The Leading Mode of Wintertime Cold Wave Frequency in Northern China during the Last 42 Years and Its Association with Arctic Oscillation

WEI Jun-Hong$^{1,2}$ and LIN Zhao-Hui$^1$

$^1$ International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
$^2$ Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Received 3 March 2009; revised 3 April 2009; accepted 18 April 2009; published 16 May 2009

Abstract This study examined wintertime (November–April) cold wave frequency (CWF) in northern China during the last 42 years and its association with Arctic Oscillation (AO) through analysis of daily mean surface temperature from 280 stations across northern China and European Centre for Medium-Range Weather Forecasts (ECMWF) 40-Year Re-analysis ERA-40 data. The leading empirical orthogonal function EOF mode of wintertime CWF (CWF-EOF1) indicates an identical signal over most northern China, with the characteristic trend of linear decline for the leading principal component (CWF-PC1). After the linear trend is removed, remarkable inter-annual variability is found to be the dominant feature of the CWF-PC1. The regression map for sea level pressure variability is found to be the dominant feature of the CWF-PC1. The datasets employed in this study include the daily mean surface temperature recorded at 833 stations across China by the China Meteorological Administration. The longest observation period for a particular station is from 1 January 1951 to 31 December 2006. In order to focus on northern China, this study examines only the stations that are north of 34°N. Furthermore, missing values are screened before the data are used in the subsequent analysis. Stations with too many missing values are removed. A year is considered to be missing if more than 1% of the days are missing. A total of 280 stations (Figs. 1a and 1c) with non-missing years during 1960–2002 are retained in this study.

This study calculates CWF for a single station by the criteria of both $\Delta T >10^\circ C$ and $T_{\min} <-5^\circ C$ (National Climate Center, 1986), where $\Delta T$ is the difference between the maximum and the minimum daily temperature within 10 days during a cold event, and $T_{\min}$ is a deviation of the minimum daily temperature from its 10-day average.

Keywords: cold wave frequency, Arctic Oscillation


1 Introduction

Disastrous weather phenomena frequently affect northern China during wintertime (November–April), and cold wave events in particular are distinguished by invasions of cold air masses over large areas. Cold wave events in East Asia have been classified into three categories by the orientation of the cold air masses (Li, 1955). The headstream and routes of the cold air masses experienced on the Chinese Mainland have also been investigated (Ding, 1990). Since the 1980s, relevant studies have mainly focused on the geophysical process of the cold wave (Chou, 1984; Zhang et al., 1994; Joung and Hitchman, 1982). Based on the classical theory of cold wave (Zhu et al., 2007), the research of the winter monsoon in East Asia (Zhang et al., 1997) and the investigation of Arctic Oscillation (AO) (Thompson and Wallace, 1998, 2001) have furthered the understanding cold wave events in northern China.

Because of the huge loss caused by several severe cold wave events during the winter of 2004/05 (Zhao and Zeng, 2005) and the long-lasting snow storms in January 2008 (Li et al., 2008), it is commonly accepted that an understanding of the mechanisms responsible for the variability of cold wave events over East Asia and its predictability is of high priority for climate research. Generally speaking, most recent studies have placed particular emphasis on local cold air activity (Liu et al., 1995; Lin and Wu, 1998). Wang and Ding (2006) and Qian and Zhang (2007) utilized the latest observational data to reveal the climatology and the climate change of cold wave frequency (CWF) in China, but as to the explanation for the inter-annual variability of CWF, both studies concentrated on the atmospheric circulation at regional scale rather than global scale. In particular, it remains unclear whether and how the northern annular mode is associated with CWF in China, especially in the northern China. Thus, the main objective of this study is to characterize the leading mode of CWF in northern China with empirical orthogonal function EOF analysis, and further explore its connection with the Arctic Oscillation.

2 Data and method
mean temperature. When $\Delta T$ is above 10°C and $T_{\text{min}}$ is below $-5^\circ$C, a cold wave event is calculated for the corresponding station. The criteria used in this research are also adopted by Wang and Ding (2006) and Ma et al. (2008). Wintertime CWF at each station is defined as the cumulative number of cold wave events for that station from November to April of each year.

The monthly datasets of European Centre for Medium-Range Weather Forecasts (ECMWF) 40-Year Re-analysis (ERA-40) Data are used for the period of 1960–2002 (Uppala et al., 2005), and the data are averaged for the six wintertime months (November–April). The definition of the wintertime AO follows Thompson and Wallace (1998, 2000) except when the ERA-40 re-analysis datasets are used. Specifically, at a positive AO phase, wintertime circulations in the Northern Hemisphere are characterized by low-pressure anomalies throughout polar region and surface westerly anomalies across medium latitudes, and vice versa during a negative AO phase.

The methods of statistical analysis adopted in this study include EOF, linear regression and correlation analysis. First, it should be noted that EOF modes are demonstrated by regression maps of principal components (PC). Second, in order to better reflect the inter-annual variability instead of the linear trend, regression maps and correlation maps of the original data are shown with maps of the de-trended data for comparison.

3 Results

Based on CWF calculated from 280 stations over northern China during the wintertime of 1960/61–2001/02, the leading EOF mode of wintertime CWF (CWF-EOF1) and its leading principal component (CWF-PC1) are acquired with EOF analysis (Fig. 1). With CWF-EOF1 accounting for 47.8% of the total variance, the positive signal for CWF-EOF1 is found over most parts of northern China (Fig. 1a), which suggests that the main spatial pattern is a consistent increase or decrease at most stations in northern China. Overall, cold wave frequency increases from the southwest to the northeast, with the positive center located in northeast China. From a long-term perspective, the last 42 years is characterized by a trend of linear decline as indicated by CWF-PC1 (Fig. 1b). The coefficient of this linear trend is $-0.046$ per year, and is significant at the 99% confidence level. The linear decline of CWF-PC1 can be clearly displayed in its 9-year running mean. After data are de-trended (Fig. 1c), CWF-EOF1 still accounts for 40.3% of the total variance while its spatial distribution remains similar to Fig. 1a. However, remarkable inter-annual variability is the dominant feature for the de-trended CWF-PC1 (Fig. 1d).

The regression maps for pressure at sea level from CWF-PC1 are shown in Fig. 2. From a large-scale perspective, the spatial distribution resembles the negative phase of AO derived from the original data (Fig. 2a). Specifically, significant negative regression coefficients are mainly distributed over medium and low latitudes in the Northern Hemisphere, while high northern latitudes mainly demonstrate significant positive signals. After the data are de-trended (Fig. 2b), the large-scale pattern remains similar to those in Fig. 2a over the Northern Hemisphere. Note that the significant positive signals over the
high latitudes of the Southern Hemisphere can be hardly found when the de-trended data are used.

Figure 3 further indicates the times series of both AO and CWF-PC1. Using the original data, CWF-PC1 has a significant negative correlation of $-0.626$ with the AO at the 99% confidence level (Fig. 3a). With the use of de-trended data, CWF-PC1 maintains its negative correlation of $-0.573$ with the AO at the 99% confidence level (Fig. 3b). This illustrates that CWF-PC1 and AO are related to each other at the inter-annual scale.

The map of correlation coefficients between AO and wintertime CWF in northern China (Fig. 4a) shows that there is an identical negative correlative signal across most parts of northern China. Specifically, negative correlations that are above the 95% confidence level cover Northwest China, North China, and Northeast China. With the de-trended data being analyzed, correlations between AO and wintertime CWF (Fig. 4b) remain similar to those shown in Fig. 4a. Note that both of the correlation maps in Fig. 4 are also able to demonstrate the pattern of the CWF-EOF1 (Fig. 1a).

In recent years, there has been great interest in the AO and its relationship with the climate in East Asia (e.g., Zhou and Li, 2008). It has been suggested that, during a positive AO phase, downward motion remarkably weakens over Siberia, and vice versa, which further influences the winter Siberia High (Wu and Wang, 2002). As a result, the negative correlation between AO and Siberia High may influence the climate in East Asia during the boreal winter (Gong et al., 2001). In order to study the association of the northern annular mode with cold air activity over East Asia, the simultaneous correlations of the AO with surface air temperature are investigated (Fig. 5). Whether analyses of original data or de-trended data are
examined, the AO and surface air temperature exhibit remarkable positive correlations over the middle and high latitudes of Eurasia (Figs. 5a and 5b). Consequently, during a positive AO phase, the intensity of cold air weakens over Eurasia, which leads to a consistent decrease of CWF for most of northern China, and vice versa. In addition, we define the Siberian Temperature Index (STI) as the surface temperature during the wintertime averaged over the key region of cold wave (43°–65°N, 70°–90°E) (Zhu et al., 2007). We found that the STI is closely connected with the AO, having a correlation coefficient of 0.666 at the 99% confidence level. In the analysis of de-trended data, the STI is also associated with the AO, with a correlation coefficient of 0.612 at the 99% confidence level. Moreover, the STI also exhibits a significant negative correlation of −0.476 with CWF-PC1 at the 99% confidence level, and such a negative correlation between the STI and CWF-PC1 remains at 99% confidence level with the correlation coefficient of −0.407 in the analysis of de-trended data. And this may suggest that the anomalies of atmospheric circulation in Siberia serve as a bridge for interaction between the AO and CWF-PC1 during the wintertime.

4 Conclusion and discussion

With daily mean surface temperature from 280 stations across northern China and ERA-40 reanalysis data, CWF in northern China during wintertime for the last 42 years and its relationship with AO are investigated. Accounting for 47.8% of the total variance, the leading mode of wintertime CWF indicates an identical positive signal over most northern China, and its leading principal component is distinguished by a linear decline. With the linear trend removed, the leading mode of wintertime CWF still accounts for 40.3% of the total variance, and its leading principal component exhibits significant inter-annual variability. During the wintertime, a negative AO-like pattern can be found in the regression map of pressure at sea level based on the leading principal component of wintertime CWF. This component is related to the AO with a correlation of −0.626 at 99% confidence level in the analysis of the original data (analysis of de-trended data results in correlation of −0.573 at the 99% confidence level). Furthermore, the significant positive correlation can be found between Arctic Oscillation and the surface air temperature over Siberia region during wintertime, this indicates that the intensity of cold air over Eurasia may be significantly influenced by the AO activities, hence leading to the inter-annual variability of wintertime CWF in northern China, and the atmospheric circulation anomalies in Siberia may serve as a bridge for interaction between AO and cold wave frequency in northern China in inter-annual time scale. Further study may investigate the CWF and its interaction with external forcing factors. In addition, the possible mechanism responsible for the linear trend of the CWF has not yet been discussed in this paper, and it may be attributed to global warming, which should also be addressed in the later research.

Acknowledgements. This research was supported by the National Basic Research Program of China (973 Program) (Grant No.2009CB421406), the National Key Technologies R&D Program of China (Grant No.2007BAC29B03), and the National Natural Science Foundation of China Project (Grant No.40821092). The authors would like to thank the National Meteorological Information Centre for the daily observational data. Special thanks to Professor Lu Riyu, editor of Atmospheric and Oceanic Science Letters. In addition, the insightful comments of two anonymous reviewers are appreciated.

References


Wang, Z., and Y. Ding, 2006: Climate change of the cold wave frequency of China in the last 53 years and the possible reasons, Chinese J. Atmos. Sci. (in Chinese), 30(6), 14–22.