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Detecting Primary Precursors of January Surface Air Temperature Anomalies in China

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ABSTRACT

This study aims to detect the primary precursors and impact mechanisms for January surface temperature anomaly (JSTA) events in China against the background of global warming, by comparing the causes of two extreme JSTA events occurring in 2008 and 2011 with the common mechanisms inferred from all typical episodes during 1979–2008. The results show that these two extreme events exhibit atmospheric circulation patterns in the mid–high latitudes of Eurasia, with a positive anomaly center over the Ural Mountains and a negative one to the south of Lake Baikal (UMLB), which is a pattern quite similar to that for all the typical events. However, the Eurasian teleconnection patterns in the 2011 event, which are accompanied by a negative phase of the North Atlantic Oscillation, are different to those of the typical events and the 2008 event. We further find that a common anomalous signal appearing in early summer over the tropical Indian Ocean may be responsible for the following late-winter Eurasian teleconnections and the associated JSTA events in China. We show that sea surface temperature anomalies (SSTAs) in the preceding summer over the western Indian Ocean (WIO) are intimately related to the UMLB-like circulation pattern in the following January. Positive WIOSSTAs in early summer tend to induce strong UMLB-like circulation anomalies in January, which may result in anomalously or extremely cold events in China, which can also be successfully reproduced in model experiments. Our results suggest that the WIOSSTAs may be a useful precursor for predicting JSTA events in China.

Key words: Eurasian teleconnection, anomalous temperature in China, seasonal climate prediction, SST anomaly, western Indian Ocean, model experiment

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1. Introduction

In January of 2008 and 2011, extremely low temperature events with blizzard conditions and freezing rain occurred in southern China, resulting in adverse impacts such as broken power transmission lines and chaotic traffic conditions (Ding et al., 2008; Wang Y. F. et al., 2008). Although many studies have investigated the impact factors and associated mechanisms of cold events since 2008, some important questions remain unclear. For example, did the two events have similar causes or different mechanisms, and what are the possible precursors for predicting these kinds of anomalous temperature events in China? Therefore, from the predictability point of view, it is important to examine the causes and mechanisms of these two extreme events in the context of all anomalous episodes in order to provide clues for reducing the economic losses caused by such disasters in the future.

The winter surface air temperature in China is mainly influenced by the Siberian high over the Eurasian continent (Gong and Wang, 2003), which is closely related to

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the Asian winter monsoon (e.g., Guo, 1994; Lu et al., 2007; Zhang et al., 2014). For example, when the Siberian high is stronger than normal, the winter monsoon usually becomes stronger. This is accompanied by northerly anomalies controlling eastern China, with the corresponding ridge located over the Ural Mountains and the trough to the south of Lake Baikal at middle levels stronger than normal (Li et al., 2010; Xie and Bueh, 2017). Accordingly, this is associated with a weaker subtropical high moving eastward and southward, and the surface air temperature becomes colder in China (e.g., Ding et al., 2008; Hong et al., 2008; Wang D. H. et al., 2008). Some studies have shown that the East Asian trough also plays an important role in the Asian winter monsoon and associated temperatures in China (Wang et al., 2009; Wen et al., 2009; Zuo et al., 2015). In addition, the North Atlantic Oscillation/Arctic Oscillation (NAO/AO), well-known as a prominent planetary-scale phenomenon, is closely related to the surface air temperature in China (e.g., Jeong and Ho, 2005; Warren II and Bradford, 2010; Park et al., 2011; Gong et al., 2014), though the causes of the NAO/AO can be both internal and external (Wu and Wang, 2002; Tan et al., 2014, 2015). Furthermore, anomalies in the stratosphere, which may propagate downward and couple with anomalies in the troposphere, can also lead to extreme surface air temperature events (e.g., Black, 2001; Perlwitz and Graf, 2001; Chen and Huang, 2005; Chen et al., 2008; Wang and Chen, 2010; Li et al., 2017). Some studies have reported that large-scale circulation anomalies, such as the AO, were responsible for the cold events in January 2008 (Wang Y. F. et al., 2008; Song and Li, 2009; Tan et al., 2009, 2010), while others have noted that the features of the coupling between the NAO and the blocking circulation over the Ural Mountains were opposite to those under regular conditions (Li et al., 2008; Li and Gu, 2010; Li and Zhang, 2015). Besides, there are also other results relating extreme cold/warm events in China and global warming (Ding et al., 2008; Zuo et al., 2013; Chen et al., 2015; Zhou et al., 2015).

Tropical SSTs are important drivers of global/mid–high latitude climate (e.g., Li et al., 2008), including not only annual oscillation (Li et al., 1989) and El Niño–Southern Oscillation but also decadal oscillations (Li and Bates, 2007; Wang et al., 2007) like the Atlantic Multidecadal Oscillation and North Pacific Oscillation. However, the influence of these anomalies on temperature is also modulated by other factors (Fu et al., 2008; Li and Gu, 2010). For example, many studies have shown that La Niña events usually occur in conjunction with a stronger than normal winter monsoon season. However, La Niña was not the main cause of the extreme cold episode noted in January 2008 (Li et al., 2008). The sea surface temperature anomalies (SSTAs) in the North Atlantic Ocean may have been responsible for the 2008 event (Fu et al., 2008).

The various investigations outlined above suggest that the causes of the 2008 event were quite complicated. In the present study, the possible causes and precursors of extreme cold/warm episodes in winter in China on the interannual timescale are examined in comparison with the January surface temperature anomaly (JSTA) events in China in 2008 and 2011. Following this introduction, Section 2 describes the data and the methodology. Section 3 presents the possible causes and precursors in the tropical ocean. Section 4 discusses the influences of the precursors on extreme cold/warm episodes on an annual basis from a predictability perspective, along with results from model experiments investigating the influence of the tropical ocean on mid–high latitude circulation. Finally, Section 5 presents the conclusions.

2. Data and methodology

The data used in this study are mainly from analyses by the NCEP–NCAR (Kalnay et al., 1996). These data include the monthly mean and long-term mean values for geopotential height, wind speed, and surface pressure. The horizontal resolution of these data is 2.5° latitude × 2.5° longitude. The sea surface temperature (SST) data are from the NOAA extended reconstructed SST dataset, which has a horizontal resolution of 2.0° latitude × 2.0° longitude. The 160-site monthly mean temperature data are from the National Climate Center of the China Meteorological Administration. The NAO index is produced by the NOAA's Climate Prediction Center, which is calculated by the 500-hPa geopotential heights. Positive NAO index values indicate that both the Azores high and Icelandic low are stronger than normal. All of the data used in this study are from 1978/79 to 2010/11. The statistical methods used in this study include composite, correlation, and regression analysis, with associated significance testing, and model experiments are also involved. Since the comparison of the two events in 2008 and 2011 is based on the possible mechanisms resulting from all typical episodes during 1979–2008, the significant composite characteristics for all typical JSTA events and their correlation distribution are shown by shaded areas, which denote test values with a confidence level exceeding 95% for the composite analysis of all typical events. The typical events are selected from the normalized time coefficients of the first EOF mode of January temperature in

China during 1979–2008 (Tan et al., 2009). The cold events having normalized time coefficients over 1.0 are in 1983, 1984, 1993, and 2008, whereas the typical warm events having coefficients below –1.0 are in 1982, 1987, 1997, and 2003. The coefficient in 2011 is calculated as –4.3 by projecting the anomalous temperature on the first EOF pattern. Here, all composites are analyzed by subtracting the warm composite from the cold composite.

The atmospheric general circulation model used here is the Community Atmosphere Model, version 3 (T42L26) (Collins et al., 2004). The numerical experiments are conducted by prescribing positive SSTAs in the western Indian Ocean during the summer season. The experiment is initialized in June to August and time-integrated for eight months. The control experiments are conducted with prescribed seasonally varying climatological SST. Ten samples in total are collected and the means of the results are shown in the context, with the mean values out from the control experiment removed.

3. Possible causes

3.1 *Features of the two extreme events*

The JSTAs in 2008 and 2011 are shown in Fig. 1. The anomaly patterns are very similar to the pattern with colder-than-normal air temperature occurring in most parts of China, except in the south and east of the Tibetan Plateau and northeastern China. However, the surface air temperature in northeastern China was negative in January 2011 but positive in 2008. Additionally, the weather in 2011 was colder than in 2008, with amplitudes of –8.3 and –6.6°C, respectively.

3.2 *Features of atmospheric circulation anomalies*

Based on the typical cold/warm events defined by Tan et al. (2009, 2010), the circulation anomalies in January 2008 and 2011 are examined to identify the causes of the cold events (see Fig. 2). When the NAO is in a positive phase, accompanied by positive anomalies in the Ural Mountains and negative ones to the south of Lake Baikal (UMLB) at 500 hPa, the Siberian high is usually stronger and surface air temperatures in China are lower. In January 2008, the prominent circulation anomalies over the regions from North Atlantic–Europe to the south of the Lake Baikal area formed a wave pattern similar to the composite results for all typical cold/warm events. In January 2011, the circulation over North Atlantic was reversed, with a negative NAO phase. However, the anomalies over the Ural Mountains and the south of Lake Baikal were in accordance with those in previous studies. This finding suggests that, for all cold episodes, including the 2008 and 2011 cases; both the blocking high over Ural Mountain areas and the trough to the south of Lake Baikal were stronger than normal, which created favorable conditions for cold air to intrude into the areas south to Lake Baikal. In Fig. 2, we can also see that anomaly values in the centers were larger in January 2011 than those in January 2008. The results suggest that the Siberian high was stronger in January 2011 than in 2008. Besides, due to the warming background, the anomalous northerly flow at 850 hPa was not significant in January for the typical episodes, which likewise occurred in January 2008. However, in January 2011, there were apparent northerly anomalies over eastern China.

As described above, the common UMLB anomalies occurred for all cold/warm events, but the anomalies over North Atlantic were reversed during 2008 and 2011. In other words, it might be UMLB that was responsible for the temperature anomalies over large parts of China, while the NAO was responsible for the temperature vari-

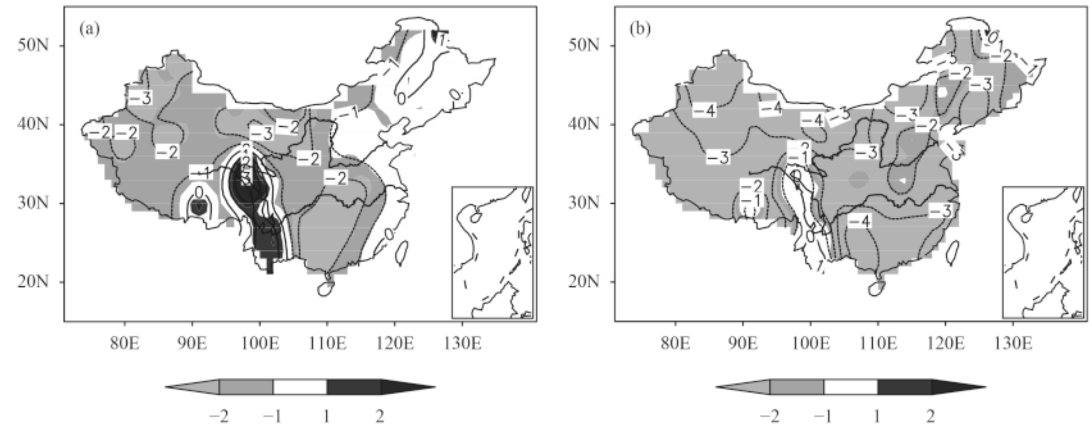

Fig. 1. January surface temperature anomalies (°C) in (a) 2008 and (b) 2011. Shaded areas indicate the absolute values of temperature anomalies larger than 1°C.

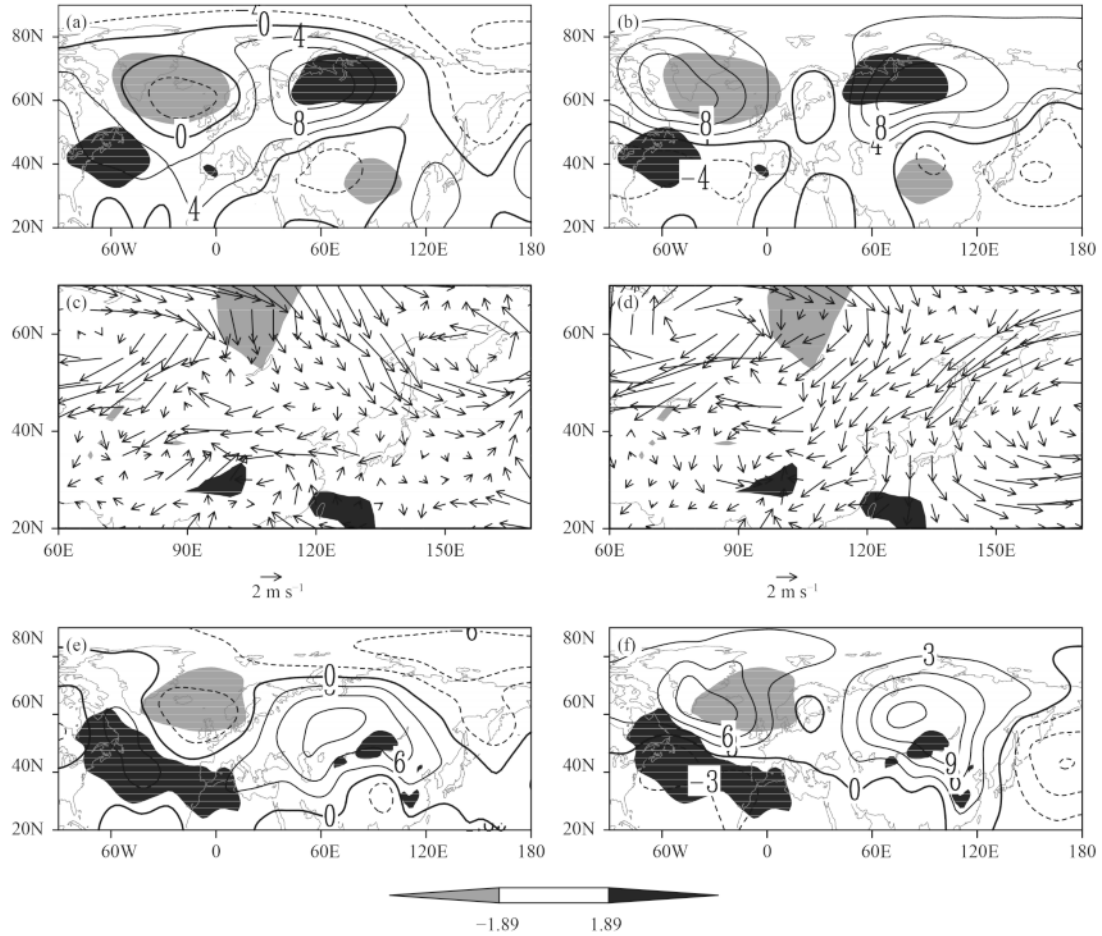

Fig. 2. January circulation anomalies and composite *t*-test values for the differences between typical cold and warm events: (a) 500-hPa geopotential height, (c) 850-hPa winds, and (e) sea level pressure for 2008; (b, d, f) as in (a, c, e), but for 2011. Shaded areas indicate the confidence level exceeding 95%.

ation over Northeast China. To test this speculation, we further check the temperature features associated with the NAO and UMLB. The time series that represent the variation of UMLB are calculated from the deviations for all the grids over the Ural Mountains (40°–85°N, 20°–110°E) and the south of Lake Baikal (20°–60°N, 60°–110°E) from the composite 500-hPa geopotential heights for typical events at the 95% confidence level. Next, an index is defined as the difference between the north center and the south one (denoted as the UMLB index). Over North Atlantic, an NAO index is adopted (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). The typical years are defined according to one standard deviation (refer to Table 1). In Fig. 3a, under the influence of UMLB, it is colder than normal over most parts of China, apart from the northeastern region. Furthermore, under the condition of the NAO (see Fig. 3b), no significant variation of surface air temperature occurs in West China. However, the temperature over northeastern China is apparently warmer than normal under the circumstance of a positive phase of the NAO. In combination with Fig. 1, it can be noted that the different phases of the NAO are responsible for the different temperature anomaly patterns over northeastern China in the two years, with a warm one in January 2008 and a relatively cold one in 2011.

Table 1. Typical events as defined by the circulation index anomaly exceeding plus or minus one standard deviation from the mean (±1σ)

		Year
UMLB	+1σ	1980 1981 1995 1996 2004 **2005** 2008 2011
	−1σ	**1979** 1982 **1987** 1990 1992 1997 2002 2003 2009
NAO	+1σ	1983 1984 1986 1989 1993 **2005** 2006
	−1σ	**1979** 1985 **1987** 2010 2011

Note: Bold years are those common to both UMLB and NAO occurrence.

3.3 *Features in the tropical Indian Ocean*

To predict the interannual climate variations, we investigate the lead signals of the UMLB-like circulation anomalies and the associated SST by evaluating the trop-

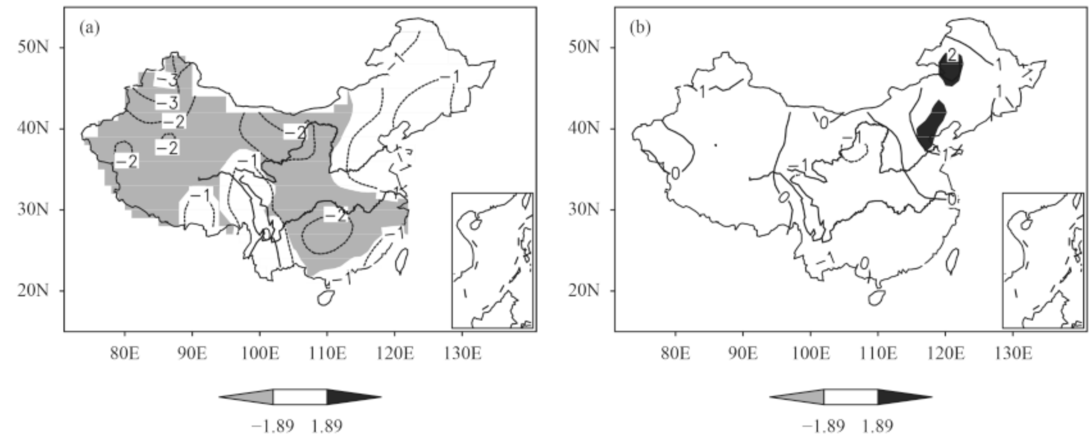

Fig. 3. Composite January surface temperature anomalies (°C) and *t*-test values for the typical episodes. (a) UMLB and (b) NAO. Shading indicates the confidence level exceeding 95%.

ical SSTs. As we know, SSTs in the tropics have a significant influence on the atmospheric circulation. The UMLB-like circulation in January has a remarkable relationship with the tropical SST (see Fig. 4). The positive anomalies are in the western tropical Indian Ocean, while the notable negative ones are in the western tropical Pacific and the low-latitude Atlantic. In addition, there are also some significant values in the extratropics. If we focus on the tropics, interestingly, positive SSTAs occur in the western tropical Indian Ocean during the preceding summers, while the anomalies in the western Pacific and low-latitude Atlantic are negative (shaded areas in Fig. 4). In summer 2007 and 2010, the tropical Indian Ocean exhibits a similar pattern of variation (see contours in Fig. 4), while in the western Pacific and low-latitude Atlantic the amplitudes of the SSTAs are very small in 2007 but much bigger in 2010, with positive anomalies opposite to those in typical cold events. As noted, the positive SSTAs in the western Indian Ocean appear in all typical anomalous JSTA events, including in both the 2008 and 2011 episodes. This suggests that the SSTAs in the western Indian Ocean (WIO) are indeed closely related to the temperature anomalies in China. In Fig. 5a, we can see that the amplitudes of the composite WIOSSTAs are most apparent from the leading summer to the following January. Here, the time series of the WIOSSTAs are obtained by averaging the grid-point SSTAs with monthly composite notable *t*-test values over 30°S–30°N, 20°–80°E. Furthermore, the evolutions of the WIOSSTAs for the typical cold JSTA events, that is, a decrease from summer to later seasons, are opposite to those for the warm episodes. For the cold JSTA events of 2008 and 2011, the variation of the WIOSSTAs in both 2007/08 and 2010/11 was in accordance with the features of the evolutions of the WIOSSTAs for all the cold episodes, with a weakening trend. This suggests that the WIOSSTAs from the leading summer do have a close relationship with the JSTA events in China.

4. Influences of the WIOSSTAs

From the analysis mentioned above, the UMLB-like

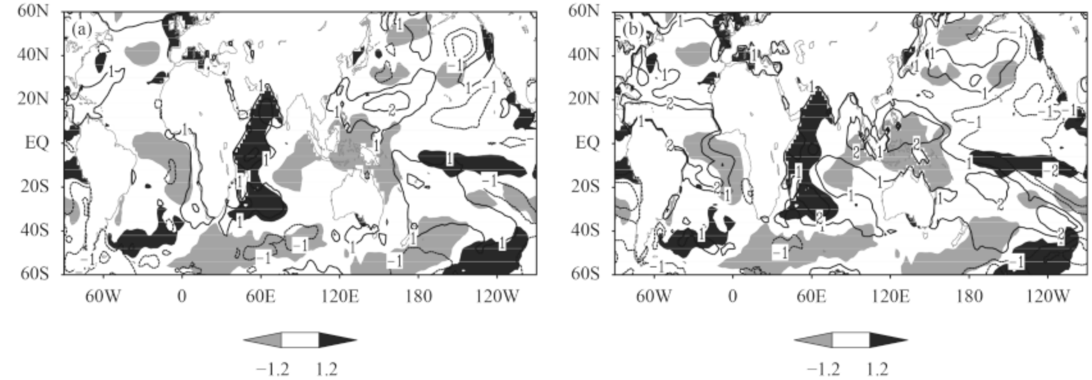

Fig. 4. Sea surface temperature anomalies (contours; °C) and *t*-test values for the typical events (shading) in (a) 2008 and (b) 2011. Shaded areas indicate the confidence level exceeding 95%; black areas denote positive values and grey ones denote negative values.

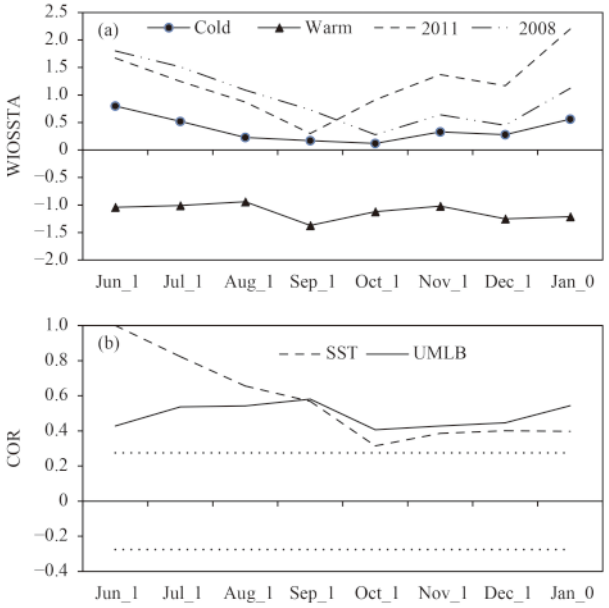

Fig. 5. (a) Composite monthly evolution of normalized WIOSSTAs from the leading June to the following January for the typical events. (b) Correlation coefficients between monthly WIOSSTAs and subsequent January UMLB index values (solid line) and leading June WIOSSTAs (dashed line). The dotted lines are values with the confidence level exceeding 95%.

circulation pattern usually exists during all anomalous temperature events in China, and the most apparent features in the tropical oceans are the SSTAs in the WIO. Therefore, a question arises—Is there any relationship between January UMLB and the leading summer WIOSSTAs?

4.1 *Relationship between January circulation patterns and the leading summer WIOSSTAs*

The correlation coefficients between monthly WIOSSTAs and the following January UMLB indices are significant (see Fig. 5b). Furthermore, those between the WIOSSTAs in the leading June and the monthly WIOSSTAs from the leading June to the following January are also high, suggesting that the leading June WIOSSTAs can persist to the following January. The results confirm a close relationship between the leading summer WIOSSTAs and the following January ones.

To evaluate the role of the WIOSSTAs in generating the UMLB circulation, we also examine the regression/correlation coefficients of/between the monthly WIOSSTAs from the leading June to the following January on/and following-January 500-hPa streamfunction (see Figs. 6a–h). The patterns over the Atlantic to the Eurasian continent are similar to the teleconnection patterns for the cold JSTA events as shown in Fig. 2, with the positive center over the Ural Mountains and the negative one to the south. The correlation pattern is clearly prominent from the leading summer to the following winter. This indicates that the leading WIOSSTAs bear a close relationship with the following January UMLB-like circulation, and the relationship is most reliable from the leading June to September. In Figs. 6i–p, it is apparent that the regression/correlation coefficients between the January UMLB index values and the monthly SSTAs from the leading June to the following January are also very prominent in the WIO during the leading summer. This means that there is likely some linkage between the following January UMLB-like circulation pattern and the variation of the WIOSSTAs in the leading summer. We also regress the January sea level pressure, wind vectors at 850 hPa, and streamfunction at 500 hPa onto the leading summer WIOSSTAs and January UMLB index, respectively (see Fig. 7), to detect the possible variation produced by the WIOSSTAs. The patterns regressed on the WIOSSTAs are like those on UMLB, which are favorable for strong UMLB-like circulation anomalies and may result in extreme temperature events in January over China.

In most years, the WIOSSTAs are closely correlated with the UMLB index values, in which the points in summer of 2007 and 2010 are near the diagonal line, suggesting that the WIOSSTAs in the leading summer can reasonably account for the variation of the UMLB index values in the January of both 2008 and 2011 (figure omitted). Actually, the interannual variations of the WIOSSTAs and the UMLB index values have similar tendencies, with a correlation coefficient of 0.53 beyond the 95% confidence level. When the WIOSSTA is positive, the UMLB tends to increase, apart from in 1995 and 2005 only.

To further examine the influence of the WIOSSTAs and UMLB-like circulation on January surface air temperature in China, we also regress the January temperature field onto the UMLB and WIOSSTA (figure omitted) indices separately. We find that the regression coefficients in most parts of China are significantly negative, especially in the Hetao Plain area to southern China. This indicates that the UMLB and WIOSSTA indices are closely related to the JSTA events in China. However, apparent differences are located in northeastern China. The map regressed on the WIOSSTA index has remarkable positive values in northeastern China, whereas the map regressed on the UMLB index shows no relevance in northeastern China. The results are consistent with the fact that different NAO phases in 2008 and 2011 are responsible for the different January temperature anomalies in northeastern China.

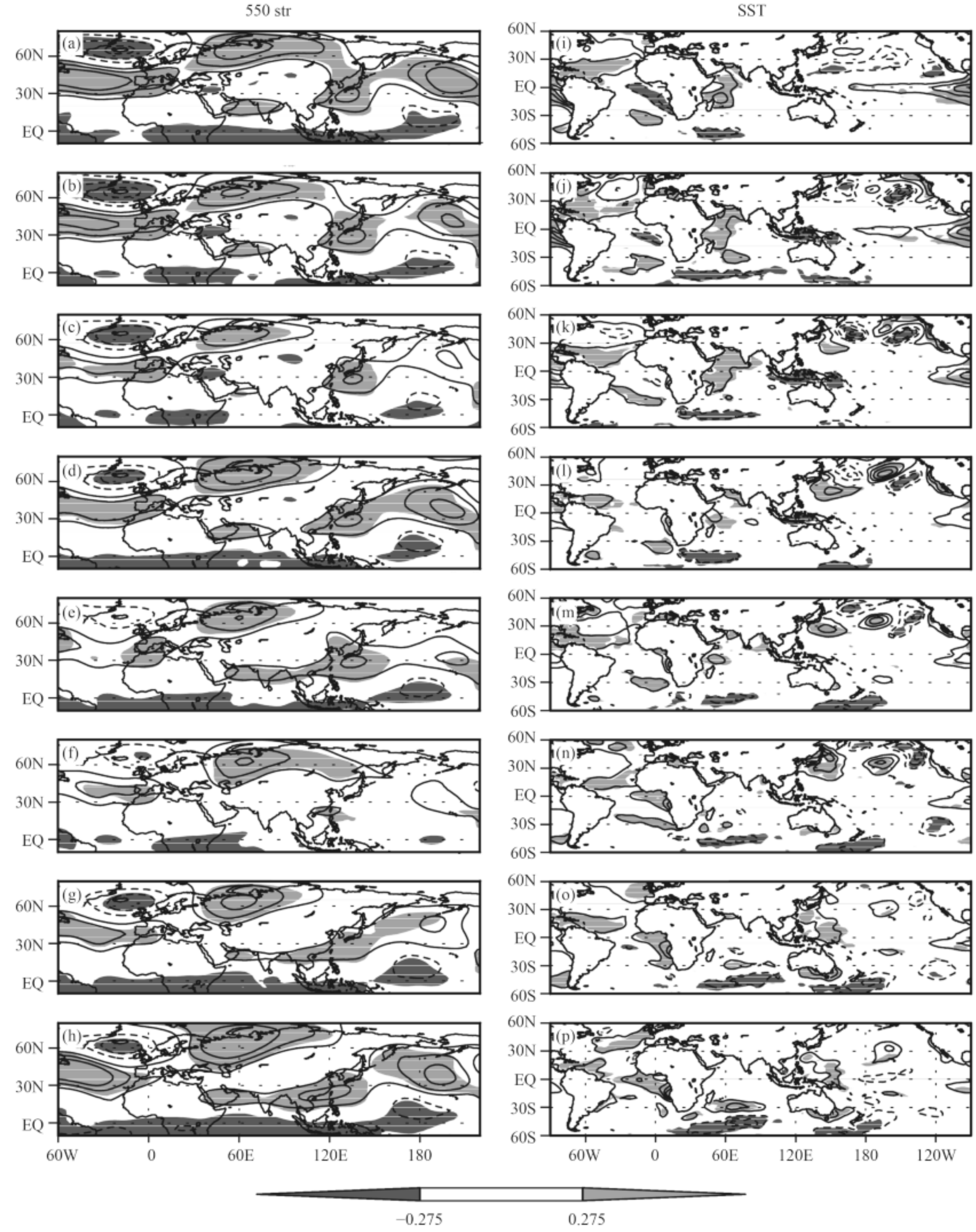

Fig. 6. The regression/correlation coefficients (contours/shaded) of/between the January streamfunction at 500 hPa on/and the WIOSSTA index values from the leading June to January [panels (a–h)], and those of/between the January UMLB index values on/and the SSTAs from the leading June to the following January [panels (i–p)]. The contour intervals in (a–h) and (i–p) are 1×10^6 m^2 s^{-1} and 0.2°C, respectively, with the zero line omitted. Areas with the confidence level exceeding 95% are shaded.

4.2 *Possible mechanisms*

To understand the mechanisms of influence of the summer WIOSSTAs on the following-January UMLB, we first present the monthly regression/correlation coefficients of the velocity potential (from the leading July to the following January) and following-January UMLB indices (Figs. 8a–h), along with the monthly contemporaneous regression/correlation with the WIOSSTAs (Figs. 8i–p). From Fig. 8, we can see that the January UMLB index values are notably correlated with the velocity potential anomalies in the WIO, especially from the leading June to September. Furthermore, the monthly con-

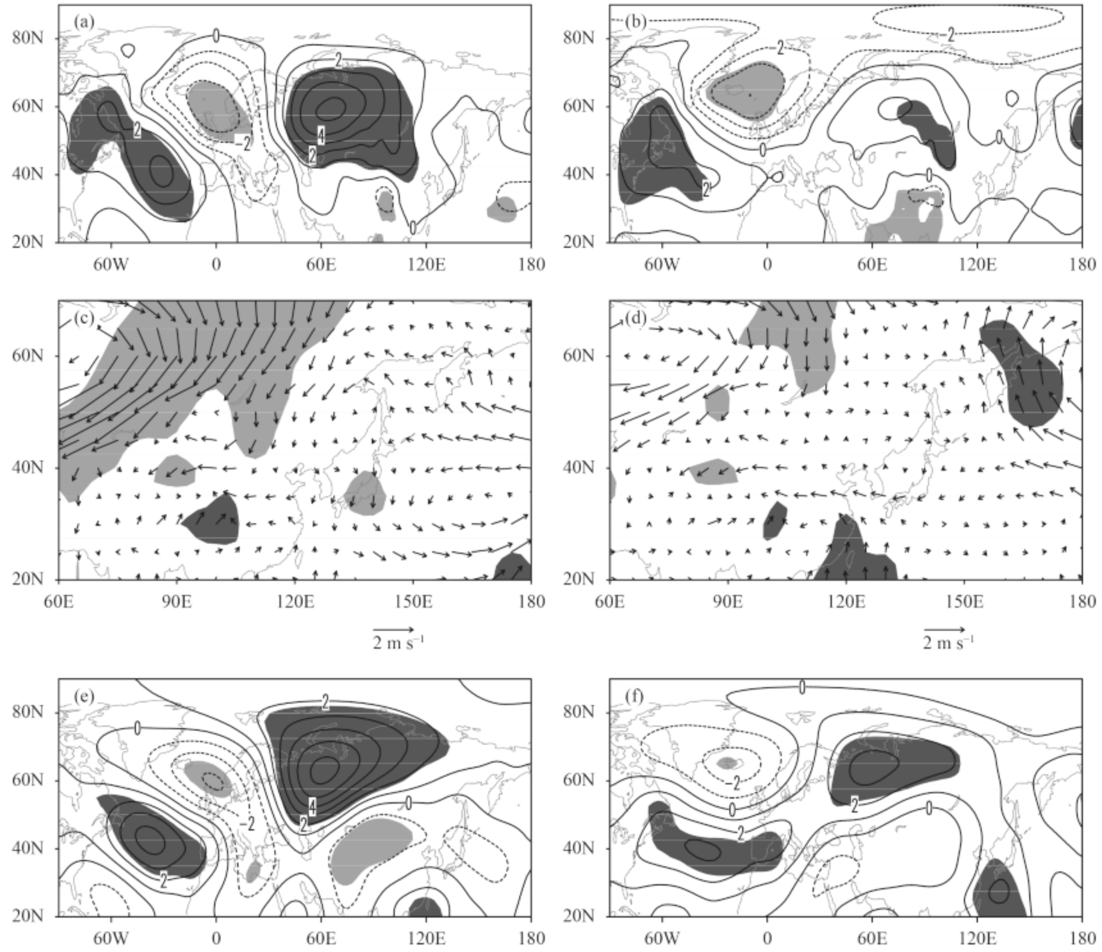

Fig. 7. Regressed January circulation anomalies on UMLB and the leading summer WIOSSTA index values. Related significant coefficient areas with the confidence level exceeding 95% are shaded. Panels (a), (c), and (e) are for the sea level pressure (hPa), 850-hPa winds (m s^{-1}), and 500-hPa streamfunction (10^6 m^2 s^{-1}) on UMLB. Panels (b), (d), and (f) are the same as (a), (c) and (d), but for the WIOSSTAs (°C).

temporaneous correlation coefficients are all significant in the WIO. At 850 hPa, they both have positive regression/correlation coefficients over the WIO and negative regression/coefficients in the tropical Pacific (Fig. 8), but opposite ones at the upper 200 hPa. This suggests that the WIOSSTAs may induce velocity potential anomalies over the WIO from the low to high levels, which act as tropical forcing. The local anomalies may stay significant from the leading August to the following January at low levels. Through such tropical forcing, the UMLB-like circulation pattern can be induced, like a Rossby wave response to tropical heating (Hoskins and Karoly, 1981; Wang et al., 2007).

To test the hypothesis influence of the summer WIOSSTAs on the UMLB-like circulation in the following January, numerical experiments are conducted by prescribing positive SSTAs in the WIO (see Fig. 9) during the summer season. This idealized SSTA pattern is similar to the pattern of the composite analysis in Fig. 4, with uniform anomalies of 0.5°C in the area shaded in Fig. 9.

To compare the results from the model and observations, we also show the monthly 500-hPa heights (from the leading July to the following January) regressed on the leading-July WIOSSTA index values (see Fig. 10). The height fields from the model are obtained by subtracting the results of the control experiments from the positive WIOSSTA experiments. Although in July the model pattern does not look like the regressed, they become increasingly similar from November to January, especially over the Ural Mountains and Lake Baikal area. The results from the model confirm that summer WIOSSTAs can induce the UMLB circulation anomaly pattern through Rossby wave propagation. Also, the signal can stay from the leading June to the following January.

Under the warm forcing in the WIO in Fig. 10n, the observed UMLB-like circulation anomalies in Figs. 2

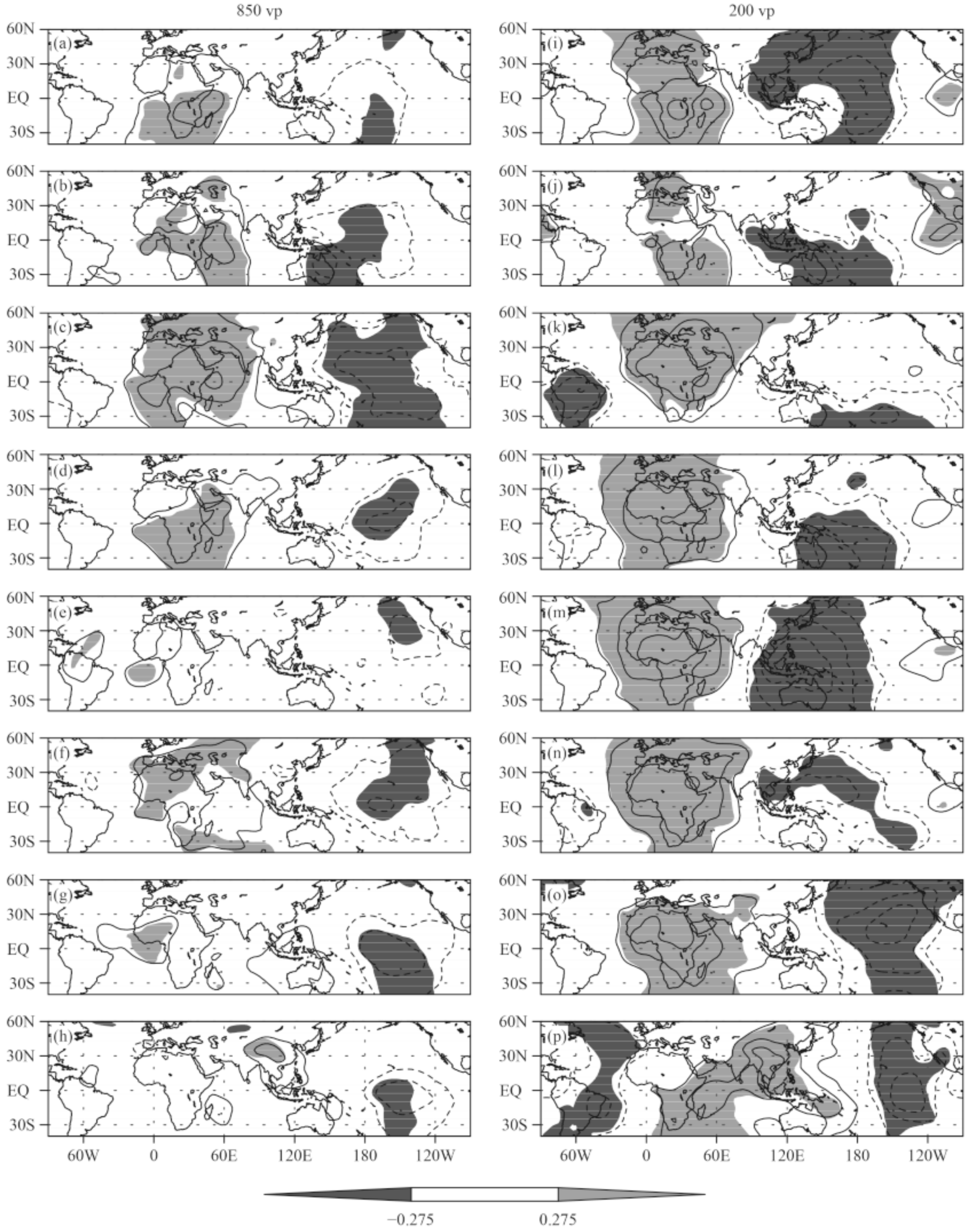

Fig. 8. Monthly regression coefficients (0.2×10^6 m^2 s^{-1}) of velocity potential at 850 hPa from the leading June to the following January [panels (a–h)] on following-January UMLB, and contemporaneous WIOSSTA index values [panels (i–p)]. Shaded areas denote the significance of the corresponding correlation coefficients with the confidence level exceeding 95%.

and 6b are captured well by the simulations. The warm WIOSSTAs in summer can cause the UMLB anomalies in the following January, which means that the Siberian high is stronger than normal. The consistent results between the observations and simulation indicate that the leading-summer WIO warming is actually associated with the UMLB-like circulation in the following January, which eventually results in cold events over China.

5. Conclusions

Based on the possible mechanisms of typical episodes that have occurred in the past 30 years, the anomalously lower temperature over China in January 2008 and 2011

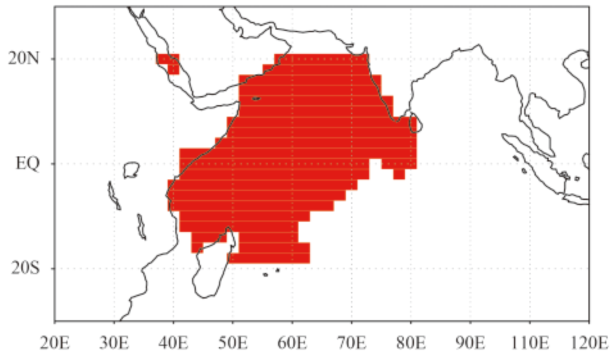

Fig. 9. Model domain for the WIOSSTAs with an amplitude of 0.5°C (shaded) in the numerical experiment.

are compared to detect the main causes and lead precursors of such extreme events. The main conclusions can be summarized as follows:

(1) The anomaly patterns coincided with colder-than-normal air temperature in most parts of China in January 2008 and 2011. However, the surface air temperature in northeastern China was negative in January 2011 and positive in January 2008.

(2) Favorable atmospheric conditions for low-temperature events in China were the UMLB-like anomalous circulation with a stronger Siberian high since 1979. The UMLB-like circulation appeared in all episodes and was an important climate system directly associated with cold/warm events in January over China. However, a positive NAO phase appeared in January for all episodes, including 2008, and a negative NAO appeared in January 2011.

(3) Further examination shows that both the NAO and UMLB-like circulation anomalies are associated with lower temperature in China, except in the Tibetan Plateau area. However, a positive/negative NAO phase usually leads to significantly higher/lower temperatures in

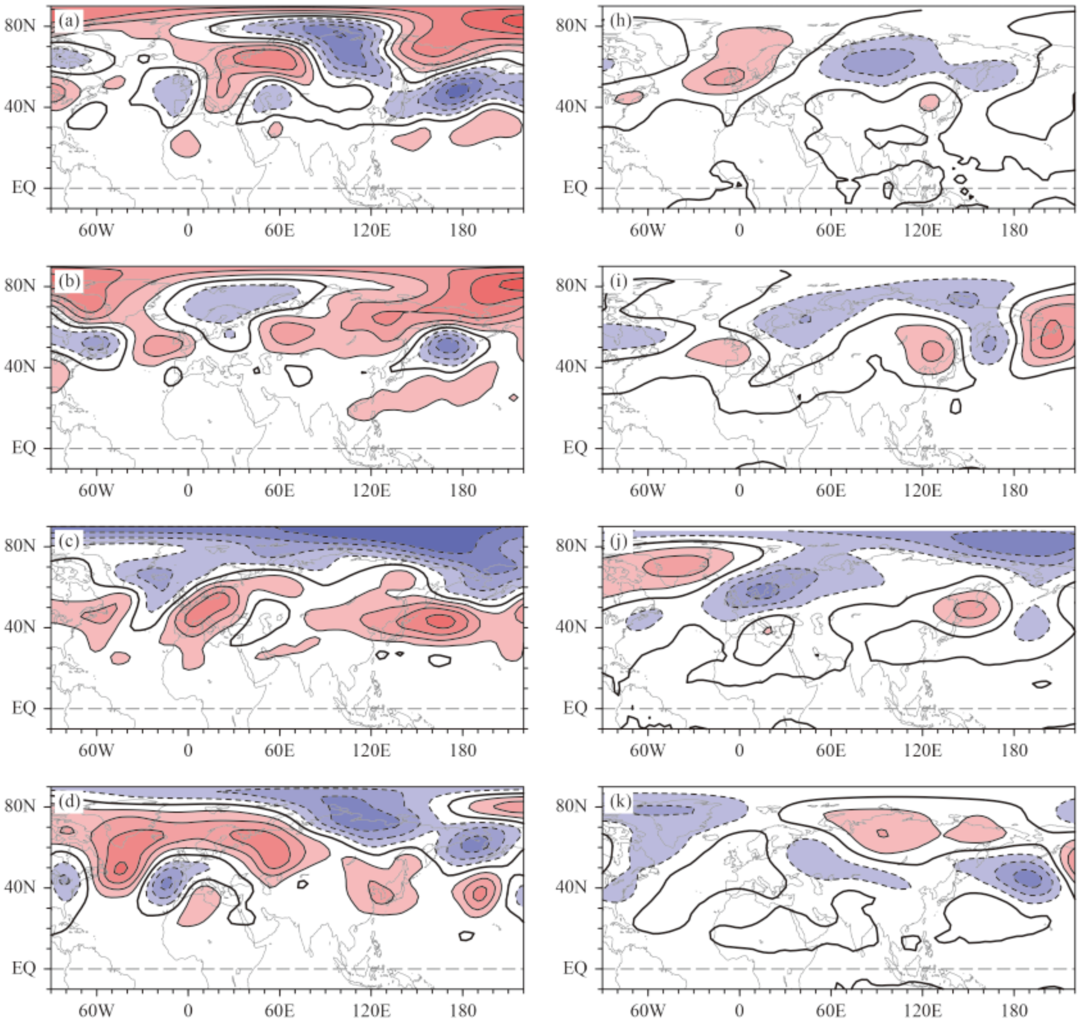

Fig. 10. (a–g) Monthly regression coefficients (gpm) of geopotential heights at 500 hPa on leading-July WIOSSTA index values, and (h–n) monthly 500-hPa geopotential height anomalies of model experiments, from the leading July to the following January.

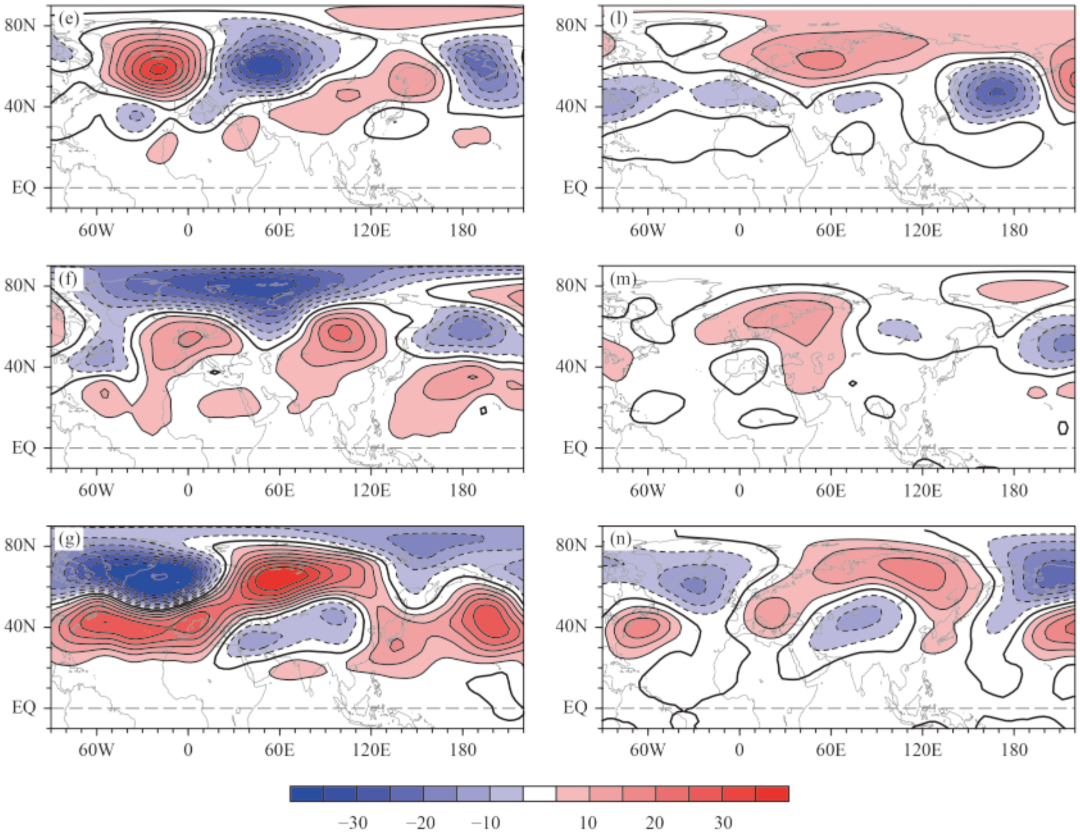

Fig. 10. (Continued.)

northeastern China, which may be responsible for the warmer northeastern China in January 2008 than in January 2011.

(4) Leading-summer SSTAs in the WIO are closely related to the UMLB-like circulation in the following January. Positive WIOSSTAs occurred in the leading summer for all anomalous cold events, including 2008 and 2011, which favored a strong UMLB-like circulation anomaly pattern in the following January and may result in extreme cold events in China. The WIOSSTA signal appearing in the leading summer may be a precursor of following-January UMLB-like teleconnections and associated JSTA events in China. Numerical experiments confirmed the observed relationship.

In this paper, we only examined the possible relationship between the WIOSSTAs in the leading summer and the temperature in the following January in China through the UMLB-like circulation pattern. An open question needing further study is how the SST warming in the WIO influences following-January temperature anomalies in China. Remarkable velocity potential anomalies occurring over the WIO imply that the WIOSSTAs as forcing is strong enough to induce Rossby wave, and the wave may influence the mid–high latitude circulation by atmospheric response there to the the remote tropical forcing. We hope to provide an explanation of the mechanism involved in the future.

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