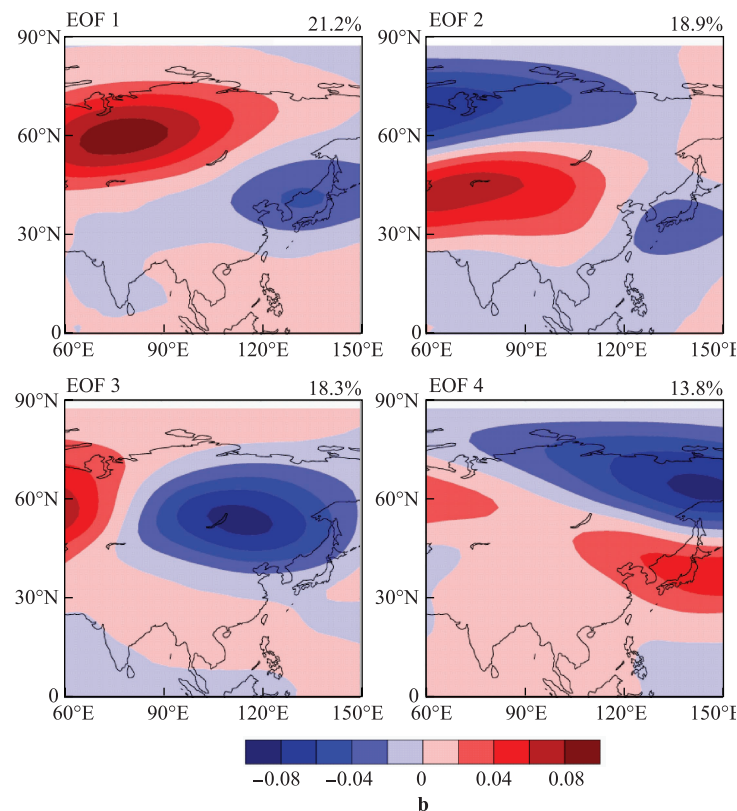


Figure 5 Rotated empirical orthogonal function (REOF) mode: **a**, four modes of T1000_4; **b**, four modes of Z500_4.

mode in Figure 5 (data omitted). We found that only the AO index could act as a predictor. The simultaneous correlation between the AO index and temperature disturbance field was -0.46 ; the correlation was -0.31 if the AO index was 1 month earlier and -0.18 if it was 2 months earlier (critical value of significance level; 0.18). In other words, the AO index could be used to predict the winter temperature in China up to 2 months ahead.

5 Discussion and conclusions

Global warming has meant that the Arctic climate system has changed more obviously than in other areas, i.e., it is both an amplifier and an indicator of climate change. Generally, researchers have analyzed the effects of changes in the Arctic climate on the temperatures of the Northern Hemisphere and China using the climate anomaly statistical method. However, in this paper, we used physical decomposition to analyze the effects of the AO and Arctic polar vortex on the westerly trough–ridge activities in the mid–high latitudes. The advantage of the latter method is that it can amplify insignificant signals of abnormality to increase the correlation between the variables. Based on this method, we found a clearer relationship between Arctic factors and the mid–high latitude westerlies.

(1) The effect of the AO on the zonally averaged temperature can persist for 1 month. When the AO is in

negative phase in winter, it is colder in the mid–high latitudes and warmer in the lower latitudes compared with other years. When the polar vortex area is more extensive, the zonally averaged temperatures are lower at 50°N . The analysis of the correlation between the AO index and zonally averaged height disturbance at 500 hPa showed that if the AO is in negative phase, or if the polar vortex area is more extensive, the zonal wind is weakened in high latitudes and meridional circulation enhanced because of the pressure rise in the Arctic. This favors the flow of cold air in the high latitudes towards the mid–latitudes and thus the mid–latitude areas become colder.

(2) Some studies have shown that since 2009, winter extreme temperatures on the Eurasian continent have not only been related to the AO negative phase, but have also been associated with a more extensive polar vortex area over Asia; however, they do not consider the North American continent. In fact, temperatures over the Eurasian continent and the Bering Sea–Canada–Greenland region exhibit opposite phases. If the AO is in negative phase and the polar vortex area in the Northern Hemisphere is more extensive, Siberia will be colder than usual, but Greenland and the Bering Strait will be warmer. Influenced by the westerly troughs and ridges, the cold polar air mainly spreads to the mid–latitudes along the quasi-stationary activity centers.

(3) If the AO is in negative phase, or if the intensity of the Asian polar vortex is stronger, Northeast China and Inner Mongolia will be colder than usual. This is because of the

southward movement of cold air caused by the Siberian high-pressure center and the cold vortex in Northeast China.

(4) The AO index can be used as a predictor for winter temperatures in China up to 2 months ahead.

The physical decomposition method abstracts the anomaly fields and avoids the subjective definition of the 30-year climate state. If we analyze the case on a daily time scale, the factitious division of the months can be avoided (i.e., 28, 30, or 31 d in a month). We established the effects of Arctic factors on the winter temperature in the Northern Hemisphere and China using the physical decomposition method; however, the mechanisms of these effects have not been explained in this study. Our future work will present an in-depth analysis of the effects of Arctic factors on the Northern Hemisphere and regional temperatures from the perspective of stratospheric–tropospheric interactions. In addition, other results indicate that autumn–winter Arctic sea ice concentration and concurrent sea surface temperature anomalies are responsible for the winter Siberian High and surface air temperature anomalies over the mid–high latitudes of Eurasia and East Asia^[24–25]. Therefore, we should consider supplementing other factors in the analysis.

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