Decadal Change of Heavy Snowfall over Northern China in the Mid-1990s and Associated Background Circulations

BOTAO ZHOU,^{a,b,c} ZUNYA WANG,^d BO SUN,^{a,b,c} AND XIN HAO^{a,b,c}

^a Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters,
Nanjing University of Information Science and Technology, Nanjing, China

^b Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing University of Information
Science and Technology, Nanjing, China

^c Joint International Research Laboratory of Climate and Environment Change, Nanjing University of Information
Science and Technology, Nanjing, China

^d National Climate Center, China Meteorological Administration, Beijing, China

(Manuscript received 27 October 2019, in final form 4 October 2020)

ABSTRACT: Analyses of observation data from 1961 to 2014 by using the empirical orthogonal function (EOF) method indicate that the primary mode (a monosign pattern) of heavy snowfall over northern China in winter shows evident variations from a negative polarity to a positive polarity in the mid-1990s. Associated with this decadal change, the southward displacement of the polar front jet stream and northward shift of the subtropical jet stream in the upper troposphere are apparent. Accordingly, a negative height anomaly dominates the region from Lake Balkhash to Lake Baikal and a positive height anomaly occupies the midlatitudes of the North Pacific in the middle troposphere. Such anomalous patterns in the middle and high troposphere correspond approximately to the northern mode of the East Asian winter monsoon (EAWM) and may favor the interaction of cold air with moist airflows over northern China, which helps increase local heavy snowfall. Further investigation shows that the shift in the Atlantic multidecadal oscillation (AMO) from a cold phase to a warm phase in the 1990s may also play a role, through its linkage to the above atmospheric circulations with the aid of a downstream propagation of wave train that emanates from the Atlantic Ocean.

KEYWORDS: Atmosphere; Asia; Atmospheric circulation; Snowfall; Interdecadal variability

1. Introduction

Heavy snowfall events present severe disasters in China, as they usually cause great damage to society and the economy through their broad and profound effects on electric networks, traffic transportation, pasturage, ecosystems, and human lives. In recent decades, an increasing tendency has been observed for heavy snowfall over parts of China (Sun et al. 2010; Zhou et al. 2018). Given the severe impacts, it is of particular interest and concern to understand the variability of heavy snowfall over China and the physical mechanisms underlying this variability. This understanding is also of great value for disaster prevention and mitigation.

During recent years, many studies have been devoted to the formation, physical mechanism, and predictability of heavy snowfall over China (e.g., Ding et al. 2008; Yang et al. 2008; Gao 2009; Wen et al. 2009; Sun et al. 2009; Zhou et al. 2009; Wang et al. 2011; Liu et al. 2012; Fan and Tian 2013; Sun and Wang 2013; Wang et al. 2017; Wang and Zhou 2018; Sun et al. 2019). Through those studies, some meaningful results have been obtained. For instance, Sun et al. (2009) investigated the cause of a heavy snowstorm over northeastern China in 2007. Their results indicated that anomalies of the Arctic Oscillation

(AO), Antarctic Oscillation (AAO), North Pacific Oscillation (NPO), and Eurasian teleconnection pattern (EU) that occurred approximately two weeks before the event provided a favorable environment for its occurrence. Wang et al. (2011) found that a great convergence of water vapor and enhanced ascending motions over northeastern China were crucial for the occurrence of an exceptional heavy snowfall event in April 2010. Wang and Zhou (2018) further revealed that the negative phase of the AO, deepening of the Lake Baikal trough, and intensification of westerly and southerly water vapor inflows favored more heavy snowfalls in northern China at the interannual time scale. For the unprecedented cold event that occurred with a concurrent snowstorm and ice freezing in southern China during the wintertime of 2008, a number of influential factors such as the intensification of the western Pacific subtropical high and the India–Burma trough (Yang et al. 2008), enhancement of the polar vortex disturbance (Gao 2009), southeastward shift and intensification of the Middle East jet stream (Wen et al. 2009), meridional dipole pattern of the Eurasian mid- to high-latitude circulation (Wang et al. 2020), and the La Niña background (Ding et al. 2008) have been documented.

Although these efforts have greatly enriched our knowledge of the occurrence of heavy snowfall events in China, most have concentrated on case studies or interannual variability. Less attention has been paid to interdecadal variability. To understand and predict heavy snowfall, interdecadal variability and related physical mechanisms are also a key issue. Several recent studies have highlighted an interdecadal change in

Denotes content that is immediately available upon publication as open access.

Corresponding author: Botao Zhou, zhoubt@nuist.edu.cn

DOI: 10.1175/JCLI-D-19-0815.1

© 2020 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

snowfall amounts and intensities over northeastern China with a negative polarity before the mid-1980s and a change to a positive polarity afterward (Wang and He 2013; Feng and Chen 2016; Zhou et al. 2017). Such an interdecadal increase may be attributed to the weakening of the East Asian winter monsoon (EAWM) (Wang and He 2013), warming of the North Pacific sea surface temperature (SST) (Feng and Chen 2016), and strengthening of the Hadley circulation (Zhou et al. 2017). Is there also an interdecadal change for heavy snowfall over northern China? If so, what are the background circulations behind the interdecadal change? With these questions in mind, in this study, we are motivated to address the interdecadal variation of heavy snowfall over northern China and explore the associated changes in background circulations with the aim of providing a new understanding for the variability of snowfall in China.

The remainder of this paper is arranged as follows. Section 2 describes the data and methods used in the present study. Section 3 shows the features of the interdecadal variation of heavy snowfall over northern China. In section 4, we investigate the underlying physical mechanisms for the interdecadal variation of heavy snowfall by analyses of decadal changes in atmospheric circulations and Atlantic SST. The major findings are summarized in section 5.

2. Data and methods

Daily snowfall records (1961–2014) identified by the weather phenomena from 836 meteorological stations in China were used in this study. Quality control of this dataset was performed by the China Meteorological Administration (CMA). Due to missing records at some stations, we excluded those stations with records less than 30 years in length, which left a total of 610 stations for analysis. According to the criteria of the CMA, snowfall events in China are classified into four categories based on daily snowfall amounts: light snowfall (0.1–2.5 mm day^{−1}), moderate snowfall (2.5–5 mm day^{−1}), large snowfall (5–10 mm day^{−1}), and snowstorm (>10 mm day^{−1}). In this study, the large snowfall and snowstorm categories are referred to as heavy snowfall. That is, heavy snowfall events are defined as those for which the daily snowfall amount is no less than 5 mm.

Atmospheric reanalysis data with a horizontal resolution of 2.5° × 2.5° from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996) and SST data with a horizontal resolution of 2° × 2° from the National Oceanic and Atmospheric Administration (NOAA) (Smith and Reynolds 2004) were also used. The Atlantic multidecadal oscillation (AMO) index (Enfield et al. 2001) was downloaded from the website <https://www.esrl.noaa.gov/psd/data/timeseries/AMO/>. To validate the influence of the AMO on atmospheric circulations, the twentieth-century reanalysis products with a horizontal resolution of 2° × 2° (Compo et al. 2011) and simulations from the Community Atmosphere Model version 3.5 (CAM3.5) that has a horizontal T85 spectral resolution and 27 hybrid sigma levels (Neale et al. 2008; Oleson et al. 2008) were employed. For the CAM3.5 simulations, two idealized

experiments with the following SST boundary conditions were performed: 1) the warm AMO run, in which the warm phase of the AMO was added to the climatology of monthly mean SST for the entire North Atlantic, and 2) the cold AMO run, in which the cold phase of the AMO was added to the climatology of monthly mean SST for the entire North Atlantic. The warm (cold) phase of the AMO was derived from the SST data using rotated EOF analysis. Readers can refer to Fig. 1 of Hao et al. (2016) for details.

This study focuses on the winter season, which is the period from December in a given year to the following February (DJF). For example, the winter season of 1961 is defined as the average of December 1961, January 1962, and February 1962. The target region is confined to northern China (north of 35°N in China). The methods adopted mainly include EOF analysis, regression analysis, composite analysis, and correlation analysis. The Student's *t* test was employed for statistical significance tests. As the variables may not be independent from each other for the decadal component that was obtained through Fourier harmonics by using periods longer than 10 years in this study, the effective degree of freedom calculated based on the following equation (Bretherton et al. 1999) was applied for the significance tests at the interdecadal time scale:

$$N^* = \frac{N}{\sum_{\tau=-(N-1)}^{N-1} (1 - |\tau|/N) \rho_x(\tau) \rho_y(\tau)},$$

where N^* is the effective degree of freedom and $\rho_x(\tau)$ and $\rho_y(\tau)$ are the autocorrelation functions of the time series $x(t)$ and $y(t)$, respectively.

The horizontal wave activity flux W was calculated in terms of the following equation (Takaya and Nakamura 2001):

$$W = \frac{p}{2|\mathbf{U}|} \left[\begin{aligned} &U(\psi_x'^2 - \psi' \psi_{xx}') + V(\psi_x' \psi_y' - \psi' \psi_{xy}') \\ &U(\psi_x' \psi_y' - \psi' \psi_{xy}') + V(\psi_y'^2 - \psi' \psi_{yy}') \end{aligned} \right],$$

in which ψ' is the perturbation streamfunction, $|\mathbf{U}|$ is the horizontal wind speed, U (V) is the zonal (meridional) component of the basic flow, and p is the pressure divided by 1000 hPa.

The wave source S was expressed by the formula (Sardeshmukh and Hoskins 1988)

$$S = -\nabla \cdot [V_x(\zeta + f)],$$

where V_x is the divergent part of the horizontal velocity, ζ is the relative vorticity, and f is the planetary vorticity.

The Mann–Kendall test (Mann 1945; Kendall 1975) was used to detect abrupt points in time series, which was calculated as follows:

- 1) Construct an order series S_k for the given time series x_i ($i = 1, 2, \dots, n$):

$$S_k = \sum_{i=1}^k r, \quad k = 2, 3, \dots, n,$$

FIG. 1. (a) EOF1 mode of winter heavy snowfall over northern China. (b) Normalized time series (PC1; bar) of the EOF1 mode from 1961 to 2013, superimposed by its decadal component (black line).

where

$$r_i = \begin{cases} 1, & x_i > x_j \\ 0, & x_i \leq x_j \end{cases}, \quad j = 1, 2, \dots, i.$$

- 2) Define a statistical series UF using the assumption that the distribution of the time series is random and independent:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\text{Var}(S_k)}}, \quad k = 1, 2, \dots, n,$$

where $UF_1 = 0$ and $E(S_k)$ and $\text{Var}(S_k)$ represent the mean and variance of S_k , respectively.

- 3) Calculate the statistical series UB by repeating the above steps for the reversed time series x_i ($x_n, x_{n-1}, \dots, x_1$) and let $UB_1 = 0$ and $UB_k = -UF_k$ ($k = n, n-1, \dots, 1$).

If the curves for UF and UB are plotted in the same coordinate system and a significance level is given, the intersection of UF and UB, which falls within the significance interval, indicates the abrupt point.

3. Decadal change of heavy snowfall over northern China

Figure 1 shows the first leading EOF mode (EOF1) and associated principal component (PC1) of heavy snowfall in

FIG. 2. Percentage (%) of heavy snowfall to total snowfall amounts during the wintertime of 1961–2013.

northern China during the winters from 1961 to 2013. The EOF1 mode (Fig. 1a), which accounts for 36% of the total variance, presents a consistent variation over most areas of northern China. The positive value centers are located in the southeastern part of Northeast China and the northwestern part of Northwest China. Of interest is that the locations of these extreme value centers correspond to those of great snowfall shown by the climatology (Ding 2013; Sun et al. 2010; Zhou et al. 2018). Over these regions, the percentage contribution of heavy snowfall to total snowfall exceeds 20% (Fig. 2).

PC1 is primarily characterized by a pronounced interdecadal increasing tendency superimposed with interannual variations (Fig. 1b). Before the mid-1990s, most years were in the negative phase. After the mid-1990s, in contrast, most years were in the positive phase. Considering the consistent variation of heavy snowfall in northern China, we further defined the area-averaged heavy snowfall over northern China as an index (NCSI) to measure its variations. Clearly, the change in NCSI from 1961 to 2013 (Fig. 3a) is quite similar to that of PC1 (Fig. 1b). The correlation coefficient between the two time series is 0.81, significant above the 99% level. Their correlation coefficient at the decadal time scale reaches 0.87 (the effective degree of freedom is 12) and is also higher than the 99% significance level.

The Mann–Kendall test on the NCSI was performed to check the significance of interdecadal shift. As shown in Fig. 3b, an intersection of UF and UB (see section 2 for the explanation of UF and UB) is detected approximately in 1996, which is at the 95% significance interval. This result indicates that the heavy snowfall in northern China did experience an interdecadal shift in the mid-1990s. In the following, two subperiods with equal sample length (15 years), 1981–95 (P1) and 1999–2013 (P2), were defined to depict this decadal change in heavy snowfall and were used for composite analyses.

Figure 4 presents the heavy snowfall anomalies during the P1 and P2 periods. A general out-of-phase variation is clearly visible between the two subperiods. During the former subperiod (1981–95), the negative anomalies are rather pronounced over northeastern China and northwestern China. During the latter subperiod (1999–2013), the anomalies in northern China generally shift to a positive phase. This pattern bears an overall resemblance to the EOF1 mode.

FIG. 3. (a) Time series of the normalized NCSI from 1961 to 2013, superimposed by its decadal component (black line). (b) Result of the Mann-Kendall test for the NCSI time series. The red (blue) curve indicates the statistical series UF (UB) of the Mann-Kendall test, and the dashed lines indicate the 95% significance interval.

In summary, heavy snowfall over northern China experienced an interdecadal change in the mid-1990s, after which the local heavy snowfall has increased. This interdecadal change also reflects an upward trend over the course of the entire time period from 1961 to 2013.

4. Decadal changes in background circulations

a. Atmospheric circulations

Before exploring the changes in atmospheric circulations underlying the interdecadal variation of heavy snowfall, we first determined the planetary-scale three-dimensional structures that are associated with heavy snowfall over northern China by regressing the winter atmospheric circulations with the synchronous NCSI.

Figure 5a shows the NCSI-regressed anomalies in 200-hPa zonal winds. Corresponding to the increase of heavy snowfall in northern China, the westerly anomalies at midlatitudes (40° – 60° N) accompanied by the easterly anomalies at high latitudes (north of 60° N) are pronounced over the Eurasian continent in the upper troposphere. Regarding the climatology, there are two jet streams (i.e., the polar front jet stream and the subtropical

FIG. 4. Anomalies of winter heavy snowfall in northern China during (a) 1981–95 (P1) and (b) 1999–2013 (P2).

jet stream) that reside on either side of the Tibetan Plateau. The cores of the polar front jet stream and the subtropical jet stream are located at approximately 57.5° and 30° N, respectively (Hudson 2012; Luo and Zhang 2015; Xue and Zhang 2017; Huang et al. 2017). Thus, the anomalous pattern with strengthening of zonal winds at midlatitudes and weakening of zonal winds at high latitudes reflects a southward displacement of the polar front jet stream and a northward shift of the subtropical jet stream. As revealed by previous studies, this pattern is conducive to the southward invasion of cold air from polar regions (Eichelberger and Hartmann 2007; Zhang et al. 2008; Luo and Zhang 2015; Lu et al. 2016; Huang et al. 2017; Xue and Zhang 2017). Moreover, the cyclonic vorticity caused by the upper-tropospheric zonal wind shear could exert an impact on the middle-tropospheric atmospheric circulations by decreasing geopotential heights (Woollings et al. 2008; Luo and Zhang 2015; Hao et al. 2016; Huang et al. 2017). As shown in Fig. 5b, a salient negative height anomaly is clearly observed around the region from Lake Balkhash to Lake Baikal (hereafter abbreviated as LBB for simplicity) at 500 hPa. In addition, the midlatitudes of the North Pacific are dominated by positive height anomalies (Fig. 5b). The anomalous northerlies to the west of the cyclonic circulation may drive cold air from high latitudes to break out southward, subsequently invading northern China from the west side (Ding 2005). Because anomalous southwesterlies over the East Asian coast abate the climatologically prevalent northwesterlies (Chen et al. 1991), cold air is prevented from moving farther southward and thus accumulates in northern Asia.

FIG. 5. Regressions of (a) zonal wind (m s^{-1}) at 200 hPa, (b) geopotential height (shadings; gpm) and horizontal winds (arrows; m s^{-1}) at 500 hPa, and (c) water vapor transport ($\text{kg m}^{-1} \text{s}^{-1}$) vertically integrated from surface to 300 hPa against the normalized NCSI during the wintertime of 1961–2013. Regions above the 95% significance level are shaded in (a) and (c) and dotted in (b). The contours in (b) indicate the climatological geopotential height (gpm) at 500 hPa.

On the other hand, the strong southerly anomalies along the East Asian coast, which are associated with the anomalous anticyclonic circulation in the North Pacific, could enhance water vapor transport from the Pacific Ocean toward northeastern China. This may be confirmed in the regression of the vertically integrated water vapor transport flux with the NCSI (Fig. 5c), which shows northward transport of water vapor from the Ocean to northeastern China. In addition, associated with the cyclonic anomaly over LBB, there is a prevalence of

anomalous westerly water vapor transport into northwestern China. As a result, the moisture increases in northern China. Recent studies have indicated that enhancement of water vapor transport plays a key role in triggering heavy snowfall in northern China, since the northern China region is climatologically dominated by cold and dry airflows (Wang and Zhou 2018; Xie and Sun 2019).

Based on the above analysis, it is suggested that the southward displacement of the polar front jet stream and northward shift of the subtropical jet stream in the upper troposphere, as well as the cyclonic circulation anomaly over LBB and anticyclonic circulation anomaly over the North Pacific in the middle troposphere, seem to be favorable large-scale atmospheric circulations for the occurrence of heavy snowfall over northern China. Such a configuration could enable more cold air and more moist airflow to interact in northern China. This interaction has been widely recognized as an essential condition for the occurrence of heavy snowfall (e.g., Zhou et al. 2009; Wang et al. 2011; Sun and Wang 2013; Wang and He 2013; Zhou et al. 2017; Wang and Zhou 2018). Generally, when the moist airflows meet cold air bodies, the moist airflows climb along the cold air and reach saturation at the uplift condensation height. Above the condensation height, the moisture turns into supercooled water droplets and ice crystals, which develop gradually and eventually fall to the ground in the form of snow due to the low temperatures.

As is known, the winter climate in China is affected by the EAWM (Chen et al. 1991; Huang et al. 2014; W. Chen et al. 2019). One of the unique features of the EAWM is its large meridional extent that stretches from the high latitudes to the tropics and its distinct components at different levels from the lower troposphere to the tropopause (Chen et al. 1991; Jhun and Lee 2004; Wang et al. 2010; Wang and Chen 2010; Wang and He 2012; Huang et al. 2014; W. Chen et al. 2019). According to previous studies (Wang et al. 2010; Luo and Zhang 2015), the aforementioned large-scale atmospheric circulations that are associated with heavy snowfall over northern China generally coincide with the northern mode of the EAWM, which is defined as the first leading EOF mode of East Asian air temperatures and features cold winters in northern East Asia (Wang et al. 2010).

To examine the interdecadal change in atmospheric circulations, Fig. 6 plots the composite differences of 200-hPa zonal winds, 500-hPa geopotential heights, and vertically integrated water vapor transport between the P2 and P1 periods. Interestingly, the composite difference pattern (Fig. 6) shows a general resemblance to the circulation pattern that favors an increase of heavy snowfall over northern China (shown in Fig. 5). With respect to the former period (1981–95), during the latter period (1999–2013) the polar jet stream shifts equatorward and the subtropical jet stream shifts poleward in the upper troposphere (Fig. 6a). In the middle troposphere (Fig. 6b), the LBB region is dominated by a negative height anomaly (cyclonic circulation anomaly). This suggests a prevalence of the EAWM northern mode (Wang et al. 2010; Luo and Zhang 2015). In terms of sea level pressure, Huang et al. (2014) revealed an interdecadal reamplification of the EAWM in the 1990s. This amplification was determined to be confined to

FIG. 6. Composite difference of (a) zonal wind (m s^{-1}) at 200 hPa, (b) geopotential height (shadings; gpm) and horizontal winds (arrows; m s^{-1}) at 500 hPa, and (c) water vapor transport ($\text{kg m}^{-1} \text{s}^{-1}$) vertically integrated from surface to 300 hPa in winter between 1999–2013 (P2) and 181–95 (P1). Regions above the 95% significance level are shaded in (a) and (c) and dotted in (b). The contours indicate the climatological geopotential height (gpm) at 500 hPa.

northern East Asia and contributed to lower in situ temperatures. Additionally, southerly water vapor transport toward northeastern China and westerly water vapor transport toward northwestern China are remarkable (Fig. 6c). Anomalous moisture convergence over northeastern and northwestern China is also observed in the divergence field of the water vapor flux (figure not shown). All of these factors may provide a beneficial background for the increase of heavy snowfall in northern China.

FIG. 7. (a) Temporal evolution of the winter AMO index based on Enfield et al. (2001). (b) Composite difference of detrended sea surface temperature (10^{-1}°C) in winter between 1999–2013 (P2) and 181–95 (P1). Regions above the 95% significance level are dotted.

By comparing Figs. 6 and 5, some discrepancies are noted. For instance, the locations of anomalous centers of the zonal wind difference at 200 hPa (Fig. 6a) and the negative height anomaly at 500 hPa (Fig. 6b) shift somewhat southward and eastward when compared to their counterparts in the regression map. Figure 6c shows anomalous southeasterly water vapor transport in northeastern China while anomalous southwesterly water vapor transport is shown in Fig. 5c.

b. Influence of the AMO

The Atlantic SST oscillation with a period of 65–80 years, which is the so-called AMO (Kerr 2000), contributes to a wide range of regional climate signals such as the decadal variations in East Asian circulations and climate (e.g., Lu et al. 2006; Dong et al. 2006; Li and Bates 2007; Wang et al. 2009; Chen et al. 2010; Ding et al. 2014; Hao et al. 2016; Li et al. 2017). Based on these studies, one may speculate that the AMO phase change might also account for the increase in heavy snowfall over northern China in recent two decades. In this section, the possible influence of the AMO on the interdecadal variability of heavy snowfall in northern China is discussed.

Figure 7a displays the time series of the winter AMO index based on the definition of Enfield et al. (2001). From the beginning of the twentieth century, the winter AMO index has exhibited four interdecadal fluctuations, with the most recent decadal transition appearing in the 1990s, which was represented by a shift from a negative (cold) phase to a positive (warm) phase. Changes in heavy snowfall toward an increase over northern China occurred in the transition of the AMO to a

FIG. 8. Regressions of the decadal component of (a) zonal wind at 200 hPa and (b) geopotential height (gpm) at 500 hPa against the AMO index during the wintertime of 1961–2013. Regions above the 95% significance level (based on the effective degree of freedom) are dotted.

warm phase. As expected, the SST differences between the P2 period and P1 period are positive in the Atlantic Ocean in the Northern Hemisphere (Fig. 7b). From 1961 to 2013, the correlation coefficient of the AMO index with the NCSI at the decadal time scale is 0.62 (the effective degree of freedom is 13), significant at the 95% level. Thus, the phase change of the AMO is speculated to be linked to the decadal change of heavy snowfall over northern China.

Concurrent with the AMO phase shift in the 1990s, the Pacific decadal oscillation (PDO), which is another important decadal signal, switched from a warm phase to a cold phase (Kosaka and Xie 2013). To identify the independent linkage of the AMO and PDO to the heavy snowfall in northern China, we calculated partial correlations of the NCSI with the AMO and PDO at the decadal time scale. From 1961 to 2013, the partial correlation coefficient is 0.54 for the decadal relationship between the NCSI and AMO and is -0.28 for that between the NCSI and PDO, suggesting a much closer linkage of the AMO to the decadal changes of heavy snowfall over northern China.

Thus, we focus on the possible influence of the AMO in this study. Given that the shift of the polar front jet stream (subtropical jet stream) in the upper troposphere and the height anomalies over LBB (the North Pacific) in the middle troposphere are atmospheric circulations influencing heavy snowfall in northern China, the decadal changes in 200-hPa zonal winds and 500-hPa geopotential heights associated with the AMO were analyzed by regressing their decadal component against

FIG. 9. Composite difference of (a) zonal wind (m s^{-1}) at 200 hPa and (b) geopotential height (gpm) at 500 hPa in winter calculated from the twentieth-century reanalysis data between the positive and negative AMO phases. Regions above the 95% significance level are shaded.

the AMO index (Fig. 8). Of particular interest, as is shown in Fig. 8, the dominant features of the atmospheric anomalies are generally similar to their decadal changes from the P1 period to P2 period. Corresponding to the warm phase of the AMO, the zonal winds in the upper troposphere delineate a strengthening of westerly airflows at midlatitudes and weakening of westerly airflows on the north side (Fig. 8a). The negative and positive height anomalies are observed to concurrently dominate the LBB region and North Pacific in the middle troposphere, respectively (Fig. 8b). These anomalies are generally in agreement with the circulation situation for increased heavy snowfall in northern China.

To provide more solid evidence, we extended our analyses by using the twentieth-century reanalysis data. Figure 9 displays the composite differences of 200-hPa zonal winds and 500-hPa geopotential heights from the twentieth-century reanalysis between the positive and negative AMO phases. The selective positive AMO phases (1931–62 and 1999–2013) and negative AMO phases (1902–22 and 1966–95) are based on Fig. 7b. As shown in Fig. 9a, the meridional pattern with positive and negative anomalies alternating from the midlatitudes to high latitudes is evident in the upper troposphere of the Eurasian region, which indicates a southward shift of the polar

FIG. 10. Wave source (10^{-11} s^{-2}) at 300 hPa calculated from the twentieth-century reanalysis data for the difference between the warm and cold AMO phases.

front jet stream and a northward shift of the subtropical jet stream. In the middle troposphere, negative height anomalies are predominant around the LBB region while the North Pacific is mainly dominated by positive height anomalies extending southwestward (Fig. 9b). Therefore, we hypothesize that the AMO phase change from a cold phase to a warm phase may contribute to the increase of heavy snowfall in northern China through its impacts on the upper and middle tropospheric atmospheric circulations.

An emerging question is in what manner the phase transitions of the AMO are linked to the decadal change of above atmospheric circulations. Owing to atmospheric Rossby waves, the climate variability over a certain region generally shows a teleconnection with upstream disturbances (e.g., Zhou and Cui 2014; Orsolini et al. 2015; Zhou and Wang 2015; Li et al. 2017; Shi et al. 2019). Thus, the AMO-related wave train propagation was examined to explore the candidate mechanisms underlying the linkage between the AMO and downstream atmospheric circulations. In accordance with wave source theory (Sardeshmukh and Hoskins 1988), sea surface thermal conditions in the North Atlantic Ocean could induce Rossby wave sources by upper-tropospheric divergence anomalies (Hoskins and Ambrizzi 1993; Branstator 2002; Manola et al. 2013; Hao et al. 2016). As is seen in Fig. 10, an anomalous wave source located over the northwest Atlantic at approximately 40° – 50° N is associated with the SST differences for the positive and negative AMO phases. In this manner, a Rossby wave is forced and propagates downstream along the waveguide of zonal mean flow (Takaya and Nakamura 2001). Figure 11 shows that the anomalous wave, which emanates from the northwest Atlantic, propagates eastward and splits into two branches over western Europe. One branch moves toward the south; the other branch first moves northeastward and then shifts southeastward to northeastern Asia. The latter branch could propagate the AMO signal downstream to northeastern

FIG. 11. Streamfunction (shadings; $10^6 \text{ m}^2 \text{ s}^{-1}$) and horizontal wave activity flux (arrows; $\text{m}^2 \text{ s}^{-2}$) at 300 hPa calculated from the twentieth-century reanalysis data for the difference between the warm and cold AMO phases.

Asia and then exerts effects on local atmospheric circulations. Therefore, the atmospheric teleconnection process in the upper troposphere from the North Atlantic to northeastern Asia seems to bridge the AMO signal and large-scale atmospheric circulations that affect heavy snowfall in northern China.

5. Conclusions and discussion

In this study, we examined the spatial and temporal characteristics of heavy snowfall in northern China. The results show that the first leading mode of heavy snowfall, which explains 36% of the total variance, exhibits a monosign variation over northern China. Moreover, a pronounced interdecadal change occurred in the mid-1990s, which is characterized by a general increase in heavy snowfall in northern China from the former period to the latter period.

The possible physical process for this decadal change is preliminarily addressed. It is indicated that the large-scale atmospheric circulations that are associated with the increased heavy snowfall over northern China include the southward displacement of the polar front jet stream and northward shift of the subtropical jet stream in the upper troposphere, and the cyclonic atmospheric circulation anomaly over LBB and anticyclonic circulation anomaly over the North Pacific in the middle troposphere. The decadal changes in the above atmospheric circulations may generally support the increase of heavy snowfall over northern China that has occurred since the mid-1990s. Compared to the former period, during the latter period the easterly and westerly anomalies in the upper troposphere have prevailed in the high and middle latitudes of Eurasia, respectively. Meanwhile, negative height anomalies occupy the LBB region and are accompanied by positive height anomalies which control the midlatitudes of the North Pacific in the middle troposphere. This anomalous pattern could enable more cold air and more moist airflow to interact in northern China and may increase heavy snowfall. Further analyses reveal that the recent AMO transition from a cold phase to a warm phase may also favor the increase of heavy snowfall over northern China through its influence on the interdecadal variation of aforementioned atmospheric circulations. The

FIG. 12. (a) EOF1 mode of total snowfall over northern China in winter. (b) Normalized time series (PC1; bar) of the EOF1 mode from 1961 to 2013, superimposed by its decadal component (black line).

AMO influence on the atmospheric circulation anomalies is hypothesized to be achieved by a downstream propagation of the Rossby wave train that emanates from the Atlantic.

Overall, the above changes in atmospheric circulations and the warm phase of the AMO may be responsible for the interdecadal increase of heavy snowfall over northern China after the mid-1990s. This finding is encouraging for a better understanding of the variability of heavy snowfall in China. It may also be helpful for improving the seasonal prediction of heavy snowfall due to the persistence of decadal signals. In recent years, some studies have documented a decadal change of Asian climate in the 1990s for different seasons (e.g., [Kwon et al. 2007](#); [Wu et al. 2010](#); [Huang et al. 2013, 2014](#); [Zhu et al. 2014](#); [Zhang et al. 2018](#); [Wang and Zhou 2019](#)). This decadal increase in heavy snowfall over northern China, as revealed by our study, may be a reflection of the regime shift in climate system.

As introduced in [section 1](#), a decadal shift in the mid-1980s was reported for total snowfall in northeastern China. Thus, we performed EOF analysis of total snowfall in northern China. The EOF1 mode, which explains 39.2% of the total variance, also shows a consistent variation ([Fig. 12a](#)). However, the total snowfall began to change from a negative polarity to a positive one in the mid-1980s and further increased after 2000 ([Fig. 12b](#)). Recently, [Zhou et al. \(2018\)](#) indicated that the changes in light snowfall and heavy snowfall in northern China

FIG. 13. As in [Fig. 9](#), but for CAM3.5 simulations.

showed different behaviors; the ratio of heavy snowfall to total snowfall has significantly increased in recent decades. Hence, the interdecadal increase of heavy snowfall may provide a dominant contribution to the increase in total snowfall over northern China after the mid-1990s. Given the different changes in heavy snowfall and total snowfall from the mid-1980s to mid-1990s, the variation of light snowfall may play a predominant role in the increase of total snowfall during that period. Although several studies have examined the changes in atmospheric circulations and moisture conditions for the decadal change of total snowfall in northeastern China in the mid-1980s, it is difficult to directly compare their differences between the mid-1980s and mid-1990s because the time period used in those studies to analyze the decadal change in the mid-1980s covered the latter period. Thus, further detailed investigations are needed in future studies to address the similarities and differences of the two decade changes.

In addition, we also examined the response of the Eurasian atmospheric circulations in the CAM3.5 simulation to AMO forcing. As shown in [Fig. 13](#), the CAM3.5 simulation produces negative–positive–negative anomalies from low latitudes to high latitudes in 200-hPa zonal winds as well as negative anomalies north of the LBB region and positive anomalies over the North Pacific that extend southwestward in 500-hPa geopotential height. However, when comparing [Figs. 13 and 9](#), we notice that the simulated patterns are more northward than the observations. A similar phenomenon was also documented

by Wu et al. (2019), who found that the climate models, for example MPI-ESM-LR, could reproduce the AMO-related wave train-like pattern, but the positions of the wave train nodes shifted from those in the observation. Zhang et al. (2019) indicated in their review paper that the understanding of AMO-associated climate is hindered by substantial biases in most climate models. Therefore, the process of AMO influence on Eurasian atmospheric circulations as proposed in our study needs further justification in the future. Furthermore, we focused on the possible role of the AMO as an external forcing factor for the change in heavy snowfall over northern China. Other external forcings such as the decline in Arctic sea ice and global warming may also have contributions. For instance, Liu et al. (2012) indicated that the decrease in autumn Arctic sea ice favors the establishment of blocking and provides a favorable condition for the increase of snowstorm. H. Chen et al. (2019) found that a decrease in autumn Arctic sea ice could intensify meridional activity and benefit the southward invasion of polar cold air, which would lead to a convergence of cold air and warm-moist air in northeastern China and hence increase heavy snowfall. Under the background of global warming, a slowdown in surface warming occurred from 1998 to 2013, which is referred to as the “global warming hiatus” (IPCC 2013). In this context, the Eurasian continent experienced cooling winters (C. Li et al. 2015; Q. Li et al. 2015), which may provide cold advection for the occurrence of heavy snowfall. However, the projection under the representative concentration pathway 4.5 (RCP4.5) showed that there would be an increase of heavy snowfall in northern China in a future warmer world, which would be mainly due to the increase in atmospheric moisture (Zhou et al. 2018).

Northeast and Northwest China are also regions with high values of snow cover. In recent two decades, the winter snow cover in the above regions showed a shift from a decrease to an increase (Qin et al. 2006; Ke and Liu 2014; Tan et al. 2019; Zhang et al. 2020). Naturally, low temperature and snowfall are essential for the formation and maintenance of snow cover. When the temperature is below the freezing point, the increased snowfall would result in an increase of snow cover (Peng et al. 2010; Luce et al. 2014; Wu and Chen 2016; Xu et al. 2019). In this sense, the decadal increase of heavy snowfall in northern China is expected to increase local snow cover during the snowy winter period. In addition, an increasing trend in snow depth was detected over western Eurasia (Popova 2007; Xu et al. 2019) while a decreasing trend in snow water equivalent was found over northern Eurasia (Zuo et al. 2011; Yeo et al. 2017; Xu et al. 2019), which have been documented to be associated with multiple factors such as large-scale atmospheric circulations, air–sea interactions, and declines of Arctic sea ice (Popova 2007; Liu et al. 2012; Kim et al. 2013; Ye et al. 2015; Wu and Chen 2016; Song and Liu 2017; Ye and Lau 2017; Yeo et al. 2017; Xu et al. 2019). The issue of whether there is intrinsic linkage of variations between the Eurasian snow pattern and that discussed in our study deserves further investigations although it is beyond the scope of the present discussion.

Acknowledgments. This research was jointly supported by the National Key Research and Development Program of China (2016YFA0600701), the National Natural Science Foundation of China (42025502, 41991285), and the Startup Foundation for Introducing Talent of NUIST (2018r060).

REFERENCES

- Branstator, G., 2002: Circumglobal teleconnections, the jet stream waveguide, and the North Atlantic Oscillation. *J. Climate*, **15**, 1893–1910, [https://doi.org/10.1175/1520-0442\(2002\)015<1893:CTTJSW>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1893:CTTJSW>2.0.CO;2).
- Bretherton, C. S., M. Widmann, V. P. Dymnikov, J. M. Wallace, and I. Bladé, 1999: The effective number of spatial degrees of freedom of a time-varying field. *J. Climate*, **12**, 1990–2009, [https://doi.org/10.1175/1520-0442\(1999\)012<1990:TENOSD>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<1990:TENOSD>2.0.CO;2).
- Chen, H., J. Luo, and F. Han, 2019: Interdecadal variation of heavy snowfall in northern China and its linkage with atmospheric circulation and Arctic sea ice. *Trans. Atmos. Sci.*, **42**, 68–77.
- Chen, L., Q. Zhu, H. Luo, J. He, M. Dong, and Z. Feng, 1991: *East Asian Monsoon*. Meteorological Press, 362 pp.
- Chen, W., B. Dong, and R. Lu, 2010: Impact of the Atlantic Ocean on the multidecadal fluctuation of El Niño–Southern Oscillation–South Asian monsoon relationship in a coupled general circulation model. *J. Geophys. Res.*, **115**, D17109, <https://doi.org/10.1029/2009JD013596>.
- , L. Wang, J. Feng, Z. Wen, T. Ma, X. Yang, and C. Wang, 2019: Recent progress in studies of the variabilities and mechanisms of the East Asian monsoon in a changing climate. *Adv. Atmos. Sci.*, **36**, 887–901, <https://doi.org/10.1007/s00376-019-8230-y>.
- Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis Project. *Quart. J. Roy. Meteor. Soc.*, **137** (654), 1–28, <https://doi.org/10.1002/qj.776>.
- Ding, Y., 2005: *Advanced Synoptic Meteorology*. Meteorological Press, 585 pp.
- , 2013: *China Climate* (in Chinese). Science Press, 557 pp.
- , Z. Wang, Y. Song, and J. Zhang, 2008: Causes of the unprecedented freezing disaster in January 2008 and its possible association with the global warming. *Acta Meteor. Sin.*, **66**, 808–825.
- , and Coauthors, 2014: Interdecadal variability of the East Asian winter monsoon and its possible links to global climate change. *J. Meteor. Res.*, **28**, 693–713, <https://doi.org/10.1007/s13351-014-4046-y>.
- Dong, B., R. T. Sutton, and A. A. Scaife, 2006: Multidecadal modulation of El Niño–Southern Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures. *Geophys. Res. Lett.*, **33**, L08705, <https://doi.org/10.1029/2006GL025766>.
- Eichelberger, S. J., and D. L. Hartmann, 2007: Zonal jet structure and the leading mode of variability. *J. Climate*, **20**, 5149–5163, <https://doi.org/10.1175/JCLI4279.1>.
- Enfield, D. B., A. M. Mestas-Núñez, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.*, **28**, 2077–2080, <https://doi.org/10.1029/2000GL012745>.
- Fan, K., and B. Tian, 2013: Prediction of wintertime heavy snow activity in Northeast China. *Chin. Sci. Bull.*, **58**, 1420–1426, <https://doi.org/10.1007/s11434-012-5502-7>.
- Feng, Y., and H. Chen, 2016: Warming over the North Pacific can intensify snow events in Northeast China. *Atmos. Ocean. Sci. Lett.*, **9**, 122–128, <https://doi.org/10.1080/16742834.2016.1133072>.

- Gao, H., 2009: China's snow disaster in 2008, who is the principal player? *Int. J. Climatol.*, **29**, 2191–2196, <https://doi.org/10.1002/joc.1859>.
- Hao, X., S. He, and H. Wang, 2016: Asymmetry in the response of central Eurasian winter temperature to AMO. *Climate Dyn.*, **47**, 2139–2154, <https://doi.org/10.1007/s00382-015-2955-9>.
- Hoskins, B. J., and T. Ambrizzi, 1993: Rossby wave propagation on a realistic longitudinally varying flow. *J. Atmos. Sci.*, **50**, 1661–1671, [https://doi.org/10.1175/1520-0469\(1993\)050<1661:RWPOAR>2.0.CO;2](https://doi.org/10.1175/1520-0469(1993)050<1661:RWPOAR>2.0.CO;2).
- Huang, D., A. Dai, J. Zhu, Y. Zhang, and X. Kuang, 2017: Recent winter precipitation changes over eastern China in different warming periods and the associated East Asian jets and oceanic conditions. *J. Climate*, **30**, 4443–4462, <https://doi.org/10.1175/JCLI-D-16-0517.1>.
- Huang, R., Y. Liu, and T. Feng, 2013: Interdecadal change of summer precipitation over eastern China around the late-1990s and associated circulation anomalies, internal dynamical causes. *Chin. Sci. Bull.*, **58**, 1339–1349, <https://doi.org/10.1007/s11434-012-5545-9>.
- , —, J. Huangpu, and T. Feng, 2014: Characteristics and internal dynamical causes of the interdecadal variability of East Asian winter monsoon near the late 1990s (in Chinese). *Chin. J. Atmos. Sci.*, **38**, 627–644.
- Hudson, R. D., 2012: Measurements of the movement of the jet streams at mid-latitudes, in the Northern and Southern Hemispheres, 1979 to 2010. *Atmos. Chem. Phys.*, **12**, 7797–7808, <https://doi.org/10.5194/acp-12-7797-2012>.
- IPCC, 2013: *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, 1535 pp.
- Jhun, J. G., and E. J. Lee, 2004: A new East Asian winter monsoon index and associated characteristics of winter monsoon. *J. Climate*, **17**, 711–726, [https://doi.org/10.1175/1520-0442\(2004\)017<0711:ANEAWM>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<0711:ANEAWM>2.0.CO;2).
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471, [https://doi.org/10.1175/1520-0477\(1996\)077<0437:TNYRP>2.0.CO;2](https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2).
- Ke, C., and X. Liu, 2014: MODIS-observed spatial and temporal variation in snow cover in Xinjiang, China. *Climate Res.*, **59**, 15–26, <https://doi.org/10.3354/cr01206>.
- Kendall, M. G., 1975: *Rank Correlation Methods*. Charles Griffin, xxx pp.
- Kerr, R. A., 2000: A North Atlantic climate pacemaker for the centuries. *Science*, **288**, 1984–1985, <https://doi.org/10.1126/science.288.5473.1984>.
- Kim, Y., K. Y. Kim, and B. M. Kim, 2013: Physical mechanisms of European winter snow cover variability and its relationship to the NAO. *Climate Dyn.*, **40**, 1657–1669, <https://doi.org/10.1007/s00382-012-1365-5>.
- Kosaka, Y., and S. Xie, 2013: Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, **501**, 403–407, <https://doi.org/10.1038/nature12534>.
- Kwon, M., J. G. Jhun, and K. J. Ha, 2007: Decadal change in East Asian summer monsoon circulation in the mid-1990s. *Geophys. Res. Lett.*, **34**, L21706, <https://doi.org/10.1029/2007GL031977>.
- Li, C., B. Stevens, and J. Marotzke, 2015: Eurasian winter cooling in the warming hiatus of 1998–2012. *Geophys. Res. Lett.*, **42**, 8131–8139, <https://doi.org/10.1002/2015GL065327>.
- Li, Q., and Coauthors, 2015: China experiencing the recent warming hiatus. *Geophys. Res. Lett.*, **42**, 889–898, <https://doi.org/10.1002/2014GL062773>.
- Li, S., and G. T. Bates, 2007: Influence of the Atlantic multidecadal oscillation on the winter climate of east China. *Adv. Atmos. Sci.*, **24**, 126–135, <https://doi.org/10.1007/s00376-007-0126-6>.
- Li, Y., Y. Ding, and W. Li, 2017: Interdecadal variability of the Afro-Asian summer monsoon system. *Adv. Atmos. Sci.*, **34**, 833–846, <https://doi.org/10.1007/s00376-017-6247-7>.
- Liu, J., J. A. Curry, H. Wang, M. Song, and R. M. Horton, 2012: Impact of declining Arctic sea ice on winter snowfall. *Proc. Natl. Acad. Sci. USA*, **109**, 4074–4079, <https://doi.org/10.1073/pnas.1114910109>.
- Lu, C., B. Zhou, and Y. Ding, 2016: Decadal variation of the Northern Hemisphere annular mode and its influence on the East Asian trough. *J. Meteor. Res.*, **30**, 584–597, <https://doi.org/10.1007/s13351-016-5105-3>.
- Lu, R., B. Dong, and H. Ding, 2006: Impact of the Atlantic multidecadal oscillation on the Asian summer monsoon. *Geophys. Res. Lett.*, **33**, L24701, <https://doi.org/10.1029/2006GL027655>.
- Luce, C. H., V. Lopez-Burgos, and Z. Holden, 2014: Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. *Water Resour. Res.*, **50**, 9447–9462, <https://doi.org/10.1002/2013WR014844>.
- Luo, X., and Y. Zhang, 2015: The linkage between upper-level jet streams over East Asia and East Asian winter monsoon variability. *J. Climate*, **28**, 9013–9028, <https://doi.org/10.1175/JCLI-D-15-0160.1>.
- Mann, H. B., 1945: Nonparametric tests against trend. *Econometrica*, **13**, 245–259, <https://doi.org/10.2307/1907187>.
- Manola, I., F. Selten, H. de Vries, and W. Hazeleger, 2013: Waveguidability of idealized jets. *J. Geophys. Res.*, **118**, 10 432–10 440, <https://doi.org/10.1002/jgrd.50758>.
- Neale, R. B., M. Jochum, and J. H. Richter, 2008: The impact of convection on ENSO: From a delayed oscillator to a series of events. *J. Climate*, **21**, 5904–5924, <https://doi.org/10.1175/2008JCLI2244.1>.
- Oleson, K. W., and Coauthors, 2008: Improvements to the Community Land Model and their impact on the hydrological cycle. *J. Geophys. Res.*, **113**, G01021, <https://doi.org/10.1029/2007JG000563>.
- Orsolini, Y. J., L. Zhang, D. H. W. Peters, K. Fraedrich, X. Zhu, A. Schneidereit, and B. van den Hurk, 2015: Extreme precipitation events over North China in August 2010 and their link to eastward-propagating wave-trains across Eurasia: Observations and monthly forecasting. *Quart. J. Roy. Meteor. Soc.*, **141**, 3097–3105, <https://doi.org/10.1002/qj.2594>.
- Peng, S., S. Piao, P. Ciais, J. Fang, and X. Wang, 2010: Change in winter snow depth and its impacts on vegetation in China. *Global Change Biol.*, **16**, 3004–3013, <https://doi.org/10.1111/j.1365-2486.2010.02210.x>.
- Popova, V., 2007: Winter snow depth variability over northern Eurasia in relation to recent atmospheric circulation changes. *Int. J. Climatol.*, **27**, 1721–1733, <https://doi.org/10.1002/joc.1489>.
- Qin, D., S. Liu, and P. Li, 2006: Snow cover distribution, variability, and response to climate change in western China. *J. Climate*, **19**, 1820–1833, <https://doi.org/10.1175/JCLI3694.1>.
- Sardeshmukh, P. D., and B. J. Hoskins, 1988: The generation of global rotational flow by steady idealized tropical divergence. *J. Atmos. Sci.*, **45**, 1228–1251, [https://doi.org/10.1175/1520-0469\(1988\)045<1228:TGOGRF>2.0.CO;2](https://doi.org/10.1175/1520-0469(1988)045<1228:TGOGRF>2.0.CO;2).
- Shi, N., X. Wang, and P. Tian, 2019: Interdecadal variations in persistent anomalous cold events over Asian mid-latitudes. *Climate Dyn.*, **52**, 3729–3739, <https://doi.org/10.1007/s00382-018-4353-6>.
- Smith, T. M., and R. W. Reynolds, 2004: Improved extended reconstruction of SST (1854–1997). *J. Climate*, **17**, 2466–2477, [https://doi.org/10.1175/1520-0442\(2004\)017<2466:IEROS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2).

- Song, M., and J. Liu, 2017: The role of diminishing Arctic sea ice in increased winter snowfall over northern high-latitude continents in a warming environment. *Acta Oceanol. Sin.*, **36**, 34–41, <https://doi.org/10.1007/s13131-017-1021-3>.
- Sun, B., and H. Wang, 2013: Water vapor transport paths and accumulation during widespread snowfall events in northeastern China. *J. Climate*, **26**, 4550–4566, <https://doi.org/10.1175/JCLI-D-12-00300.1>.
- , —, and B. Zhou, 2019: Climatic condition and synoptic regimes of two intense snowfall events in eastern China and implications for climate variability. *J. Geophys. Res. Atmos.*, **124**, 926–941, <https://doi.org/10.1029/2018JD029921>.
- Sun, J., H. Wang, and W. Yuan, 2009: A preliminary investigation on causes of the catastrophic snowstorm in March, 2007 in northeastern part of China. *Acta Meteor. Sin.*, **67**, 469–477.
- , —, —, and H. Chen, 2010: Spatial-temporal features of intense snowfall events in China and their possible change. *J. Geophys. Res.*, **115**, D16110, <https://doi.org/10.1029/2009JD013541>.
- Takaya, K., and H. Nakamura, 2001: A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies in a zonally varying basic flow. *J. Atmos. Sci.*, **58**, 608–627, [https://doi.org/10.1175/1520-0469\(2001\)058<0608:AFOAPI>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<0608:AFOAPI>2.0.CO;2).
- Tan, X., Z. Wu, X. Mu, P. Gao, G. Zhao, W. Sun, and C. Gu, 2019: Spatiotemporal changes in snow cover over China during 1960–2013. *Atmos. Res.*, **218**, 183–194, <https://doi.org/10.1016/j.atmosres.2018.11.018>.
- Wang, B., Z. Wu, C. P. Zhang, and J. Liu, 2010: Another look at interannual-to-interdecadal variations of the East Asian winter monsoon: The northern and southern temperature modes. *J. Climate*, **23**, 1495–1512, <https://doi.org/10.1175/2009JCLI3243.1>.
- Wang, H., and S. He, 2012: Weakening relationship between East Asian winter monsoon and ENSO after mid-1970s. *Chin. Sci. Bull.*, **57**, 3535–3540, <https://doi.org/10.1007/s11434-012-5285-x>.
- , and —, 2013: The increase of snowfall in Northeast China after the mid-1980s. *Chin. Sci. Bull.*, **58**, 1350–1354, <https://doi.org/10.1007/s11434-012-5508-1>.
- , E. Yu, and S. Yang, 2011: An exceptionally heavy snowfall in Northeast China: Large-scale circulation anomalies and hindcast of the NCAR WRF Model. *Meteor. Atmos. Phys.*, **113**, 11–25, <https://doi.org/10.1007/s00703-011-0147-7>.
- Wang, L., and W. Chen, 2010: How well do existing indices measure the strength of the East Asian winter monsoon? *Adv. Atmos. Sci.*, **27**, 855–870, <https://doi.org/10.1007/s00376-009-9094-3>.
- Wang, Y., S. Li, and D. Luo, 2009: Seasonal response of Asian monsoonal climate to the Atlantic multidecadal oscillation. *J. Geophys. Res.*, **114**, D02112, <https://doi.org/10.1029/2008JD010929>.
- Wang, Z., and B. Zhou, 2018: Large-scale atmospheric circulations and water vapor transport influencing interannual variations of intense snowfalls in northern China. *Chin. J. Geophys.*, **61**, 2654–2666.
- , and —, 2019: Observed decadal transition in trend of autumn rainfall over central China in the late 1990s. *J. Climate*, **32**, 1395–1409, <https://doi.org/10.1175/JCLI-D-18-0112.1>.
- , S. Yang, and B. Zhou, 2017: Preceding features and relationship with possible affecting factors of persistent and extensive icing events in China. *Int. J. Climatol.*, **37**, 4105–4118, <https://doi.org/10.1002/joc.5026>.
- , Y. Ding, B. Zhou, and L. Chen, 2020: Comparison of two severe low-temperature snowstorm and ice freezing events in China: Role of Eurasian mid-high latitude circulation patterns. *Int. J. Climatol.*, **40**, 3436–3450, <https://doi.org/10.1002/joc.6406>.
- Wen, M., S. Yang, A. Kumar, and P. Zhang, 2009: An analysis of the large-scale climate anomalies associated with the snowstorms affecting China in January 2008. *Mon. Wea. Rev.*, **137**, 1111–1131, <https://doi.org/10.1175/2008MWR2638.1>.
- Woollings, T., B. Hoskins, M. Blackburn, and P. Berrisford, 2008: A new Rossby wave-breaking interpretation of the North Atlantic Oscillation. *J. Atmos. Sci.*, **65**, 609–626, <https://doi.org/10.1175/2007JAS2347.1>.
- Wu, B., T. Zhou, C. Li, W. A. Müller, and J. Lin, 2019: Improved decadal prediction of Northern-Hemisphere summer land temperature. *Climate Dyn.*, **53**, 1357–1369, <https://doi.org/10.1007/s00382-019-04658-8>.
- Wu, R., and S. Chen, 2016: Regional change in snow water equivalent-surface air temperature relationship over Eurasia during boreal spring. *Climate Dyn.*, **47**, 2425–2442, <https://doi.org/10.1007/s00382-015-2972-8>.
- , Z. Wen, S. Yang, and Y. Li, 2010: An interdecadal change in southern China summer rainfall around 1992/93. *J. Climate*, **23**, 2389–2403, <https://doi.org/10.1175/2009JCLI3336.1>.
- Xie, Z., and B. Sun, 2019: Different roles of water vapor transport and cold advection in the intensive snowfall events over North China and the Yangtze River valley. *Atmosphere*, **10**, 368, <https://doi.org/10.3390/atmos10070368>.
- Xu, B., H. Chen, C. Gao, B. Zhou, S. Sun, and S. Zhu, 2019: Regional response of winter snow cover over the northern Eurasia to late autumn Arctic sea ice and associated mechanism. *Atmos. Res.*, **222**, 100–113, <https://doi.org/10.1016/j.atmosres.2019.02.010>.
- Xue, D., and Y. Zhang, 2017: Concurrent variations in the location and intensity of the Asian winter jet streams and the possible mechanism. *Climate Dyn.*, **49**, 37–52, <https://doi.org/10.1007/s00382-016-3325-y>.
- Yang, G., Q. Kong, D. Mao, F. Zhang, Z. Kang, and Z. Zong, 2008: Analysis on the long-lasting cryogenic freezing rain and snowstorm event at the beginning of 2008. *Acta Meteor. Sin.*, **24**, 380–396.
- Ye, K., and N. C. Lau, 2017: Influences of surface air temperature and atmospheric circulation on winter snow cover variability over Europe. *Int. J. Climatol.*, **37**, 2606–2619, <https://doi.org/10.1002/joc.4868>.
- , R. Wu, and Y. Liu, 2015: Interdecadal change of Eurasian snow, surface temperature, and atmospheric circulation in the late 1980s. *J. Geophys. Res. Atmos.*, **120**, 2738–2753, <https://doi.org/10.1002/2015JD023148>.
- Yeo, S. R., W. M. Kim, and K. Y. Kim, 2017: Eurasian snow cover variability in relation to warming trend and Arctic Oscillation. *Climate Dyn.*, **48**, 499–511, <https://doi.org/10.1007/s00382-016-3089-4>.
- Zhang, R., R. Sutton, G. Danabasoglu, Y. Kwon, R. Marsh, S. G. Yeager, D. E. Amrhein, and C. M. Little, 2019: A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic multidecadal variability and associated climate impacts. *Rev. Geophys.*, **57**, 316–375, <https://doi.org/10.1029/2019RG000644>.
- Zhang, X., K. Wang, and B. Boehrer, 2020: Variability in observed snow depth over China from 1960 to 2014. *Int. J. Climatol.*, <https://doi.org/10.1002/joc.6625>, in press.

- Zhang, Y., D. Huang, and X. Ren, 2008: Seasonal variation of the meridional wind in the temperate jet stream and its relationship to the Asian monsoon. *Acta Meteor. Sin.*, **22**, 446–454.
- Zhang, Z., X. Sun, and X. Yang, 2018: Understanding the interdecadal variability of East Asian summer monsoon precipitation: Joint influence of three oceanic signals. *J. Climate*, **31**, 5485–5506, <https://doi.org/10.1175/JCLI-D-17-0657.1>.
- Zhou, B., and X. Cui, 2014: Interdecadal change of the linkage between the North Atlantic Oscillation and the tropical cyclone frequency over the western North Pacific. *Sci. China Earth Sci.*, **57**, 2148–2155, <https://doi.org/10.1007/s11430-014-4862-z>.
- , and Z. Wang, 2015: On the significance of the interannual relationship between the Asian-Pacific Oscillation and the North Atlantic Oscillation. *J. Geophys. Res. Atmos.*, **120**, 6489–6499, <https://doi.org/10.1002/2015JD023328>.
- , —, and Y. Shi, 2017: Possible role of Hadley circulation strengthening in interdecadal intensification of snowfalls over northeastern China under climate change. *J. Geophys. Res. Atmos.*, **122**, 11 638–11 650, <https://doi.org/10.1002/2017JD027574>.
- , —, —, Y. Xu, and Z. Han, 2018: Historical and future changes of snowfall events in China under a warming background. *J. Climate*, **31**, 5873–5889, <https://doi.org/10.1175/JCLI-D-17-0428.1>.
- Zhou, W., J. C. L. Chan, W. Chen, J. Ling, J. G. Pinto, and Y. Shao, 2009: Synoptic-scale controls of persistent low temperature and icy weather over southern China in January 2008. *Mon. Wea. Rev.*, **137**, 3978–3991, <https://doi.org/10.1175/2009MWR2952.1>.
- Zhu, Z., T. Li, and J. He, 2014: Out-of-phase relationship between boreal spring and summer decadal rainfall changes in southern China. *J. Climate*, **27**, 1083–1099, <https://doi.org/10.1175/JCLI-D-13-00180.1>.
- Zuo, Z., S. Yang, W. Wang, A. Kumar, Y. Xue, and R. Zhang, 2011: Relationship between anomalies of Eurasian snow and southern China rainfall in winter. *Environ. Res. Lett.*, **6**, 045402, <https://doi.org/10.1088/1748-9326/6/4/045402>.