Roles of Anomalous Tibetan Plateau Warming on the Severe 2008 Winter Storm in Central-Southern China

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ABSTRACT

Anomalous warming occurred over the Tibetan Plateau (TP) before and during the disastrous freezing rain and heavy snow hitting central and southern China in January 2008. The relationship between the TP warming and this extreme event is investigated with an atmospheric general circulation model. Two perpetual runs were performed. One is forced by the climatological mean sea surface temperatures in January as a control run; and the other has the same model setting as the control run except with an anomalous warming over the TP that mimics the observed temperature anomaly. The numerical results demonstrate that the TP warming induces favorable circulation conditions for the occurrence of this extreme event, which include the deepened lower-level South Asian trough, the enhanced lower-level southwesterly moisture transport in central-southern China, the lower-level cyclonic shear in the southerly flow over southeastern China, and the intensified Middle East jet stream in the middle and upper troposphere. Moreover, the anomalous TP warming results in a remarkable cold anomaly near the surface and a warm anomaly aloft over central China, forming a stable stratified inversion layer that favors the formation of the persistent freezing rain. The possible physical linkages between the TP warming and the relevant resultant circulation anomalies are proposed. The potential reason of the anomalous TP warming during the 2007–08 winter is also discussed.

1. Introduction

During 10 January to 2 February 2008 severe freezing rain and heavy snow hit central and southern China, and caused tremendous damage including loss of life, property damages, many breakdowns of transportation, and widespread power outages. The total damage reaches more than $22 billion [U.S. dollars (USD); more information is available online at http://www.gov.cn/jrzg/2008-04/22/content_951622.htm]. Understanding the causes of the extreme event is an important issue in the meteorological community.

Several studies have analyzed the favorable backgrounds and anomalous conditions, which may contribute to or relate to the disastrous event. First, many aspects of the atmospheric circulation anomalies have been noticed to be closely linked with the winter storm, including the unusual persistence of the Ural blocking high, the westward extension and northward shift of the western North Pacific subtropical high (WNPSH), the enhancement of the South Asian trough, and the formation of an

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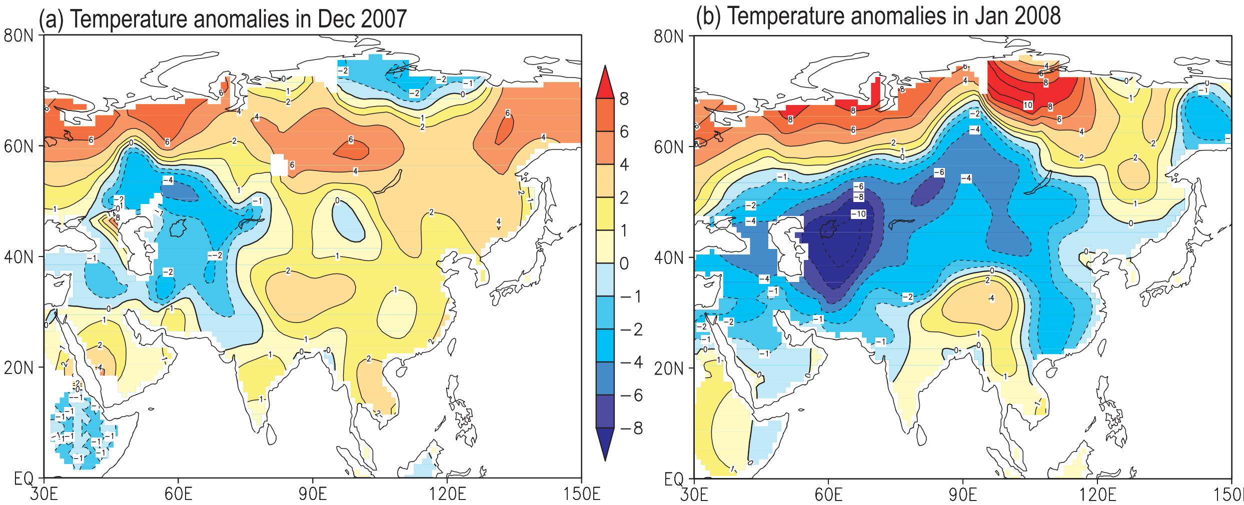

FIG. 1. Surface temperature anomalies in (a) December 2007 and (b) January 2008, after removing the climatology mean during the period from 1971 to 2000, derived from the station data in the Beijing Climate Center. The temperature dataset outside China is originated from the surface monthly climatic data (see online at http://weather.unisys.com/wxp/Appendices/Formats/CLIMAT.html) via the Global Telecommunications System (GTS).

inversion layer over central-southern China.[1] Second, the intensification and southeastward shift of the Middle East jet stream (MEJS) are considered to favor the intrusions of cold weather systems into East Asia (EA) and to deepen the South Asian trough during January 2008 (Wen et al. 2009). In addition, the downward propagation of the stratospheric polar vortex in the North Hemisphere was also considered as a possible contributor to the extreme 2008 winter storm (Gu et al. 2008).

The major boundary forcing of this extreme event has been attributed to the strong La Niña event of 2007–08 during this winter. The numerical experiments show that a strong La Niña can lead to a cold anomaly in southern China through deepening the South Asian trough and enhancing the cold Mongolia high (Fu et al. 2008). However, Gao (2009) argued that the anomalous circulation in the high latitudes may be thought as a major cause of this event rather than the La Niña event.

The thermal condition over the Tibetan Plateau (TP) is another potentially important boundary forcing that has been shown to have a close relationship with the variation of EA climate (Yeh et al. 1957; Ye and Gao 1979; Wu and Zhang 1998; Yanai et al. 1992; Ueda and Yasunari 1998; Hsu and Liu 2003; Zhang et al. 2004). The TP can store some preceding atmospheric signals through soil moisture, ice, and snow cover (Yeh et al. 1984; Wu et al. 1996; Koster et al. 2004; Hall 2004). For the summer monsoon, Ose (1996) has shown that snow cover anomalies over the Tibetan Plateau region have larger effects on the interannual variability of the monsoon than the snow cover anomalies over Eastern Europe or over Siberia. Chen and Wu (2000) and Wu and Qian (2003) both show that there is a positive correlation between the Tibetan winter snow and the subsequent summer precipitation along the EA subtropical front. Recent works of Wang et al. (2008) and Bao et al. (2008), based on a hierarchical GCMs, found that the TP warming is one of the most important reasons for the change in EA precipitation during the summer season. However, for the winter monsoon, most previous studies focus on the TP's mechanical effects (e.g., Manabe and Terpstra 1974; Yanai and Wu 2006). There are few studies about the TP's thermal effects on the Asian winter monsoon.

It is noticeable that nearly 4°C surface air temperature anomalies appeared over the TP surface starting from December 2007 (Fig. 1a) and became enhanced in January 2008 (Fig. 1b). The warming signals are also consistent with the results detected from the decreased snow cover. Wen et al. (2009) showed that the number of snow cover days is below normal over central and southern parts of the TP. How and to what extent the warming of the TP contributes to the extreme winter storm in its downstream region can now be investigated.

The aim of this paper is to investigate the possible impacts of the TP surface warming on the persistent China 2008 winter weather using an atmospheric general circulation model (AGCM). The datasets used in this study are documented in section 2. Section 3 introduces the AGCM and the experiment design, and section 4 describes the relevant numerical results. The possible

[1] Data from the regular operational Weather Consulting in the China Meteorological Administration.

physical interpretations are presented in section 5, and the last section gives conclusions and a discussion.

2. Datasets

The in situ observational air temperature datasets are obtained from the Beijing Climate Center, which covered more than 700 stations in China in December 2007 and January 2008. Particularly, there are more than 100 stations over the TP region so that the exhibited anomalies over the TP in Fig. 1 are considered reliable. The other set of the observed rainfall data is retrieved from the precipitation data reconstructed over land with the grids of 0.5° × 0.5° (hereafter PREC/L; Chen et al. 2002), which could demonstrate the precipitation field anomaly over the entire large-scale EA domain. The circulation and temperature datasets in the upper and lower troposphere are derived from the reanalysis at the European Centre for Medium-Range Weather Forecasts (ECMWF; Uppala et al. 2005), which have been regridded on the AGCM's resolution.

3. Model and experimental design

The model used in this study is the standard version 6.02 of the ECHAM4 (Roeckner et al. 1996), which is a spectral transform model with 19 atmospheric layers extending from the surface to 10 hPa, and the results used here are derived from experiments performed with a spatial resolution of T42 (which approximates to about 2.8° latitude–longitude resolution). The referenced time increment of integration in the current version of ECHAM4 T42 is 24 min, but in this study, we used 15 min to make the integration more stable. The land surface processes are described by a modified "bucket" model with an improved parameterization of rainfall–runoff (Dumenil and Todini 1992). The background albedo used in ECHAM3 has been updated by a new dataset (Claussen et al. 1994). The albedo of a snow and ice surface is a function of temperature and fractional forest area over land, while an albedo of 0.07 is assumed for all water surfaces. The radiation scheme is from the ECMWF model with some improvements, including the consideration of additional greenhouse gases [e.g., methane, nitrous oxide, and 16 chlorofluorocarbons (CFCs)], ozone, and various types of aerosols. The model can reproduce the realistic seasonal mean climate with a remarkable skill (Roeckner et al. 1996). Many previous studies have used this model to study the East Asian monsoon (Fu et al. 2002; Cherchi and Navarra 2003, 2007), it was shown that ECHAM4 has the ability to capture major features of the East Asian monsoon. The January climatology of the 850-mb winds and surface temperature in the control run is consistent with the observations (Fig. 2). The model faithfully reproduces the easterly of the winter monsoon over the northern Indian Ocean and the Asian continental anticyclonic circulation to the northern of the TP, as well as the associated lower air temperature and the large temperature gradient over East Asia. Over the TP, the simulated regions with the surface air temperature lower than 240 K are also generally consistent with the observations.

We made two suits of the numerical experiments with ECHAM4 to test the thermal impacts of the TP warming on the downstream circulation and rainfall anomalies during the winter. The control run is forced by the climatological mean sea surface temperatures of January from the Program for Climate Model Diagnosis and Intercomparison (PCMDI; more information is available online at http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS_OBS/amip2_bcs.htm), which were the average from 1978 to 1995 (hereafter the CTRL run); and the sensitive test is run under the same SST but with a reduced surface albedo (multiplying by 0.7 to match quasi-realistic warming amplitude, hereafter the TP_W run) over the TP regions (27.5°–37.5°N, 75°–104°E) to represent the anomalous warming of the TP. Both of them are perpetually runs via fixing the solar zenith angle in January, so that we can easily produce more ensemble members to reduce stochastic bias. Each experiment is integrated for 4 yr, and the first 12 months are regarded as the spinup process. The mean of the last 36 months in each experiment are taken as the numerical results for analysis in this study.

4. Numerical results

The differences of the surface air temperature and the rainfall between the TP_W run and the CTRL run are shown in Figs. 3 and 4, respectively. Consistent with the observational datasets, the significant warming occurs over the TP after reducing the TP surface albedo in the model, and notable cold anomalies appear over the region to the north of the Tibetan Plateau and the Iranian Plateau as well as over central-southern China, which are quite consistent with the observed temperature anomaly pattern (Fig. 1b). There are areas of increased rainfall along the EA subtropical front (the middle and lower reach of Yangtze River basin and the southern region of the Japan) under the TP warming condition (Fig. 4a), which is coherent with that derived from the PREC/L datasets (Fig. 4b). Moreover, the observed positive rainfall anomaly over the northern TP revealed in the in situ ground measurement (figure not shown), is also well reproduced in the case of the TP warming.

The lower-level wind anomalies (hereafter the differences between TP_W and CTRL) are shown in Fig. 5.

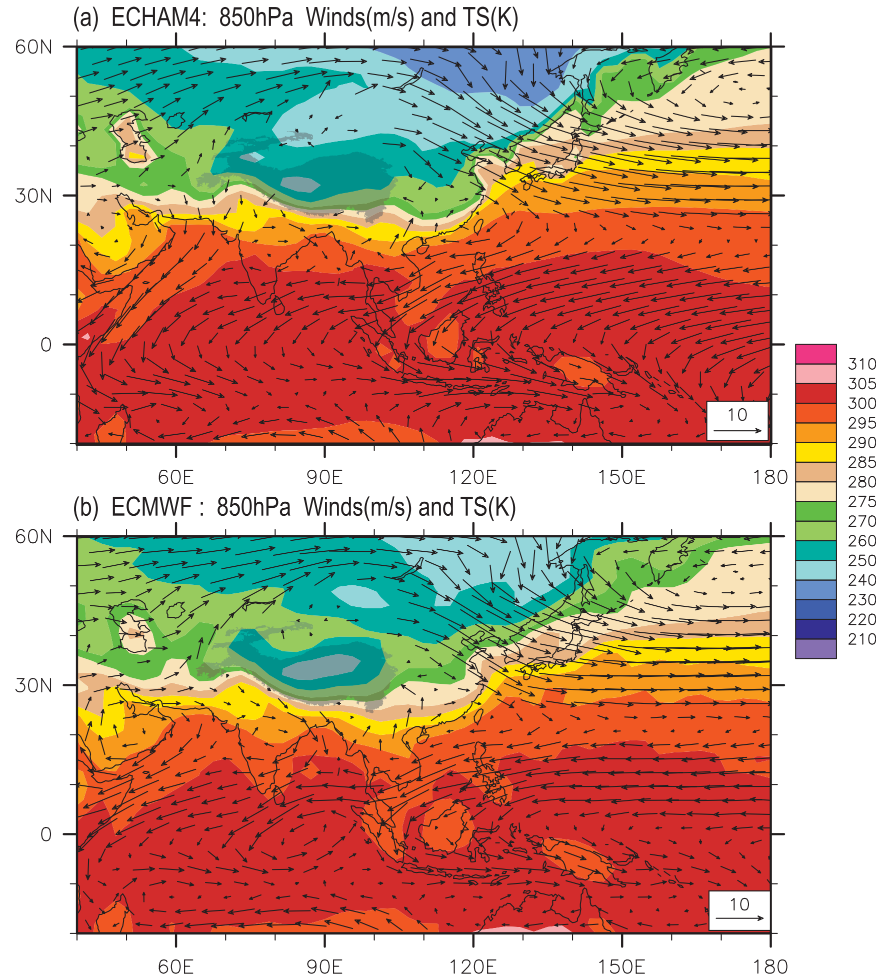

FIG. 2. The climatology of 850-hPa winds [vectors (m s^{-1})] and surface temperature [colored (K)] in January: (a) in the ECHAM4 control run and (b) in the ECMWF reanalysis. The gray shaded regions denote the TP areas with elevations over 2500 m.

Overall speaking, the warming TP causes a large-scale continental cyclonic anomalous circulation in all lower levels from 925 to 700 hPa (Figs. 5a–c). Consequently, the South Asian trough is deepened because of the occurrence of the cyclonic vorticity to the south of the TP (Figs. 5a–c), which is also an important feature revealed in the ECMWF reanalysis (Figs. 5d–f). Meanwhile, the lower-level southwesterly anomaly prevails over the EA region and enhances the warm and moist air transport toward the EA subtropical front. Over the EA regions the increased warm and moist air encounters the cold and dry northwesterly mean flow (Fig. 2), and strengthens the EA frontal system. At the 850- and 925-hPa levels, the TP warming also results in a cyclonic circulation anomaly downstream of the TP with strong cyclonic shear of the northerly flow over the EA regions (Figs. 5b,c), which has been regarded as one of the crucial reasons for the formation of the heavy snow and freezing rain.

Also, note that over central-southern China, near 30°N between 110° and 120°E, there appears to be an evident northeasterly anomaly at 925 hPa (Figs. 5c,f), which is opposite to the southwesterly anomaly at 700 hPa (Figs. 5a,d). The 925-hPa northeasterly anomaly transports the dry and cold air from the higher latitudes, while the 700-hPa southeasterly anomaly brings the warm and moist air from the lower latitudes, resulting in an inversion layer over this region, which agree well with the observations (Fig. 6). The formation of the inversion layer preconditions the environment and is favorable for the generation of the freezing rainfall seen in the 2008 winter.

The relevant mid- and upper-level wind anomalies are shown in Fig. 7. The simulated zonally elongated cyclonic circulation anomalies (Figs. 7a,b) are centered over central Asia to the northwest tip of the TP, which suggests the observed counterparts (Figs. 7c,d) may be

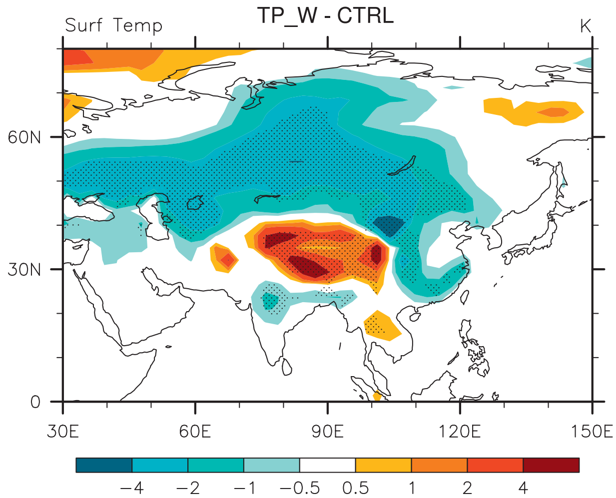

FIG. 3. The difference of surface temperature between the TP warming (TP_W) and control (CTRL) experiments with the ECHAM4 model in January (the dotted regions are at 0.05 significant levels).

induced by the rising temperatures over the TP. Along with the zonally elongated circulation anomalies, the associated MEJS anomaly is strengthened, which has been shown to have a close linkage to this extreme winter storm (Wen et al. 2009).

5. Possible linkage between TP warming and the resultant circulation anomalies

The inversion layer and the lower-level cyclonic shear in the meridional flow are two favorable environmental conditions for the extreme freezing rain occurrence. The opposite wind direction between the boundary layer (below 850 hPa) and the lower free troposphere (near 700 hPa) in southeastern China is the major cause for the inversion layer. The lower-tropospheric southwesterly anomaly is associated with the large-scale continental cyclonic anomaly induced by the rising TP temperatures. The southwesterly anomaly conveys more warm and moist air from the lower latitudes to southeastern China and increases precipitation. As a Rossby wave response to the latent heating released by the enhanced rainfall, a cyclonic anomaly (cyclonic shear in the meridional flow) appears near the surface over southeastern China as shown in Figs. 5b,c. This cyclonic anomaly induces the northeasterly anomalies over central and eastern China at 925 hPa, which increases the input of the dry-cold air from the higher latitudes and cools the surface over central and eastern China (Fig. 6).

On the other hand, the intensified MEJS may result from the rising TP temperatures in the simulation. The intensified MEJS is an important circulation anomaly that accompanied the 2008 winter storm in the observations. Section 4 has shown that the enhanced MEJS is one portion of a zonally elongated anomalous cyclonic circulation on the southern flank of the TP centered over the Aral Sea (Fig. 7a). Why does the TP surface warming result in this upper-tropospheric cyclonic anomaly? Two major factors contribute to its formation. One is the suppression of warm air advection in the low layer (or anomalous negative temperature advection) to the northwest of the TP (Fig. 8), collocated with the anomalous northeasterly. This northeasterly

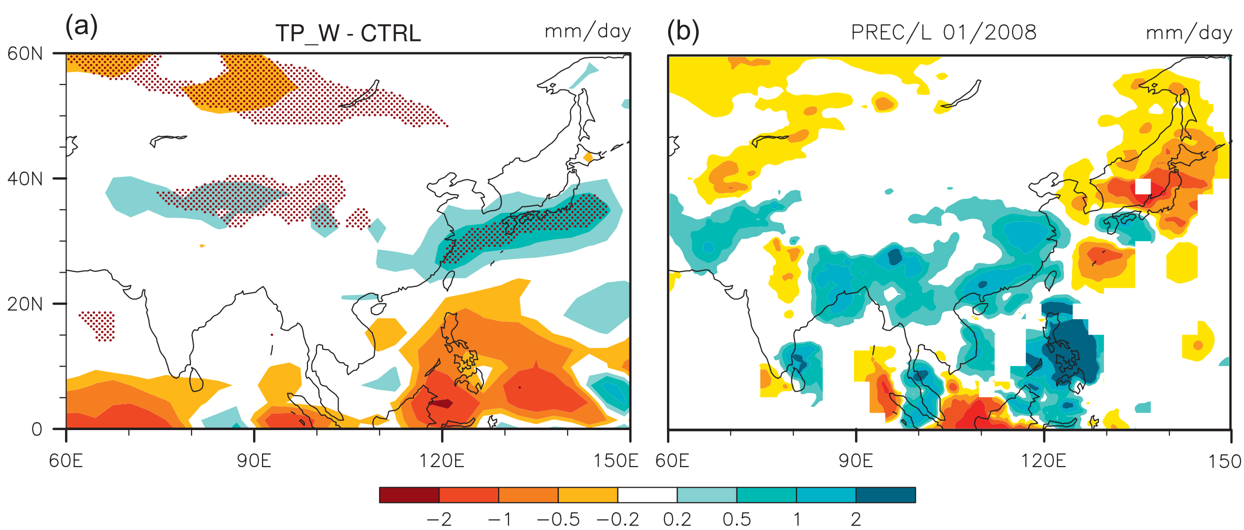

FIG. 4. (a) The difference of precipitation between the TP_W and CTRL experiments in January 2008 (the dotted regions are at 0.05 significant levels), and (b) the precipitation anomaly in January 2008 revealed from PREC/L.

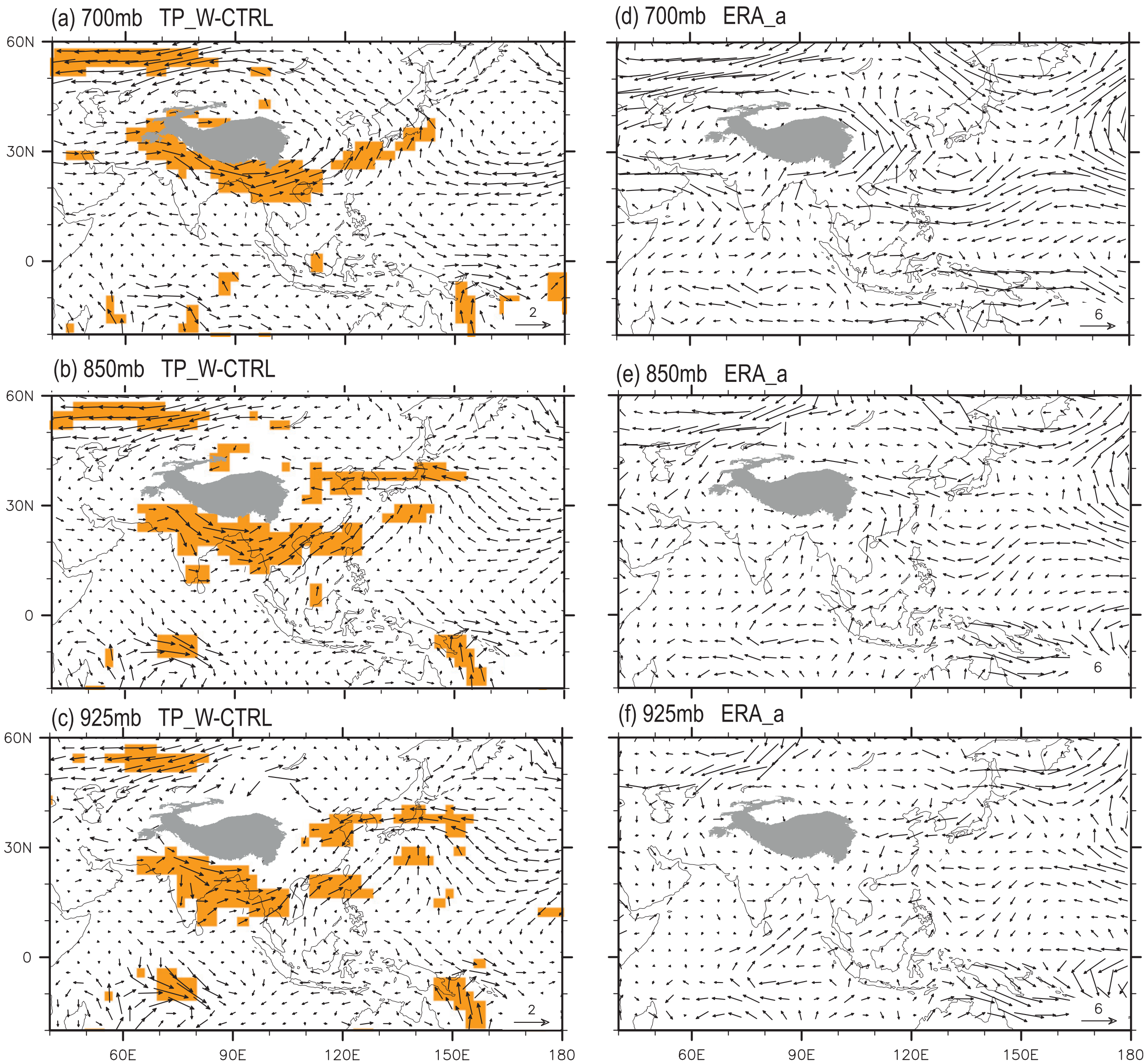

FIG. 5. (left) Mean wind anomalies (m s^{-1}) between the TP_W and CTRL experiments in January (colored cells are significant at 0.05 levels) at the levels of (a) 700, (b) 850, and (c) 920 hPa. (right) The wind anomalies (m s^{-1}) in January derived from ECMWF reanalysis at the levels of (d) 700, (e) 850, and (f) 925 hPa. The gray shadings denote the TP areas with elevations over 2500 m.

anomaly is associated with the lower-level large-scale continental low induced by TP warming (Figs. 5a–c). The anomalous negative temperature accumulates locally to the north of the Tibetan Plateau and the Iranian Plateau, and the resultant cooling anomalies throughout the lower to middle troposphere cause the shrinking of the air column below, reducing the isobaric pressure level in the upper troposphere, and thereby producing the upper-level cyclonic anomalous circulation. The other contributor to the upper-tropospheric cyclonic circulation is the existence of the lower-level cyclonic anomaly with a quasi-barotropic structure in the higher latitudes. This lower-layer cyclonic anomaly is induced by the topographic blocking of the Tibetan Plateau and the Iranian Plateau. Because of the relatively dry condition to the northwestern flank over the TP (Fig. 4), the latent heat release is absent, so that the lower-level cyclonic anomaly has a quasi-barotropic structure on the north of the TP and thus maintains the upper-tropospheric cyclonic circulation anomaly (Smagorinsky 1953). In addition, influenced by the topographic effect of the Tibetan Plateau and the Iranian Plateau, the cooling anomalies and the lower-level cyclonic anomaly get deformed and zonally elongate along

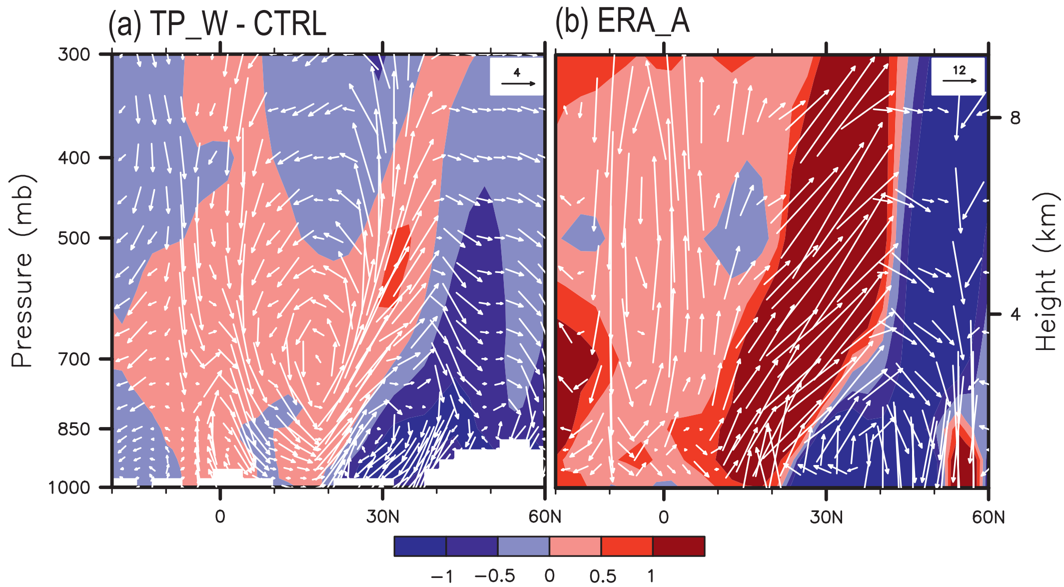

FIG. 6. Latitude–height cross section of temperature (colored) and vertical–meridional wind (vectors) anomalies averaged along 110°–120°E in (a) simulations and (b) observations derived from ECMWF reanalysis.

the northern flanks of the Plateaus (Fig. 8), therefore, both the negative temperature anomaly and the anomalous cyclonic circulation become zonally elongated along the north of the Plateaus.

6. Conclusions and discussion

Based on two groups of January perpetual runs with ECHAM4 AGCM, the roles of the TP warming on 2008

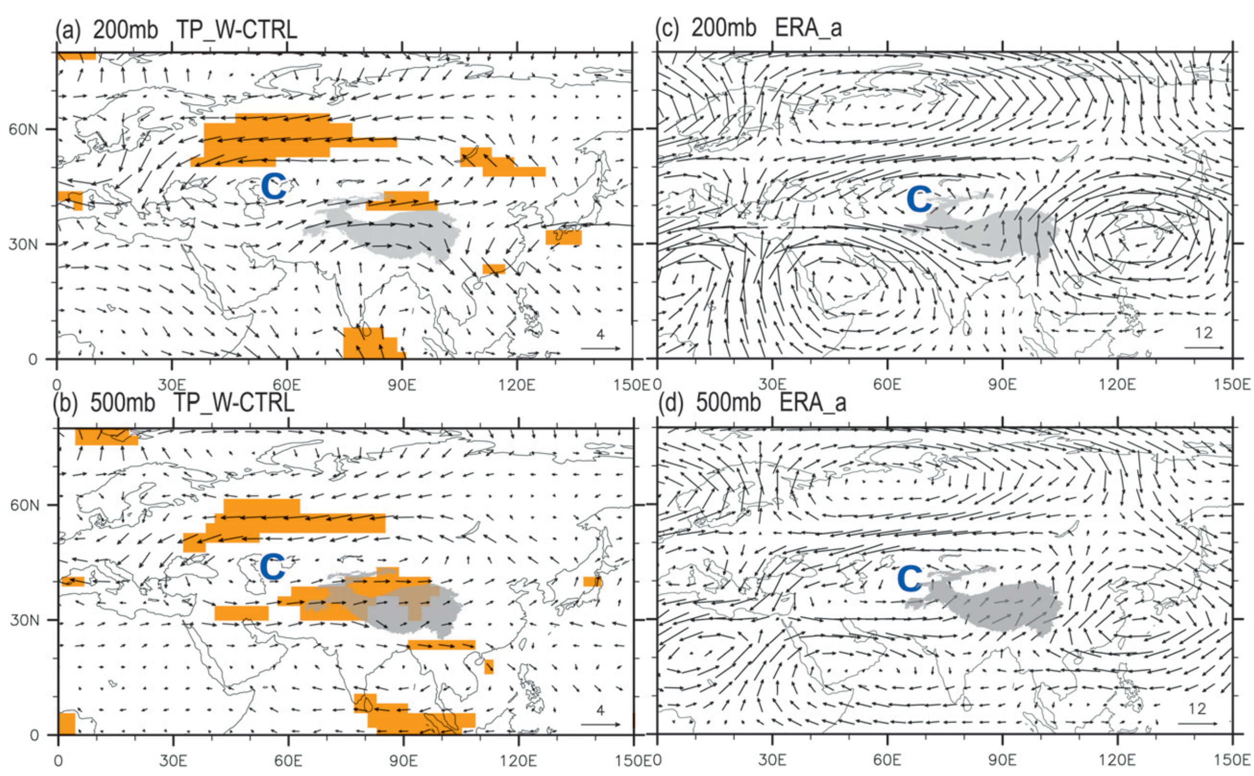

FIG. 7. As in Fig. 5, but for (a),(c) 200- and (b),(d) 500-hPa wind anomalies (m s^{-1}). The letter "C" denotes the cyclonic circulation center.

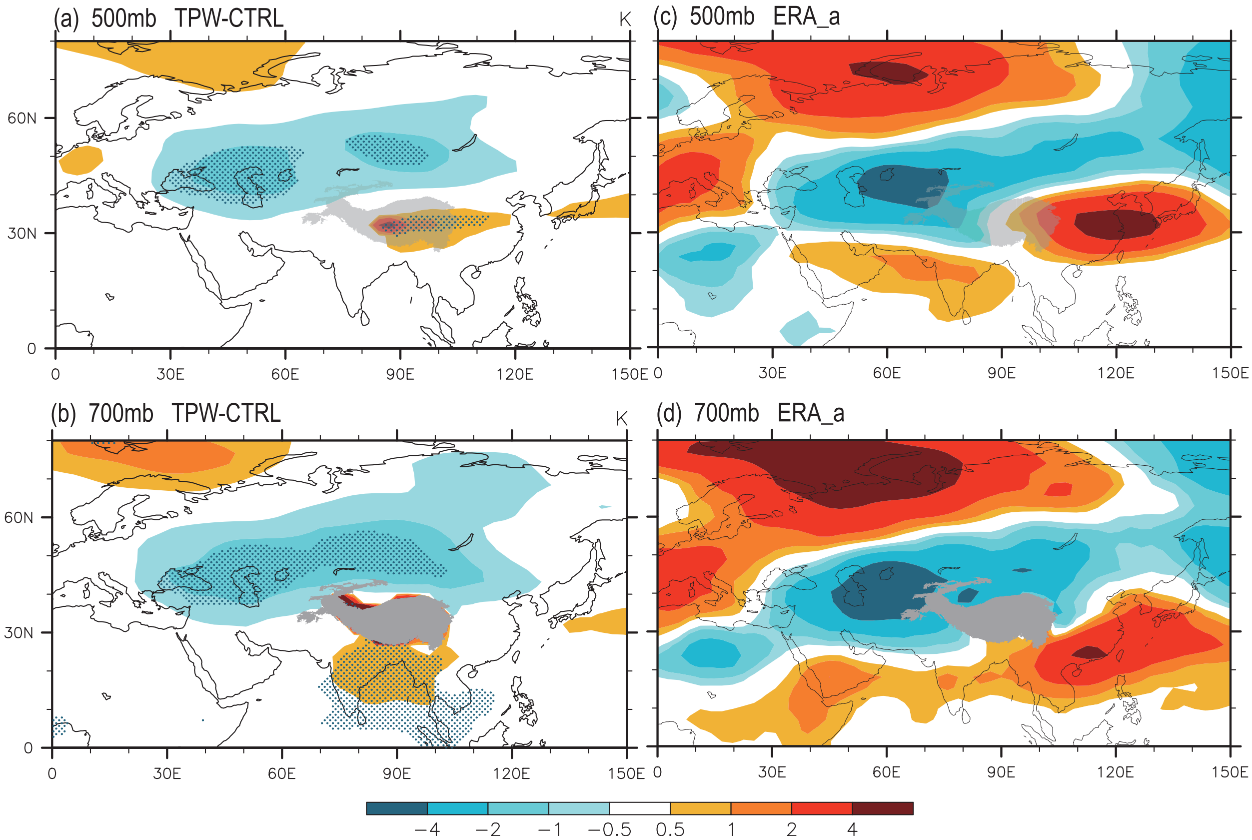

FIG. 8. As in Fig. 7, but for (a) 500- and (b) 700-hPa temperature anomalies (K). (left) Dotted regions are significant at 0.05 levels.

winter storm in China has been investigated in this study. First, compared with the control run, the anomalous cooling and the positive rainfall are well reproduced over central-southeastern China in the TP warming run. According to the circulation differences between with and without the TP warming, five major favorable conditions for this extreme winter storm are associated with the rising TP temperatures, including the deepened South Asian trough, the enhanced lower-level southwesterly anomaly over Southern China, the lower-level cyclonic shear with the southerly flow along the subtropical East Asian front, the inversion layer over central-southeastern China, and the strengthened Middle East jet stream. Both the deepened South Asian trough and the enhanced lower-level southwesterly anomaly are linked to the continental large-scale cyclonic anomaly triggered by the increased surface temperatures over the TP; both the lower-level cyclonic shear with the southerly flow and the inversion layer are the secondary Rossby responses to the enhanced latent heating over southeastern China. All these circulation anomalies induced by the TP warming favor for the formation of the freezing rain and the heavy snow over the central-southern China. The intensified MEJS is associated with the negative temperature advection to the northwestern flank of the TP caused by the rising TP surface temperature and the existence of the lower-level cyclonic anomaly with the quasi-barotropic structure.

However, the anomalies with TP warming in simulation are basically confined to the surrounding and downstream regions of the TP. As such, the anomalies far away from the TP cannot be explained by the TP warming effects. For example, the strong lower-level southeasterly from the tropical western Pacific cannot be seen in the TP warming results, which might be linked to SST anomalies (the La Niña event in 2007–08 winter). In this sense, the TP warming is one of the important contributors to this 2008 winter storm, but not the only one.

During the last 50 yr, only in 2006 is the warming amplitude in the TP surface comparable to the amplitude in January 2008. However, no disastrous snow storm or ice rain occurred in that year. It suggests that the anomalous TP surface warming alone may not guarantee the occurrence of the snow disaster.

What causes the TP warming? We notice that the TP warming signal has appeared early in December 2007, which hints that this TP warming might carry some precursory atmospheric signals and then get enhanced

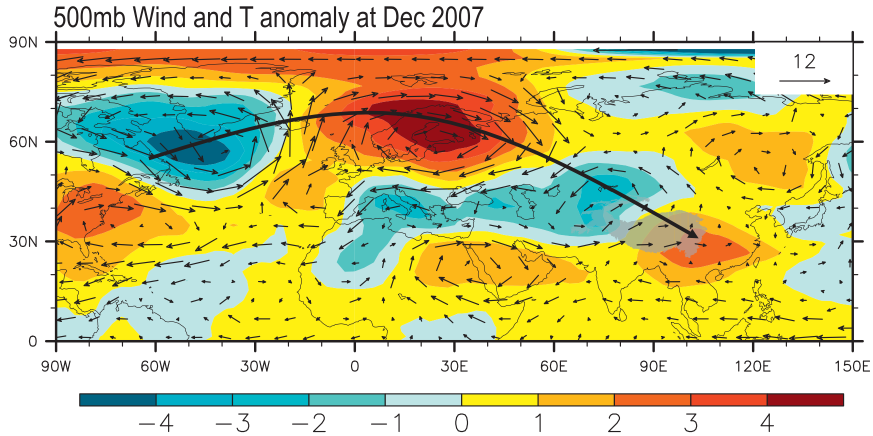

FIG. 9. 500-mb wind and temperature anomalies at December 2007, the black arrow illustrates the teleconnection starting from the northwest Atlantic.

during the following month (January 2008) through the local land–atmosphere interaction. Figure 9 shows the observed wind and temperature anomalies at 500 hPa in December 2007, which exhibit a notable teleconnection pattern starting from the northwestern Atlantic across Scandinavia toward central-southern China. The positive temperature anomalies induced by the teleconnection pattern could contribute to the TP warming in December 2007, and this teleconnection might be linked to the activity of North Atlantic Oscillation (NAO) or Arctic Oscillation (AO; Wallace and Gutzler 1981; Li et al. 2008). It seems that to further understanding of the occurrence of this disastrous weather event, investigations from the global perspective and land–air–sea interaction are required.

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