An Analysis of the Large-Scale Climate Anomalies Associated with the Snowstorms Affecting China in January 2008

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ABSTRACT
Extraordinarily frequent and long-lasting snowstorms affected China in January 2008, causing above-normal precipitation, below-normal temperature, and severe icing conditions over central–southern China. These snowstorms were closely linked to the change in the Middle East jet stream (MEJS), which intensified and shifted southeastward. The change in MEJS was accompanied by southeastward shifts of the ridge and the trough over Europe and western Asia. The intensified MEJS also strengthened the trough embedded in the southern branch of the subtropical westerlies over the southern Tibetan Plateau, enhancing the water vapor transport from western Asia and the Bay of Bengal to China. In the meantime, the subtropical western Pacific high (SWPH) was stronger and its ridgeline was farther north than normal. The anomalous high slowed down the eastward propagation of weather systems to the Pacific and favored convergence of water vapor over central–southern China. The MEJS is usually strong when the Arctic Oscillation (AO) is positive and the SWPH is farther north than normal in La Niña winters. Compared to the SWPH and the Niño-3.4 sea surface temperature (SST), the MEJS and the AO exert stronger influences on the temperature and the precipitation over central–southern China, despite the fact that these possible impacting factors are not completely independent from each other. Although the La Niña event might contribute to the climate anomalies through its relation with the SWPH in January 2008, an analysis of historical events indicates that La Niña conditions alone can hardly cause severe and persistent snow conditions over central–southern China. In addition, compared to the Niño-3.4 SST and the SWPH, the conditions of December MEJS and AO exhibit stronger precursory signals of the variability of January temperature over central–southern China.

1. Introduction
In January 2008, extraordinarily frequent and long-lasting snowstorms affected China, leading to excessive snow amount, low temperatures, and severe icing conditions over central and southern China (Z. Wang et al. 2008). The snowstorms occurred in four major periods: 10–16, 18–22, and 25–29 January, and from 31 January to 2 February 2008. They brought severe icing conditions to broad regions and reached unusually low latitudes. Figure 1 shows the number of days that snow cover was observed in January 2008 and its departure from normal, based on the National Oceanic and Atmospheric Administration (NOAA) satellite-derived snow-cover data (direct snowfall observations are not available to this study). For the month, snow cover was observed nearly all the time over most of the northeast and part of the northwest China and found frequently

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Fig. 1. (a) Number of days with snow cover and (b) anomalies of snow-cover days in January 2008. (c) January snow-cover days averaged over 25°–37°N, 105°–121°E [see the box in (b)].
over central China. However, it was over central China where the snow-cover days were significantly above normal (Fig. 1b). Snow cover was also observed over the usually snow-free regions in south China. Figure 1c indicates that the number of snow days over central and southern China in January 2008 was absolutely highly above the mean of the past several decades (also see Z. Wang et al. 2008). The above-described snowstorms caused enormous damage to the life and property of the people in China and raised tremendous public and scientific interest. In this study, we analyze the large-scale climate anomalies associated with these snowstorms.

The climate over China is strongly affected by the East Asian monsoon system (see Huang et al. 2007 and references therein). In winter, the climate over a large part of the country is characterized by low temperature, snowstorms, and icy precipitation owing to the influences of frequent cold surges associated with the south-eastward intrusions of atmospheric circulation systems from Siberia, southern Europe, and western Asia. The strong fluctuations of the East Asian winter monsoon also lead to significant variations of the climate over China from one year to another. For example, when the winter monsoon is strong, temperature decreases over eastern China and precipitation decreases over southern China, and vice versa (Zhang et al. 1996, 1999; Zhang and Sumi 2002).

Previous studies have attributed the interannual variability of the East Asian winter monsoon, and thus of the winter climate over China, to El Niño–Southern Oscillation (ENSO). The monsoon is strong during La Niña winters and weak during El Niño winters (e.g., Zhang et al. 1999; Chen et al. 2000; Yang et al. 2002). During El Niño winters, the cold surges affecting southern China and Southeast Asia become weaker and less frequent (Zhang et al. 1997). According to Wang et al. (2000), a La Niña (an El Niño) event leads to a strong (weak) monsoon through the influence of an anomalous lower-tropospheric cyclone (anticyclone) over the western North Pacific.

The variations of the East Asian monsoon and the temperature and precipitation over China in winter have also been linked to the influence of the Arctic Oscillation (AO; Thompson and Wallace 1998). When the AO is positive, the monsoon is weak and temperature and precipitation increase over China (Wu and Wang 2002; Gong and Wang 2003; Jeong and Ho 2005; Chen and Kang 2006). While the increase in precipitation occurs over a large part of the country, the warming is mainly limited to northern and northeastern China (e.g., Chen and Kang 2006). Li et al. (2005) examined the relationships of the winter precipitation over China with ENSO and other dominant modes of atmospheric variability for the past century and concluded that, except over the northeast where the precipitation was significantly linked to the North Pacific Oscillation and the Pacific decadal oscillation, the precipitation over the rest of China was most strongly and positively associated with the variability of AO (see their Fig. 3). Over southern China, the precipitation was also positively correlated with the sea surface temperature (SST) over the tropical central-eastern Pacific.

To further understand its climate impact, many studies have emphasized the importance of the AO through its associated changes in extratropical atmospheric circulation systems such as the Siberia high and the East Asian jet stream, which are important phenomena influencing the climate over China (e.g., Ding and Krishnamurti 1987; Ding 1990; Wu and Wang 2002; Jeong and Ho 2005; Takaya and Nakamura 2005; Wang and Ding 2006; Mao et al. 2007). However, the AO is also accompanied by significant changes in the subtropical westerlies over the Middle East and western Asia and thus fluctuations in the southern branch of the westerlies over the southern flank of the Tibetan Plateau (Yang et al. 2004). The importance of the southern branch of westerlies for the winter climate over China, via its control on water vapor supply, has been discussed by He et al. (2006) and Q. Li et al. (2007).

The winter climate over China may also be affected by other factors including the subtropical western Pacific high (SWPH), the Indian Ocean SST, and the western Pacific warm pool (e.g., Y. Li et al. 2007), although these impacting factors are not completely independent from each other. For example, the fluctuations of SST over the warm pool cause changes in the SWPH, the East Asian jet stream, and the East Asian winter monsoon (Dong et al. 1994; Chen and Wu 2000). Furthermore, a warming over the tropical Indian Ocean increases the meridional temperature gradient and thus intensifies the Middle East jet stream (MEJS), which affects the climate over southern Asia significantly (Yang et al. 2004).

In this study, we analyze several observational datasets to document the temperature, precipitation, and atmospheric and oceanic features associated with the series of snowstorms over China during early 2008, focusing on the large-scale climate features that may have been responsible. The datasets applied in the study are described in section 2. In section 3, we depict the features of surface temperature, precipitation, and atmospheric circulation that are related to the snowstorms.

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2 The northern branch of the westerlies is over the northern flank of the Tibetan Plateau.
We investigate the possible roles of the MEJS and the SWPH in section 4 and those of the AO and La Niña event in section 5. We further discuss the importance of the superposition of multiple factors and explore the precursory signals of the snowstorms in section 6. A summary of the results obtained is provided in section 7.

2. Data

The datasets analyzed in this study include station observations of surface air temperature and precipitation over China and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). They also include the NOAA weekly 2° × 2° (latitude–longitude) snow-cover dataset (see online at http://www.cpc.ncep.noaa.gov/data/snow/) and the NOAA Extended Reconstructed Sea Surface Temperature dataset (Smith and Reynolds 2004). The temperature and precipitation over China are from the daily observations over 593 stations (see online at http://data.cma.gov.cn/shuju/index3.jsp?tpcat=RADI&dsid=RADI_MUL_CHN_DAY_CE). The analyzed variables from the NCEP–NCAR reanalysis are the winds, geopotential height, and specific humidity at various pressure levels. In addition, we use the AO index from the NOAA/Climate Prediction Center (CPC; see online at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml). Monthly means for respective variables are calculated from daily values, and monthly anomalies are computed relative to the means of the analysis period (i.e., from December 1978 to January 2008).

3. Observed climate anomalies in January 2008

a. Temperature, precipitation, and snow

In January 2008, the temperature over China was mostly above (below) freezing over south (north) of about 30°N (Fig. 2a). The highest temperature was observed over the southwest and the south–southeastern coastal regions, while the lowest temperature was found from the northeast to the northwest. As shown in the anomaly pattern (Fig. 2b), the temperature in January 2008 was mostly below normal, with exceptions over the southwestern portion. Large negative anomalies of temperature were found over an arch-shaped band from the northwest through central China to southern China. Particularly, over central–southern China, the temperature was below normal by more than 2°C. For the
analysis period from 1979 to 2008, such extensive cold anomalies were rare for January and were only seen in the cold and dry January of 1984.

Heavy precipitation occurred over southern and central China but light precipitation was found over western and northern China in January 2008 (Fig. 2c). Precipitation was above normal over most of the country, with exceptions over the northeast and part of the northwest (Fig. 2d). In particular, large positive anomalies appeared over southern China and the lower reach of the Yangtze River. However, below-normal anomalies were also seen over the northwest of southern China (mainly in the Hunan and Guizhou provinces), which will be discussed shortly. It should be pointed out that, compared to other gridpoint precipitation analyses such as the NOAA/CPC precipitation reconstruction data...
(Chen et al. 2002). Fig. 2 reveals larger amplitude and more detailed spatial features in the pattern of precipitation anomalies.

We further analyze the patterns of cold days and water-equivalent snow and frozen rain by following the definitions of Z. Wang et al. (2008). We define a cold day as the day when daily temperature is $<1^\circ$C, and the water-equivalent snow amount (including frozen rain) as the precipitation when daily temperature is $<1^\circ$C. (The major features of the results remain similar when the threshold value of temperature is changed from $1^\circ$ to $0^\circ$C.) Figure 3 shows the total numbers of cold days and the mean snow amount in January 2008 and their anomalies. The large numbers of cold days mainly appeared to the north of $30^\circ$N (Fig. 3a). However, for this particular month, these numbers were mostly normal but the numbers of cold days over central–southern China were above normal by 10–15 days (Fig. 3c). In January 2008, snowfall occurred over a large part of China (Fig. 3b). However, highly above-normal snowfall occurred mainly over central–southern China (Fig. 3d). Over the northwestern South China where negative precipitation anomalies were found (see Fig. 2d), positive snow anomalies appeared. Over the northeast and the northwest, the snowfall was moderately below normal. In Fig. 3e, we further show the snowfall (and frozen precipitation) and the numbers of cold days averaged over the spatial domain outlined in Fig. 1b. Like the numbers of days with snow cover, the snowfall and the numbers of cold days in January 2008 were significantly above normal. The correlations of the numbers of snow-cover days with the snowfall and with the numbers of cold days are 0.760 and 0.564, respectively.

The societal impact of snowstorms varies from one region to another. The same low temperature and large snow amount that may not cause any significant impact in northern China could lead to disasters in the warm and mostly snow-free southern China. In January 2008, although the temperatures over central and southern China were not as low as in northern China, they were significantly below normal and caused tremendous damages to the regions. Thus, it was the combination of the influences of both temperature and precipitation that exerted large impacts on the life and property in central–southern China.

b. Atmospheric circulation patterns

Figure 4 shows the patterns of 200-mb zonal wind (U200) and 500-mb geopotential height (H500), as well as their anomalies. In January 2008, westerly flow was found over Asia except over the equatorial regions such as the Maritime Continent (Fig. 4a). A strong jet stream (the East Asian jet stream) was located over southern Japan and a secondary jet stream (MEJS) was located over northern Saudi Arabia. The MEJS was stronger than normal and shifted southeastward (Fig. 4b). As a result, the westerlies from its western to northern peripheries weakened evidently. On the other hand, the East Asian jet stream retracted northwestward, strengthening over northeast China and the Koreas and weakening over southeastern China.

Figure 4c reveals several significant circulation features in H500 with a ridge extending from southwestern Russia through the western Mediterranean Sea to the West Africa coast, a trough stretching from the Aral Sea through the eastern Mediterranean Sea to northwestern
Africa, and the well-known East Asian trough. The ridge over Europe and the trough near western Asia were stronger than normal and shifted southeastward (Fig. 4d), indicating an evident blocking over the Ural Mountain. An analysis of the geopotential height and temperature fields also reveals strong and southeastward cold advection from the high latitudes. The blocking, which was quite persistent in January 2008 (D. Wang et al. 2008), and the cold advection were favorable for the accumulation of cold air over the Mongolia. Over East Asia, although the trough deepened over north of about 45°N, it became shallower over the East China Sea, eastern China, Korea, and southern Japan. Therefore, the H500 anomalies were characterized by a west-low and east-high pattern over tropical–subtropical China and western Asia. This circulation pattern including the wave train to the west favors intrusions of cold circulation systems from Europe and western Asia, whose propagation to the Pacific was slowed down by the anomalous high over East Asia and the northwestern Pacific.

We also analyzed the changes in sea level pressure and daily surface atmospheric circulation (figures not shown). It is found that in January 2008 the Asian continent high was stronger than normal, with largest positive anomalies near 55°N, 70°E. The strong surface high was accompanied by negative pressure anomalies south of 30°N, with a center over the east of the Tibet Plateau. The cold air, accumulated over Mongolia, moved southward along with the cold fronts, reaching as far as the southeast coast of China. Many of the synoptic features associated with the snowstorms have been discussed in detail by D. Wang et al. (2008).

Shown in Fig. 5 are the patterns of vertically integrated water vapor transport and its anomaly for January 2008, which are similar to the patterns of lower-tropospheric winds. The water vapor over central–southern China mainly originated from western Asia,

![Fig. 5. (a) Mean vertically integrated (surface to 300 mb) water vapor flux (vectors; kg m⁻¹ s⁻¹) and the amount of water vapor transport (shadings, kg m⁻¹ s⁻¹), and (b) the anomalies of water vapor flux (vectors) and water vapor divergence (shadings; 10⁻⁵ kg m⁻¹ s⁻¹) for January 2008. The anomalies were computed relative to the climatologies of 1979–2008.](image-url)
the Bay of Bengal, and the northern South China Sea. The anomalous water vapor transport was consistent with the anomalous circulation features shown in Fig. 4. Associated with the intensified westerly flow over subtropical Asia linked to the strengthened MEJS, above-normal water vapor was transported from western Asia and the Bay of Bengal. The water vapor transport from the South China Sea was also above normal, associated with the anomalous high centered over the East China Sea (Fig. 4d). These branches of enhanced water vapor flux led to convergence of water vapor over southern-central China, increasing the precipitation.

4. Relationships with regional atmospheric anomalous signals

In the above section, we have discussed the patterns of temperature, precipitation, and atmospheric circulation
associated with the snowstorms in January 2008. We have in particular noticed the significant changes in the MEJS and the SWPH. Here, we further examine the general relationships of these atmospheric systems with the variability of temperature and precipitation over China.

a. The Middle East jet stream

Following Yang et al. (2004), we define an index of MEJS as \( U_{200} (20^\circ-30^\circ N, 40^\circ-70^\circ E) \) minus \( U_{200} (30^\circ-40^\circ N, 15^\circ-45^\circ E) \), which is shown in Fig. 6a. Indeed, there is a similarity between Fig. 4b, which shows the January 2008 \( U_{200} \) anomalies, and Fig. 6b, which portrays the regression of \( U_{200} \) against the MEJS. Similarity also exists between Fig. 4d, the January 2008 \( H_{500} \) anomalies, and Fig. 6c, the regression of \( H_{500} \) against the MEJS. Thus, when the MEJS index is positive, the jet stream strengthens and expands southeastward, enhancing the westerlies over India and southern Tibetan Plateau (Fig. 6b). At the same time, geopotential height decreases over subtropical Asia including southern Tibetan Plateau (Fig. 6c), indicating a deepening of the trough (mostly apparent at the lower troposphere) embedded in the southern branch of the westerlies. However, comparison between the corresponding regression patterns also reveals differences in both \( U_{200} \) and \( H_{500} \) over East Asia, which will be addressed in the section 4b.

Figure 7 shows the correlations of surface temperature and precipitation with the MEJS. The intensification and southeastward shift of the MEJS are accompanied by a decrease in temperature over most of China with exceptions over the northwest and the northeast. The changes in the MEJS are also accompanied by wet conditions over southern China. In particular, over the majority of southern–central China, an intensified and southeastward shifted MEJS is associated with cold and wet conditions similar to those in January 2008.

b. The subtropical western Pacific high

An examination of the \( H_{500} \) pattern (Fig. 4d) also indicates positive height anomalies over East Asia related to the change in the subtropical western Pacific high. To analyze the possible influence of the subtropical high, we further define an index of the SWPH as the mean latitudes of maximum \( H_{500} \) over the longitude band of \( 110^\circ-130^\circ E \) (Fig. 8a) and examine its relationship with the snowstorms that affected central–southern China. Figure 8 shows the regressions of \( U_{200} \) and \( H_{500} \) against this index. When the SWPH is strong and is located farther north than normal, the 200-mb westerlies are strong over East Asia centered over northeastern China, Korea, and southern Japan but weak over southern China and Southeast Asia (Fig. 8b). Correspondingly, \( H_{500} \) increases over East–Southeast Asia, between \( 10^\circ \) and about \( 38^\circ N \) (Fig. 8c). Thus, over East–Southeast Asia, the changes in \( U_{200} \) and \( H_{500} \) associated with the strong and north-extended SWPH are similar to the anomalies observed in January 2008 (see Figs. 4b,d), which are not explained by the MEJS.

It can be seen from Fig. 9a, which shows the correlation of surface temperature with SWPH, that a north-expanded SWPH is accompanied by a warming over southwestern China and the east coast region and a cooling over northwestern and central–southern China.
The SWPH–temperature relationship, therefore, is consistent with the observed temperature anomaly of January 2008 (see Fig. 2b). However, the correlations over central and southern China are insignificant. Figure 9b shows that the SWPH is positively and significantly correlated with the precipitation over northern China. However, weak SWPH–precipitation correlation is found over southern China. Different from the precipitation anomaly for January 2008, the SWPH is negatively correlated with the precipitation over southern China.

In spite of the weak linear correlation of SWPH with the temperature and precipitation over southern China, we further examine the historical cases of large SWPH anomalies. When the SWPH was farthest north (e.g., 1989), the temperature was generally below normal and the precipitation was significantly above normal over central–southern China, as in 2008. On the other hand,
when the SWPH was farthest south (e.g., 1992 and 1982), central–southern China was characterized by a significant increase in temperature and decrease in precipitation. Thus, the SWPH seems to have a relationship with the temperature and precipitation over central–southern China when its ridgeline experiences extreme deviations from normal.

c. The tropical Madden–Julian Oscillation

Because the Madden–Julian oscillation (MJO), which has been argued to be associated with the winter climate over East Asia (see Jeong et al. (2008) and references therein), was very active in the winter of 2007/08, we briefly examine the link of the snowstorms of January 2008 to the phase of MJO. Jeong et al. (2008; see their Fig. 2) recently showed that the winter precipitation over southeastern China, Korea, and Japan increases (decreases) significantly when the MJO is in phases 2–3 (phases 6–7) in the definition of 8 MJO phases by Wheeler and Hendon (2004). Precipitation also increases (decreases) moderately when the MJO is in phases 4–5 (phases 1 and 8). In January 2008, the snowstorms over China occurred in four major periods: 10–16, 18–22, 25–29 January, and from 31 January to 2 February 2008. As seen from Fig. 10, the MJO was in phase 7 during 8–21 January. That is, the MJO was in a phase of usually decreased precipitation during the first two major periods of the snowstorms. However, the MJO was in phases 2–3, the phases corresponding to usually increased precipitation over southeastern China and East Asia, from 26 January to 2 February, the last two periods of the snowstorms. Therefore, the relationship between the phases of MJO and the snowstorms seems inconsistent between the first two periods and the last two periods of the snowstorms. Because only the data of Januarys, mostly monthly means, are analyzed, a more thorough study of the relationship between MJO and the snowstorms affecting China is beyond the scope of this study.
5. Possible roles of the Arctic Oscillation and the La Niña event

In the above section, we have addressed the potential importance of the MEJS and the SWPH for the variability of temperature and precipitation over central-southern China. It is more preferable if the temperature and precipitation anomalies can be attributed to any possible forcing of more remote or larger-scale climate variability. Because of the La Niña event in 2007/08 winter and the possible link of MEJS to AO (Yang et al. 2004), we further investigate the roles of AO and La Niña in the temperature and precipitation anomalies associated with the snowstorms.

a. The Arctic Oscillation

As shown from Fig. 11, the AO, whose value was 0.82 in January 2008 (Fig. 11a), is associated with a distinctive upper-tropospheric wave train extending from

![Fig. 11. (a) Normalized January AO index. (b) Regression of 200-mb zonal wind against AO (m s\(^{-1}\)) and (c) regression of 500-mb geopotential height against AO (in m) for January during the period of 1979–2008. Areas of statistical significance exceeding the 95% confidence level (t test) are shaded.](1122 MONTHLY WEATHER REVIEW V OLUME 137)
northeastern Atlantic, through the Mediterranean Sea and western Asia to southern Asia (Fig. 11b). This wave train is similar to the teleconnection associated with MEJS shown in Fig. 6b. When the AO is positive, the MEJS intensifies and shifts southeastward. Positive AO is also accompanied by increase in H500 over western Europe and the Mediterranean Sea and decrease in H500 from western Russia to the Middle East (Fig. 11c). The similarity between Figs. 11c and 6c, especially over the regions from Europe through western Asia to southern Asia, again confirms the strong relationship between the AO and the MEJS.

The more direct links of the AO to the temperature and precipitation over China are shown in Fig. 12. Positive AO is accompanied by increasing temperature over the northeast and part of northwestern China and decreasing temperature over a majority of China especially over the central and southern portions of the country. It is also accompanied by wet conditions over most of China with an exception over the northwest. Overall, as for the MEJS, the link of the AO to temperature and precipitation in January 2008 is consistent with the general relationship between the AO and the parameters.

b. La Niña event

Figure 13 shows the anomalous SST of January 2008 (Fig. 13a) and the correlation of grid SST with negative Niño-3.4 SST index (Fig. 13b). The SST anomalies observed over the Pacific in January 2008 were consistent with the SST variability associated with La Niña conditions. Namely, cooling occurred in the tropical central-eastern Pacific and warming appeared over the subtropics in both hemispheres. Figure 13a also shows several features that may not be clearly related to La Niña: the warming over the subtropical northwestern Pacific and eastern North Atlantic and the near-zero anomalies over the tropical Indian Ocean. The SST over the northwestern Pacific (20°–32.5°N, 120°–150°E) is also positively and significantly correlated with SWPH ($r = 0.78$) and this warm SST enhances water vapor supply to the atmosphere through evaporation.

Here, we focus on the effect of La Niña by examining the relationships of Niño-3.4 SST (Fig. 14a) with the temperature and precipitation over China, as well as the atmospheric circulation over Asia. The regressions of both U200 and H500 against negative Niño-3.4 SST (Figs. 14b,c) show atmospheric features that are different from those observed in January 2008 and those associated with the MEJS and the AO over western-central Asia and to its west. However, the 200-mb westerlies increase over northeastern China and decrease over the northern South China Sea. Meanwhile, H500 tends to be above normal over the East China Sea. These features over East–Southeast Asia are somehow similar to those observed in January 2008, which, on the other hand, cannot be explained by the MEJS and the AO.

Negative Niño-3.4 SST is associated with low temperature over the northeast and northern northwest China and high temperature over the southwest (Fig. 15a). Negative Niño-3.4 SST is also linked to increased precipitation over northern China and decreased precipitation over the northwest of southern China (Fig. 15b). These associations of temperature and precipitation with ENSO are similar to those linked to the SWPH shown in Fig. 9. Nevertheless, the correlations between the Niño-3.4 SST and the temperature and precipitation over southeastern China are overall insignificant.
As for the SWPH, we also analyze the nonlinear impact of ENSO by examining the temperature and precipitation anomaly patterns for El Niño and La Niña events. During 1979–2008, the Niño-3.4 SST was significantly above normal in the Januarys of 1998, 1983, and 1992 and below normal in the Januarys of 1989, 2000, 1999, and 2008. However, there exists no clear distinction in the temperature and precipitation patterns between the El Niño and La Niña events.

### 6. Further discussion

#### a. Importance of multiple factors

In the above analysis, we have discussed the links of multiple factors to the snowstorms over central and southern China in January 2008. Table 1 shows the cross correlations among MEJS, AO, SWPH, and negative Niño-3.4 SST and their relationships with the temperature and precipitation averaged over 171 stations within 20°–30°N, 100°–125°E. The variability of both temperature and precipitation over southern China is strongly correlated with the MEJS and the AO. A particularly significant correlation exists between the MEJS and the precipitation ($r = 0.61$). The MEJS is also significantly correlated with the AO (near the 99% confidence level), although it is associated with Niño-3.4 SST as well. There is also a strong relationship between the SWPH and Niño-3.4 SST; however, the SWPH is more significantly correlated with the northwestern Pacific SST (see section 5b). It should be pointed out that, although we have discussed several possible impacting factors in this study, it is unlikely that any single factor caused the large-scale and long-lasting snowstorms. It is also true that a combination of these factors could only explain part of the climate anomalies associated with the snowstorms. Furthermore, the various factors are not fully independent from each other. However, some of these factors are more influential than the others.

Figure 16 demonstrates the mutual associations of MEJS and AO with the temperature and precipitation over China. When both the MEJS and the AO are stronger than normal by 0.5 standard deviation or when either MEJS or AO is stronger than normal by one standard deviation, the temperature over central–southern China is below normal and the precipitation is above normal (Figs. 16a,b). On the contrary, when the MEJS and the AO are weaker than normal by 0.5 standard deviation, or when either the MEJS or the AO is weaker than normal by one standard deviation, the temperature is above normal and the precipitation is below normal.
The changes in temperature and precipitation, especially those over southern China, are evidently distinguished between the two categories. It should be pointed out that the AO and the MEJS are not two fully independent phenomena. As indicated by Yang et al. (2004), the wave train associated with the variability of MEJS could be a branch of the atmospheric wave trains associated with the variability of AO. Nevertheless, we construct a combined index of the MEJS and the AO as the mean of normalized MEJS and AO to indicate their correlations with the temperature and the precipitation over China. It is seen from Figs. 16c,f that the correlations of southern China temperature and precipitation with this combined index are similar to those with the MEJS or the AO. However, the combined index yields broader areas of large statistical significance.

We have examined the relationships between the temperature and precipitation over central–southern China and various larger-scale environmental factors.
We have also analyzed the features of atmospheric circulation patterns associated with the variability of the temperature and the precipitation. Without assuming any link of the southern China temperature and precipitation to the factors examined, we further analyze the patterns of regression of \( U_{200} \) and \( H_{500} \) against the temperature and precipitation to understand how these patterns are compared with those shown above (sections 4–5). Figures 17a,b show that the most prominent atmospheric features associated with the variability of the temperature over southern China are the wave train extending from the eastern North Atlantic to western-central Asia. These features are to a certain extent similar to those related to the AO. The figure also shows that the temperature over southern China is linked to the change in the atmospheric circulation over central Russia. The atmospheric features associated with the southern China precipitation (Figs. 17c,d) are particularly similar to the features associated with the MEJS (see Fig. 6). On the contrary, there is little resemblance between the features shown in Fig. 17 and the features related to the SWPH (see Fig. 8) and ENSO (see Fig. 14).

### b. Precursory signals

Prediction of anomalous snowfall over China has long been a challenge in extended long-range forecasts. Here, we briefly examine the general relationships between the January temperature and precipitation over China and the conditions of the MEJS and other factors in the previous December that can be potentially used to anticipate the conditions in the following January. Figure 18 shows the correlations of January temperature and precipitation with December MEJS, AO, negative Niño-3.4 SST, and SWPH. It is seen that the January temperature over most of China is negatively correlated with the December MEJS and AO (Figs. 18a,c), but positively correlated with the December SWPH (Fig. 18g). The most significant relationship is found between the temperature and the AO and a moderately significant relationship is seen between the temperature and the MEJS. A weak relationship is found between the January temperature and the December Niño-3.4 SST (Fig. 18e). Although positive December AO is associated with more January precipitation over southwestern China (Fig. 18d) and more (less) January precipitation tends to fall over northern–central (southwestern) China when the December Niño-3.4 SST is below normal (Fig. 18f), the lag relationships between precipitation and all the factors examined are generally weak.

The above result is confirmed by the correlations of area-averaged temperature and precipitation with the various antecedent factors. The December AO is significantly and negatively correlated with the January
temperature over 20°–30°N, 100°–125°E at the 99% confidence level ($r = -0.47$). It is also positively correlated with the January precipitation over the region at the 90% confidence level ($r = 0.30$). The December MEJS is significantly and negatively correlated with the January temperature as well ($r = -0.31$). However, the correlations between the January temperature and precipitation over this region and the conditions of

![Composite anomalies of (left) January temperature and (right) precipitation for (a),(b) strong MEJS and positive AO and for (c),(d) weak MEJS and negative AO. The years in (a) and (b) include 1983, 1989, 1991–93, 2002, 2007, and 2008 when both MEJS and AO are above 0.5 standard deviation or one of them is above one standard deviation. The years in (c) and (d) include 1979, 1980, 1985–87, 2003–04, and 2006 when both MEJS and AO are below –0.5 standard deviation or one of them is below –1 standard deviation. (e),(f) The correlations of temperature and precipitation with the combined index of MEJS and AO, where areas of statistical significance exceeding the 90% confidence level are highlighted by thick lines.](image-url)
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December Niño-3.4 SST and SWPH are insignificant. That is, the precursory signals of January temperature and precipitation over southern China may be found in the AO and the MEJS, instead of the Niño-3.4 SST and the SWPH in the preceding December. It is also interesting to note that, from January to February 2008 when central–southern China was not severely affected by snowstorms, the MEJS became significantly weaker than normal and the SWPH was farther south than normal. However, the sign of Niño-3.4 SST and AO anomalies remained unchanged.

7. Summary

In this study, we have analyzed the patterns of surface temperature, precipitation, atmospheric circulation, and other fields associated with the extraordinarily frequent and long-lasting snowstorms that affected central and southern China in January 2008. We have discussed the large-scale climate anomalies associated with the snowstorms with a focus on the relative importance of several possible impacting factors. We have also compared the January 2008 case with historical events to demonstrate the robustness of the results obtained.

The Middle East jet stream and the Arctic Oscillation played important roles in the occurrence of the snowstorms. In January 2008, the AO was in its positive phase and the MEJS intensified and shifted southeastward, accompanied by the southeastward shift of the ridge and the trough over Europe and western Asia. The associated wave train and the southeastward shift of the ridge and trough favored the intrusions of cold weather systems into East Asia. The intensification and southeastward shift of the MEJS also strengthened the trough embedded in the southern branch of the subtropical westerlies over the southern Tibetan Plateau, enhancing the water vapor transport from western Asia and the Bay of Bengal to China.

In January 2008, the subtropical western Pacific high was farther north than normal, as usually seen during La Niña events. An anomalous high appeared over the East Asian coast and far northwestern Pacific, and it slowed down the eastward propagations of weather systems to the Pacific and increased water vapor supply from the northern South China Sea to the snowstorm regions. Thus, while the MEJS and the AO were directly associated with the temperature and precipitation patterns in the west, the SWPH and the La Niña event tended to contribute to the anomalies from the east. However, the MEJS and the AO exert stronger influences on the snowstorms compared to the SWPH and Niño-3.4 SST, given that they have more significant relationships with the temperature and precipitation over southern China and these relationships are more consistent with those seen in historical events. An analysis of historical events also suggests that the SWPH and the Niño-3.4 SST exert an influence on the January temperature and precipitation over southern China only when they deviate significantly from normal and when favorable conditions associated with the MEJS or the AO are found. La Niña conditions alone cannot explain the severe and persistent snow conditions over central–southern China. Finally, compared to the Niño-3.4 SST and the SWPH, the conditions of December MEJS and

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![Fig. 17. Regression of (a) 200-mb zonal wind and (b) 500-mb geopotential height against the negative temperature over southern China (SCT). Regression of (c) 200-mb zonal wind and (d) 500-mb geopotential height against southern China precipitation (SCP) for January during the period of 1979–2008. Areas of statistical significance exceeding the 95% confidence level (t test) are shaded.](image-url)
FIG. 18. Correlations of (left) January temperature and (right) precipitation with December (a),(b) MEJS; (c),(d) AO; (e),(f) negative Niño-3.4 SST; and (g),(h) SWPH. Areas of statistical significance exceeding the 90% confidence level (t test) are highlighted by thick lines.
AO exhibit stronger precursory signals for the variability of January temperature over central–southern China.

It should be pointed out that, in this observational study, we have mainly depicted the large-scale climate anomalies associated with the snowstorms affecting China in January 2008. Although we have discussed the possible effects of several potential impacting factors, most of the features examined are associated with the atmospheric internal processes and more studies are needed to understand the attribution of the snowstorms to possible external forcing. The different factors discussed may not be completely independent from each other and the nonlinear effects of these factors have not been fully addressed. In addition, we have only analyzed the monthly means of the various indices. The variability of these indices themselves is influenced by many causes including the upscale effects of higher-frequency weather systems (e.g., Benedict et al. 2004; Loptien and Ruprecht 2005), which have not been discussed in the current study. China is in the entrance region of the East Asian jet stream and anomalous northerly (southery) flow was observed at the lower (upper) troposphere associated with strengthening entrance portion of the jet stream. The upscale effect of the snowstorms may support the anomalous divergence over southern China and these meridional flows.

The other issues about the January 2008 snowstorms that have not been fully addressed in this study include the East Asian winter monsoon and its relationship with the snowstorms. Although the relationships between the monsoon and the climate anomalies over China have been discussed previously (see the introduction), different definitions have been applied to measure the monsoon, which has led to different features about the relationships between the monsoon and the climate anomalies over China. For example, in the definition of the East Asian monsoon by Yang et al. (2002) as the mean 850-mb meridional wind over 20°–40°N, 100°–140°E, the monsoon in January 2008 was significantly weaker than normal (by 1.7 standard deviations) because of the anomalous southerly flow over East Asia associated with the anomalous high centered over the coastal region and the far northwestern Pacific. However, the monsoon would be stronger than normal if temperature is used to measure the intensity of the monsoon as done by Gong et al. (2001) because of the apparently cold anomalies over East Asia as shown in Fig. 2b. Nevertheless, further studies are needed for improving our understanding of the complex winter monsoon system and the regional climate over central–southern China.

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