Analysis on the Long-Lasting Freezing Rain and Snowstorm Event at the Beginning of 2008*

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(Received July 20, 2009)

ABSTRACT

In this paper, main characteristics of the long-lasting freezing rain and snowstorm event in southern China at the beginning of 2008, features of the related atmospheric circulation and the causes thereof are analyzed. During the event, patterns of the atmospheric circulation stayed stable; the polar vortex located in the northern part of the Eastern Hemisphere was strong with little movement; the cold front from the polar region and the active warm air mass from the tropical ocean confronted each other for a long time; the blocking high to the west of Baikal remained strong and steady; the trough over central and western Asia maintained its position for quite long with a group of little troughs splitting from it frequently; the dominant wind at 700 hPa was southwesterly while shears and vortexes at 850 hPa developed continually, providing the necessary low-level convergence for subsequent precipitation. Meanwhile, in the mid troposphere, eddies were generated over the Tibetan Plateau and positive vorticity disturbances in the Sichuan Basin propagated eastward to the coastal regions of eastern China. The western Pacific subtropical high was intensive with westward and northward migrations. The subtropical frontal zone was puissant and the north-south temperature gradient was large. Quasi-stationary fronts over South China and the Yunnan-Guizhou Plateau remained stable. Warm air masses over the tropical ocean were active, so was the trough in the southern branch of the westerlies over the Bay of Bengal. There were four episodes associated with this event. The first one was featured with the interaction of strong cold and warm air, while the other three with the quasi-stationary fronts over South China and the Yunnan-Guizhou Plateau as well as vigorous penetration of cold air from the north. The existence of the inversion layer and the thick melting layer were one of the main reasons for the long-lasting freezing rains. The main reason for the snowstorms was that the positive vorticity over the Sichuan Basin propagated eastward to the coastal regions of eastern China. Abundant water vapor and intense updraft also favored the heavy snows.

Key words: freezing rain and snowstorm, circulation characteristics, cold and warm air, inversion, western Pacific subtropical high

Citation: Yang Guiming, Kong Qi, Mao Dongyan, et al., 2010: Analysis on the long-lasting freezing rain and snowstorm event at the beginning of 2008. *Acta Meteor. Sinica*, **24**(3), 380–396.

1. Introduction

Cryogenic freezing rain and snow refers to the weather event with the highest temperature near surface $\leqslant 1°C$ and the daily average temperature $\leqslant 0°C$, lasting for at least 6 days, and with snow and freezing rain being observed. Freezing rain, also called ice rain or sleet, is a kind of disastrous weather events, which impact greatly on transportation, electric power transmission, communication facilities, agriculture, and people's life. From 10 January to 5 February 2008, a long-time freezing rain and snowstorm event prevailed over a large area of China and led to great economic losses nationwide. The chilly weather and freezing rains across the middle and lower reaches of the Yangtze River and Guizhou Province persisted even longer than that in the winter of 1954/1955, with its duration breaking the historical records (Wang et al., 2008). The disaster, which consisted of 5 respective weather processes during 10–15, 18–22, 25–28 January, 31 January to 2 February, and 4–5 February 2008, resulted in unprecedented damages on transportation, energy supply, electric power transmission, and agriculture in 20 provinces including Hunan, Hubei, An-

*Supported by the National Natural Science Foundation of China under Grant No. 40605019.
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(Chinese version published in Vol. 66, No. 5, 836–849, 2008)

hui, Jiangxi, Guangxi, Guizhou, etc. Guizhou is a place which experiences freezing rains the most in China and a great majority of the cases are related to the Yunnan-Guizhou stationary front.

Generally speaking, frozen weather refers to freezing rain and glaze.Tang (2003) made a comparison between the cases of glaze and light snow, concluding that glaze forecasting should focus on temperature increase at 700 hPa and decrease at 850 hPa. Wang et al. (2006) analyzed the most severe frozen weather that happened in Hunan in 2005, concluding that the disaster results mainly from the low height of an inversion base, warm temperature at inversion lid, and thick super-cooled layer between 1000 and 925 hPa. By analyzing the glaze in the area of Hengshan Mountain of Hunan Province, Zhu et al. (2006) pointed out that this event is closely related to winter temperature and the western Pacific subtropical high. Glaze events tend to occur in cold winter when the subtropical high is weak and eastward, otherwise the situation is completely different. Du et al. (2006) concluded that glazes in Jilin Province often happen in stable synoptic conditions under which the upper-level trough develops into a low vortex and a secondary cold front moves slowly southward so that they bring up the long duration of the glaze. When warm air is strong and cold layer produced by radiation inversion exists near the surface, glaze is usually seen in plains.

Lu et al. (2004) studied the freezing rain seen in the Tianjin Airport, pointing out that the low-level jet, ice crystal layer, melting layer and cold layer between surface and 1–2 km above ground are the characteristic atmospheric vertical structure for the freezing rain. According to historial climate and sounding data, He et al. (2007) studied the stratification characteristics of snow and freezing rain in Guiyang city, Guizhou Province. The results suggest that the freezing rain occurs along with the existence of an inversion layer and a surface temperature lower than 0°C. The wind speed at the mid-and-high level is higher than that when snowing. On a snowy day, the temperature at the mid-and-high level is colder than that during a freezing rain, and surface temperature ranges from –3°C to 3°C. For both freezing rain and snow, the atmosphere remains stable vertically. Ye et al. (2007) summarized the freezing event in Guizhou and concluded that in the year of heavy freezing rains, the height anomaly at 500 hPa is quasi-symmetric in mid-high latitudes, i.e., inside the polar circle is negative anomaly while outside positive. Especially, the pattern of positive in the south and negative in the north is more obvious over Eurasia. In the weak year of freezing rains, the height anomaly at 500 hPa in mid-high latitudes is also quasi-symmetric, but the position of positive and negative centers is opposite to that in heavy freezing rain year, usually with the pattern of negative in the south and positive in the north over Eurasia.

Through the study on mesoscale structure and evolution of precipitation type during freezing rain episodes over southern Ontario, Ronald and Patrick (1987) suggested that rain bands caused by both warm and cold fronts are mainly responsible for the freezing rain during which there is a melting layer in the temperature inversion and a cold layer near the surface. Gerorge and Gene (1988) studied the supper-cooled warm rain process and features of the freezing rain. Their observations show that, compared with the classical melting ice crystal model, about 30% of freezing rains occurs in a sub-freezing atmosphere. These cases can be explained by the concept of super-cooled warm rain process, which yields liquid hydrometeors at sub-freezing temperatures even when there are few ice nuclei. All of the freezing rain cases in a sub-freezing atmosphere show a rapid decrease of moisture content in the zone above the inferred cloud top, at temperatures ranging from 0°C to –10°C. John (2000) summarized the climatic characteristics of freezing rains surrounding the Great Lakes of North America. The spatial and temporal distributions of freezing rain show that most of the events found between December and March the next year are short-lived and last less than 1 h, and only 7% lives longer than 5 h. Besides, these events are associated with extratropical cyclones. They occur in the northeastern section of the cyclone where there is a cold layer with temperature lower than 0°C near the surface and a layer warmer than 0°C at 850 hPa.

Wang et al. (2009) analyzed the characteristics and dynamic causes of the freezing rain and snowstorm event at the beginning of 2008 in southern China and obtained some significant results. Wu et al. (2008) analyzed the possible causes for the same event. The results indicate that this case is associated with La Niña and the persistent anomaly of atmospheric circulation over Eurasia. Under the circulation pattern of a ridge and a trough in the north and south respectively as well as a strong and northward western Pacific subtropical high, cold air intrudes southward from northeast of the Tibetan Plateau. At the same time, warm and moist airflow travels from the Bay of Bengal and South China Sea to the north and northeast. As a result, the cold front and warm air confront frequently in southern China and produce an inversion layer in the mid-and-low troposphere and an anomalous local meridional circulation, which finally contributes to the persistent freezing rain and snowstorm event. By now, many studies on freezing rain have been carried out at home and abroad, but few studies have focused on the duration of associated weather processes. In this paper, the characteristics of the freezing rain and snowstorm event at the beginning of 2008 and causes for its long duration will be discussed.

Datasets used in this paper include: 1) NCEP/NCAR reanalysis four times daily data from January to February 2008, with a resolution of $1°\times1°$; 2) NCEP/NCAR reanalysis daily average data from January to February of 2008, with a resolution of $2.5°\times2.5°$; 3) as 2) but for January and February 1985–1996; 4) surface observations at 8 times daily, including 6- and 24-h precipitation, and 5) FY-2C infrared cloud outgoing long-wave radiation (OLR) data in January 2008.

2. Overview and main characteristics

2.1 Overview

Figure 1 shows the total amount of precipitation in China from 10 January to 2 February 2008. More than 10 mm rainfall is seen in the east of the Tibetan Plateau, eastern part of Northwest China, southwest of North China, the southern and western parts of Huanghuai region, Jianghuai region, Jianghan region, the south to the Yangtze River, South China, the Yunnan-Guizhou Plateau, southern and eastern parts of Sichuan, Chongqing, and southwestern parts of Tibet and Xinjiang. Heavy rains, with total precipitation up to 50–250 mm, concentrate in the regions of Jianghuai, eastern Jianghan, south to the Yangtze River, and South China as well as northwestern part of Yunnan Province. Freezing rain appears in Guizhou, Hunan, Jiangxi, northeastern Guangxi and southern Anhui. Guizhou is mainly dominated by freezing rain with a small amount of accumulated rain.

It is found from the precipitation anomaly distribution over China from 10 January to 2 February 2008 (figure omitted) that the rainfall is 50%–90% less than normal in Northeast China, northeastern part of North China, and eastern Inner Mongolia but 1–2 times more

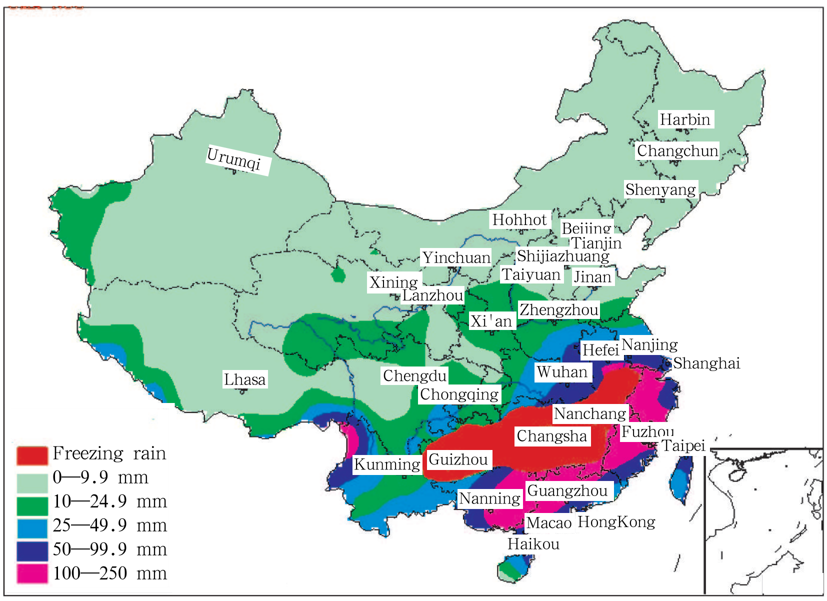

Fig. 1. Total rainfall amount (mm) in China from 10 January to 2 February 2008.

in most other regions, and over 2 times in much of Northwest China, central and southern parts of South China.

The above-mentioned long-lasting disastrous weather event can be divided into five periods/episodes (Wang et al., 2008), i.e., 10–15, 18–22, 25–28 January, 31 January to 2 February, and 4–5 February. The preceding four ones are stronger comparatively, and are to be discussed in detail.

2.2 Main characteristics

2.2.1 Severity of the event

The freezing rain and snowstorm event incurred fairly serious economic losses to China. According to the statistics of Ministry of Civil Affairs, more than 100 million people were affected and the economic losses reached more than 150 billion RMB. The disaster-hit crop areas and the direct economic loss both exceeded those found in the whole year of 2007. Hunan, Jiangxi, Anhui, Guizhou, and some other provinces are the most seriously attacked areas where electric power, traffic and transportation, agriculture, and people's life were impacted or damaged severely (Wang et al., 2008).

All of the observatory stations with only one exemption in Hunan Province were impacted by the severe disaster, and the percentage of the hit area reached 99% of the total area. Over 50% of the stations suffered 17 freezing days while 75% had more than 8 days. On 29 January, 95.9% of the stations were controlled by the frozen weather, which set a new record of the widest freeze-hit area in a single day during the whole process. The counties of Ningxiang, Lengshuijiang, Xiangxiang, Xinning, Shaoyang, Tongtao, and Guiyang were dominated by the freeze for more than 20 days. In addition, the process of glaze in Hunan Province, excluding Hengshan Mountain, existed for 28 days, overliving the longest duration in 1983 (23 days) since 1949, and the glaze at a single observatory station stayed 27 days, exceeding a similar case in 1954 (20 days) since 1949.

Beginning from 12 January, Guizhou Province was hit by strong cold air from the northeast, which led to a sharp drop in temperature and 23-day freezing weather. Ending on 17 February, the western part of the province experienced cold weather for 36 days.

In Jiangxi Province, the freezing rain swamped a large area and went on for 9 days from 24 January to 2 February.

In the north of Guangxi, frozen weather was observed at 226 stations and freezing rain at 110 stations. The longest duration of the frozen weather was 22 days and that of the freezing rain was 21 days.

Regarding the icing on the electric cable caused by freezing rain, the biggest diameter of ice on the cable was found in central, eastern and southeastern parts of Henan where the freezing rain remained a short time, only 33 h from 1400 BT 10 to 2300 BT 11 January, but affecting the mid and southeastern parts of Henan rather seriously. Based on the data collected at 0800 BT 11 January, 20 stations reported the big ice with diameter $d \geqslant 50$ mm seen on the electric cable, among which 6 stations got those with $d \geqslant 100$ mm. Xuchang, one of the six, collected the biggest diameter of 160 mm. Twenty-four hours later, 31 stations reported the big ice with $d \geqslant 50$ mm on the cable, including 12 stations with $d \geqslant 100$ mm and the biggest of 160 mm at Jigongshan station.

In fact, the electric cables in many other regions in southern China got damaged by icing very seriously as well. The ice diameter on the electric cable over Lushan Mountain in Jiangxi Province was 84 mm, and it was 61 mm over the Huangshan Mountain in Anhui Province. The most severe icing on the electric cable was seen in the central and eastern parts of Guizhou, where the ice diameter ranged from 30 to 60 mm in general, and the biggest was 83 mm, found on 29 January at Wanshan station of Tongren region.

Compared with the unusual freezing event which hit the Great Lake area in northern America in January 1998 (John, 2000), the 2008 freezing disaster across southern China is much more severe with respect to its range, intensity, and duration. Such a serious disaster could happen only once every 50 yr in many regions or once every 100 yr, extremely rare in history.

2.2.2 Main features of the weather

The freezing disaster at the beginning of 2008 in southern China is characterized by its large coverage, great intensity, long duration with almost no intermittence between different periods, persistent low temperature near the surface as well as the chilly and sullen weather conditions.

Based on the data received at 965 stations of National Meteorological Center, China Meteorological Administration (CMA), the total station-times of freezing rain can be obtained by calculating the observation times, which is eight times per day at each station from 10 January to 2 February 2008, and adding the numbers together (Fig. 2a). The temporal evolvement of the total daily freezing rain station-times demonstrates four main periods. At the beginning, freezing rain appeared around Zhengzhou of Henan Province during 10–11 January, and then in Guizhou and Hunan on 13 January. Of the four periods, the heaviest freezing rain and snowstorm occurred during the second (18–22 January) and third (25–28 January) periods, when the station-times reached up to 283 on 25 January, which was the day with the largest coverage of freezing rain during the whole event. In Guizhou, Hunan, and Jiangxi, total station-times of the freezing rain from 10 January to 2 February (Fig. 2b) shared the same feature. The peak values of station-times in Guizhou and Hunan emerged separately on 19 and 20 January, while in Jiangxi 27 January was the day with the highest number of more than 100 station-times.

The distribution of freezing rain in the four periods shows the evolution of this event (figure omitted). Firstly, the freezing rain was in a zonal belt and located in the middle of Guizhou, the south of Hunan and the east of Yunnan. Then, it extended rapidly and covered almost all of Hunan and Guizhou. During the third period when the largest area was affected, the freezing rain developed eastward to Jiangxi, southern Anhui, northwestern Zhejiang, and southward to Guilin, a famous city in the northeast of Guangxi. The western portion of the freezing rain belt was east-west oriented but its eastern portion was from northeast to southwest. During the fourth period, the range of freezing rain shrank rapidly, but it had a trend of extending to the east of Yunnan and maintained a clear feature of zonal distribution.

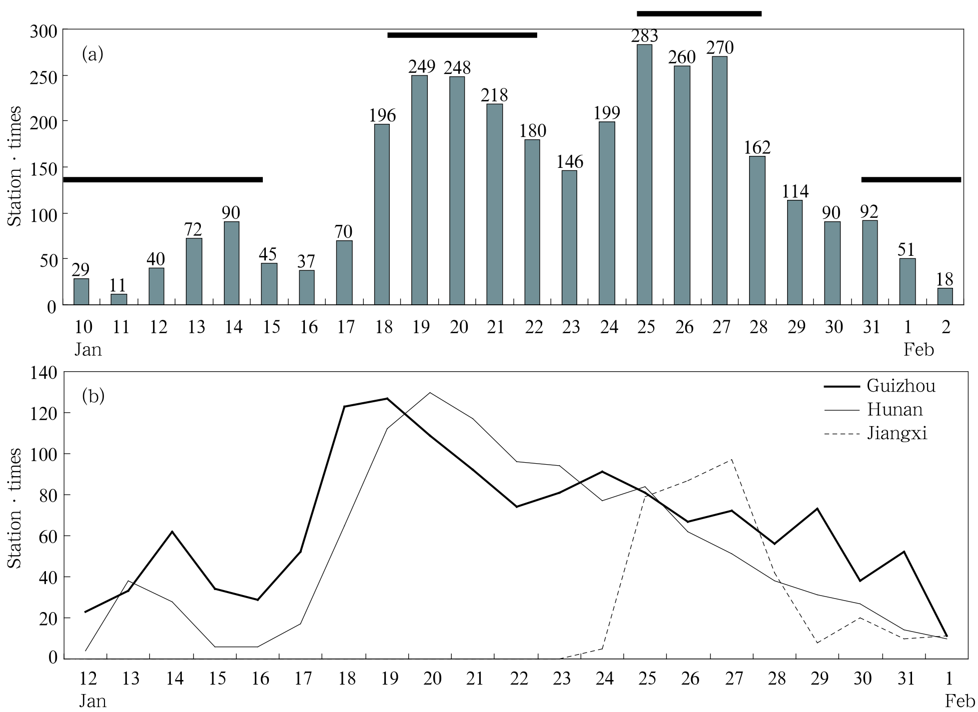

Fig. 2. Total station-times of freezing rain in (a) China and (b) Guizhou, Hunan, and Jiangxi, from 10 January to 2 February 2008. Solid lines in the upper panel mark the four periods.

3 Causes of the freezing rain and snowstorm event

3.1 Characteristics of the atmospheric circulation

3.1.1 Overview

The mean circulation at 500 hPa from 10 January to 2 February 2008 (Fig. 3a) shows that the polar vortex was in a two-wave pattern with the main center in the Eastern Hemisphere, and with the lowest geopotential height of 496 dagpm, 16 dagpm lower than the normal average (Fig. 3b). The axes of the polar vortex extended southward to 55°N, 140°E, forming a sub-center near Okhotsk where the geopotential height was 4 dagpm lower than the normal average. The mean circulation at 500 hPa for each of the four periods (figure omitted) shows that the trough and the vortex in Okhotsk and the area to its north were stable. The strong blocking high to the west of Baikal was stable along with a 12-dagpm positive height anomaly. Therefore, a northwest-southeast intense pressure gradient came into being between the two strong systems, leading to long-lasting northwesterly flows in the upper troposphere over the mid-eastern part of China while the surface was controlled by a huge cold high, which was favorable for the persistent glaze event. Under this background, the cold fronts moved southward continually; the westerly ridge of the high pressure near 40°N in East Pacific was exceptionally strong with a 20-dagpm positive anomaly, and the subtropical high in Northwest Pacific got stronger than in normal years while the trough in East Asia became weaker. In addition, the isohypse of 584 dagpm moved northward to the coast of South China Sea and during the two periods from 10 to 17 and 25 to 28 January, the geopotential height of Northwest Pacific high reached 588 dagpm, indicating that the subtropical high was extraordinarily strong. The quasi-stationary ultra-long wave mentioned above made the East Asian jet over Japan and the ocean area to its east very strong. The subtropical high around the east coast of Atlantic was also strong, with an 8-dagpm positive height anomaly. The trough from the Mediterranean Sea to the east of North Africa was strong too, especially evident on the charts of mean circulation at 500 hPa for each period (figure omitted). The wide trough region composed of the troughs from central to western Asia made the east-west oriented subtropical frontal zone and the zonal air flows from North Africa to East Asia fairly intensified while the vortex or trough from central to western Asia remained stable (figure omitted). As a result, because of the obstruction of the Pamirs, the cold front from western Siberia was separated into two branches after its arriving at the region to the west of Xinjiang. The southern branch moved southeastward along the south foot of the Tibetan Plateau, driving the trough in the southern branch of westerlies to develop strongly after it reached the Bay of Bengal; while the northern one got across the mountainous areas in western Xinjiang when strong enough, and then entered Xinjiang and marched eastward along the Hexi Corridor, resulting in consecutive heavy snows in southern Xinjiang and snowstorms in Gansu and other pertinent places. The intense trough over western Asia contributed a lot to the disastrous weather event. The cold air masses came from the trough continuously and moved eastward. When reaching the Bay of Bengal, they made the southwesterly flows strong enough, providing heat and abundant moisture to the glazing area. In the low latitude areas, the subtropical frontal zone was not only flat but also intense (Fig. 3a). In the strong westerlies, air waves were often generated or came from western or central Asia (figure omitted), producing intense southwest flows or low level jets which transported large amount of momentum, heat, and moisture for the precipitation in the middle and lower reaches of the Yangtze River.

The distribution of geopotential height anomaly at 500 hPa from 10 January to 2 February (Fig. 3b) reveals that a negative-positive-negative pattern from polar to mid-and-low latitudes appeared in Eurasia, which means that the polar vortex, the blocking high and the frontal zone in mid-and-low latitudes in the Eastern Hemisphere were stronger than normal. The Antarctic Oscillation (AO) at high phase is the typical pattern for the heavy freezing rain year (Ye et al., 2007; Wang et al., 2009). Especially, when the intense polar vortex has a long axis accompanying negative anomalies along 140°E, it will make the western Pacific jet strong and stable. The east coast of Eurasia

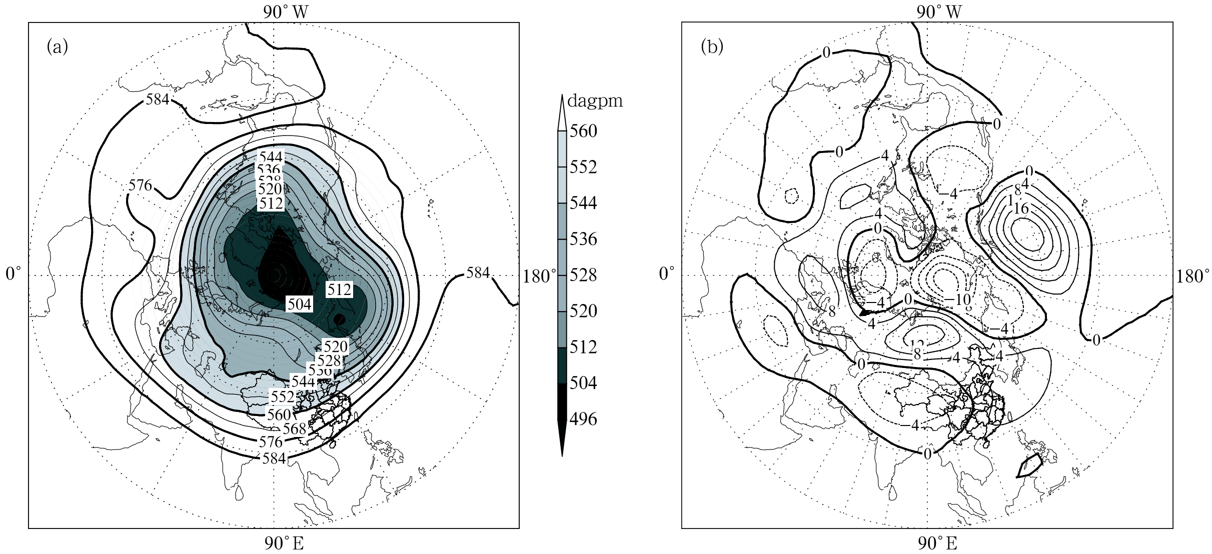

Fig. 3. 500-hPa average height (a) and anomaly (b) from 10 January to 2 February 2008.

located at the entrance of the jet is quite favorable for the persistence of the blocking high to the west of Baikal and the long-term convergence of cold and warm air over the eastern part of China.

In a word, all the analysis above discovers that the atmospheric circulation stayed extraordinarily stable during the freezing rain and snowstorm event.

3.1.2 The blocking high

Figure 3 displays that the blocking high in Eurasia was particularly strong during the freezing rain and snowstorm event. Why does such a stable synoptic situation exist?

The reasons for the stable blocking high are as follows. Temporal variations of the zonal geopotential height at 500 hPa over 75°–85°E from 10 January to 2 February (Fig. 4) indicate that, on climatology, the flows are flat with some short waves spreading in this area. One of the feature lines, i.e., isohypse of 544 dagpm, which represents the polar frontal zone, is located near 50°N. However, from 10 January to 2 February, the isohypse of 544 dapgm lay between 55° and 60°N most of the time except in 15–17 January. On 12 January, the line went up to 67°N ever, and then down sharply to 47°N on 15 January. Around 16 January, the geopotential height near 53°N decreased suddenly to 524 dapgm, which is a sign of the first outbreak of strong cold air. Thereafter, the blocking high moved northward to 67°N again and stayed near 60°N stably from 18 to 19 January, providing a synoptic background for the wide range cryogenic freezing rain and snow event in China and the glaze in southern China. From 23 to 27 January, the geopotential height near 55°N went up and the blocking high intensified, which could be used as an auspice for the most severe freezing rain and snowstorm from 25 to 28 January. This is a meaningful clue for forecasting. On 30 January, the blocking high retreated southward obviously.

During the course of the event, the blocking high was extraordinarily strong. Wang et al. (2009) made a primary analysis and argued that the extremely strong negative vorticity was transported continuously into the blocking area from its upstream around 50°N, leading to the regeneration of the blocking pattern on the verge of collapse. As a result, the blocking pattern stayed there for a long time.

3.1.3 The central-Asian vortex

The latitude-time evolution of average geopotential height at 500 hPa over 35°–45°N from 10 January to 2 February (figure omitted) shows that the stable and active central-Asian vortex played an important role in this event. Climatologically, this vortex is located near Caspian Sea at 50°E in this season. However, from 10 January to 2 February 2008, the central-Asian vortex got stronger than normal and lay around 70°E, 20 longitudes east to the average; moreover,

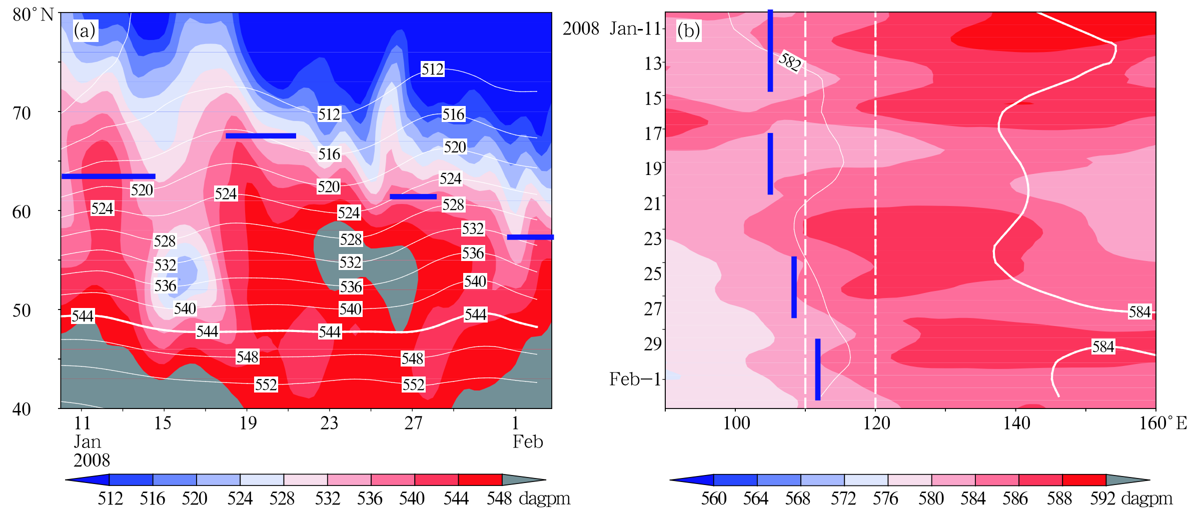

Fig. 4. The latitude-time evolution of average geopotential height at 500 hPa over 75°–85°E (a), and longitude-time evolution of the same variable but over 15°–25°N (b) from 10 January to 2 February 2008 (shaded; dagpm). The multi-year mean geopotential height in the corresponding period is also shown in solid lines.

it spread eastward and intensified in the eastern coastal areas during the two periods of 18–22 and 25–28 January, causing severe weather widely. While spreading eastward, the vortex also brought record-breaking cryogenic weather to Gansu, Qinghai, and some other places.

3.1.4 The subtropical high

The longitude-time evolution of the average geopotential height at 500 hPa over 15°–25°N from 10 January to 2 February (Fig. 4) indicates that the climatology location of the isohypse of 584 dagpm (solid lines) was to the east of 140°E. From 10 January to 2 February 2008, the average subtropical high over 15°–25°N was intense, and its western ridge point once reached 110°E. During the first period of the event, the subtropical high surpassed the multi-year mean dramatically in terms of both the intensity and the position of its western ridge point. When the intensity and the western ridge point grew up to their peaks and then weakened and dissipated to the east rapidly, the freezing rain and snowstorm event happened, which suggests that the westerlies in the mid-high latitudes are closely associated with the subtropical systems in the lower latitudes, and develop with them synchronously. Then, during the second period, the subtropical high withdrew to the east, and then forwarded to the west. For the third and fourth periods, the subtropical high retreated eastward slowly, developing in a way similar to the severe freezing weather process. The latter extended southward gradually, making much of the southern China hit by the disaster. Therefore, precipitation in China has a close relationship with the position of the subtropical high.

The longitude-time evolution of average height over 110°–120°E at 500 hPa (figure omitted) shows that the isohypse of 584 dagpm of the multi-year average lies near 20°N while that of 588 dagpm is near 15°N. During the first period, the subtropical high was strong, and the advance and retreat of its northern boundary corresponded well with the development of the four main weather processes. From the second to the fourth period, the northern boundary of the subtropical high retreated to the south, accordingly the weather process extended to the south gradually.

The main reasons for the successive large-range cryogenic freezing rains and snows from 10 January to 2 February 2008 are attributed to the subtropical-high's western and northern departure and abnormal intensity.

The infrared radiative cloud image at 2000 BT (Beijing Time) 5 January 2008 (figure omitted) shows that the convective cloud bands crossed the equator from the ocean in the north of Australia to the Philippine ocean, passing the Indonesia archipelagos. In the

OLR anomaly in January 2008 (Fig. 5a), it can be seen that the regions mentioned above were negative areas. Compared with normal years, the tropical convection over West Pacific was active and negative anomalies were strong. Active tropical convection means that the updraft is intense and so does the downdraft to its north. The heating of the downdraft may be one of the reasons for the stronger and the northward shift of the subtropical high.

Figure 5b presents the anomalous $v-\omega$ circulation averaged over 110°–130°E from 10 January to 2 February 2008. There was a deep negative circulation in the whole troposphere to the north of the equator. The downward branch of the circulation was located between 3° and 12°N while the upward one lay to the north of 12°N. This circulation intensified the subtropical high as well as its updraft in the northwestern part, which may be another reason for the abnormal intensity of the subtropical high.

3.1.5 The frontal zone

The temperature difference in the meridional direction, i.e., the temperature difference ($T_{20^\circ\mathrm{N}}$–$T_{30^\circ\mathrm{N}}$) between the northern and southern parts of the subtropical high in the region of 105°–120°E, can be used to represent the intensity of the frontal zone.

Figure 6 shows that the subtropical frontal zone below 750 hPa strengthened gradually after 10 January, with the greatest temperature difference of 22°C within 10 latitudes. Such a strong frontal zone kept the cryogenic weather in southern China (within the subtropical area) for a long time and the cold and warm fronts being in the state of long-standing across the Yangtze River basin. Especially, on 13 January and from 26 to 30 January, the temperature difference exceeded 22°C, and more over, the range of the temperature difference more than 22°C was enlarging, suggesting that the height of the melting layer that generated the freezing rain was rising, which favored the atmospheric stratification required by the freezing weather. This situation corresponded well with the reinforcement of the freezing rain in Guizhou and Hunan on 13 January, and the strongest process from 25 to 28 January.

The temperature and pseudo-potential temperature evolution along 110°E at 0800 UTC 28 January are analyzed (figure omitted). If the isentropic surface of 310 K is regarded as the upper boundary of the frontal zone and 285 K as the lower one, the cold air is below the lower boundary and warm air above the upper boundary. The result shows that both the warm and cold air are strong with an obvious temperature inversion in between. The frontal slope was small (tg$\alpha \approx$ 1/500); the frontal precipitation band was broad and beyond the surface frontal lines. Therefore, this cryogenic freezing rain and snowstorm event consisted of frequent and long-time interference of polar continental cold air and tropical warm air.

The latitude-time variation of the average radial wind over 105°–120°E at 850 hPa from 10 January to 2 February (figure omitted) indicates that shift of the

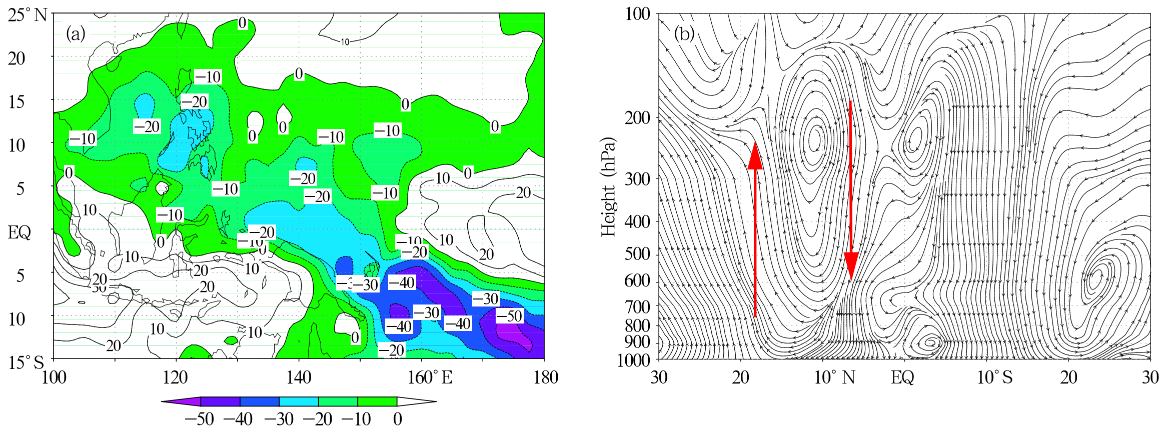

Fig. 5. (a) OLR anomalies in January 2008 (shaded areas represent the negative anomaly). (b) The anomalous $v-\omega$ circulation averaged over 110°–130°E from January 10 to 2 February (v: meridional wind, m s^{-1}; ω: vertical velocity, 10^{-2} Pa s^{-1}).

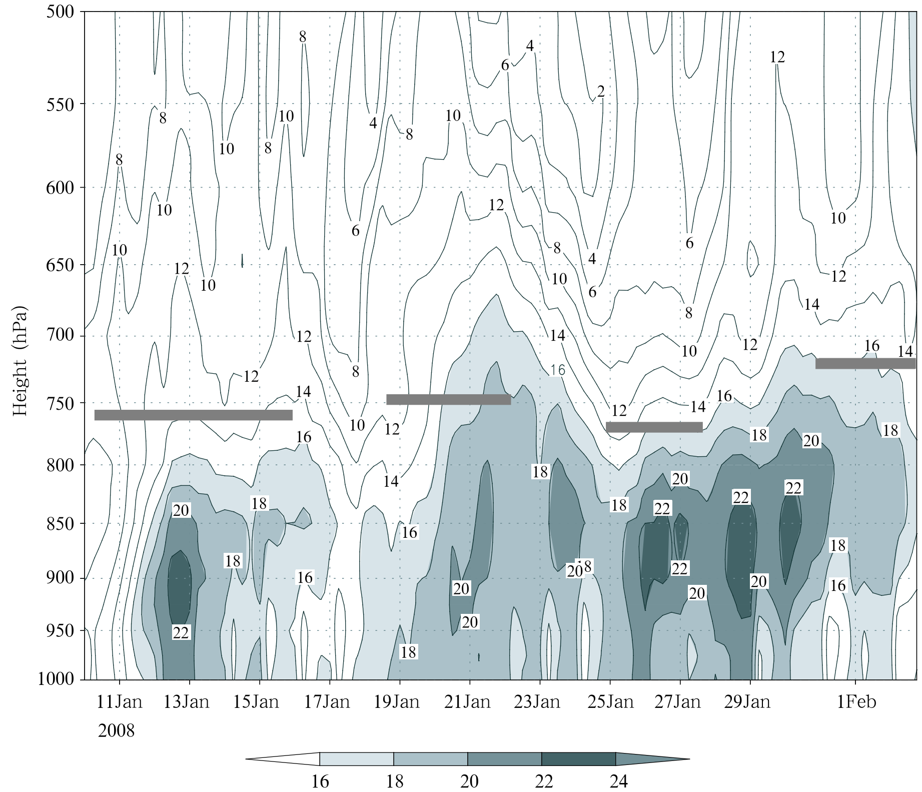

Fig. 6. The height-time evolution of the intensity ($T_{20°\mathrm{N}}$–$T_{30°\mathrm{N}}$; °C) of the frontal zone averaged over the region 105°–120°E from 10 January to 2 February 2008.

boundary between the north and south wind (the line of $v = 0$), another parameter denoting front, was rather consistent with the gradual southward extension of the disastrous weather in the four periods. In the first period, the boundary rapidly moved from 37° to 22°N, triggering the strong cold air invasion, at the beginning of which there existed a process of the southerly wind strengthening around Nanling. During the second period, the boundary was pushed back swiftly to the north of 40°N, and on 19 January, the southerly wind blew up strongly again, leading to the largest disaster-hit area of the event. Later, the boundary wandered around 26°–29°N stably, but several severe rain and snow processes occurred and were accompanied by the successive reinforcement of south winds. The daily data analysis (figure omitted) shows that all of the four periods were closely related to the reinforcement of southerly winds at low levels, and in the third and fourth periods, torrential rains even occurred in South China. The shift tendency of the boundary accorded quite well with the southward development of heavy rainfalls.

3.1.6 The troughs

There is a close relation between the cryogenic freezing rains and snows and the activities of the trough in the southern branch of the westerlies over the Bay of Bengal (southern branch trough for short hereafter) and the plateau trough. The regions of 30°–35°N and 20°–25°N near 90°E are chosen to represent the activity ranges of the plateau trough and the southern branch trough. The latitude-time variation of the average geopotential height at 500 hPa over 85°–95°E from 10 January to 2 February 2008 (Fig. 7) shows that there were 5 or 6 plateau troughs during this period, respectively on 11, 14, 21, 23, 26 and 29–30 January, and 5 southern branch troughs on 11, 14–15, 19, 25 January and 1 February. If the isohypse of 580 dagpm is chosen to indicate the trough intensity, the isohypse on 25 January and 1 February went down southward beyond 20°N, which means that the trough was in greater intensity. Every activity and reinforcement of the southern branch trough was consistent with the development of the freezing rain and snowstorm process. For example, the southern branch trough developed greatly during the third period of the event (from 25 to 28 January). There were 6 or 7 isohypses with a 4-dagpm interval within 10 latitudes. The subtropical high moved westward and reinforced. These two systems marched vis-à-vis, strengthening the moisture transport in front of the southern branch trough. This played a very important role in generating the most severe process during the whole disastrous event.

Compared with the multi-year average in the corresponding period (figure omitted), the subtropical high from 10 to 23 January in the Bay of Bengal over 85°–95°E to the south of 25°N was stronger. The geopotential height at 500 hPa once reached 588 dagpm during 15–17 January. After 23 January, the isohypse of 584 dagpm dislayed similarly to that of the corresponding period in history, but the southern branch trough enhanced gradually from 17 January, which should be responsible for the development of the freezing rain to the east of Yunnan after 23 January.

3.2 *Causes of the freezing rain*

According to Wang et al. (2006) and the Atmospheric Science Dictionary (1994), a necessary condition for freezing rain is the inversion layer at the mid level and a warm layer with temperature higher than 0°C. This is the vertical structure associated with most freezing rain events. Another condition for freezing rain is that the temperature at the top of the cloud is higher than −10 °C so that the ice particles are either difficult to form or very small. This is also a favorable condition for the formation of freezing rain even though the temperature profile of the whole layer is below zero. Huffman and Vorman (1988) summarized freezing rain of this origin as the super-cooled warm rain process. Recent studies in China indicate that freezing rain may happen when temperature of the inversion layer is below zero, which is named one-layer mode and means that the levels from the surface to 600 hPa are cold and wet, and all layers are colder

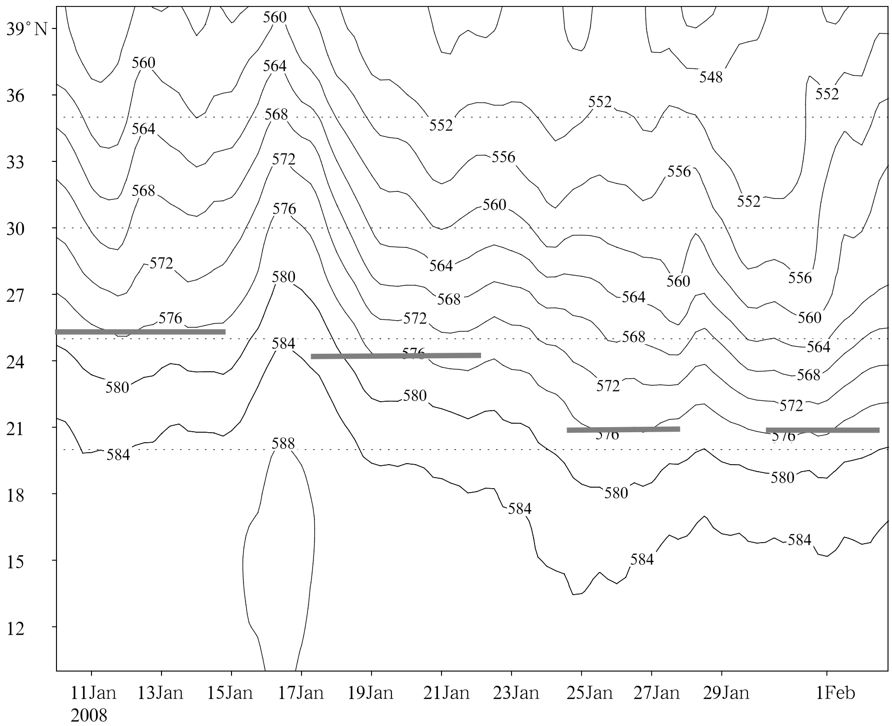

Fig. 7. The latitude-time variation of the geopotential height (dagpm) at 500 hPa averaged over 85°–95°E from 10 January to 2 February 2008.

than zero. Lately, some experts think that in addition to the typical features of freezing rain, the disastrous freezing weather in southern China has two other characteristics: 1) the mixed freezing process of ice and super-cooled water and 2) existence of the freezing process under the background of super-cooled cloud (fog), on which the topography has a great influence.

Many studies have been conducted about cold layer or cold cushion. The characteristics of the cold cushion during the event in early 2008 are consistent with the conclusion of Xu and Wang (1965). Figure 8 gives the height-time evolution of the mean temperature, wind, and relative humidity over the region 26°–28°N, 105°–116°E, roughly referring to the area of Guizhou, Hunan, and Jiangxi, during 19–29 January 2008. In Fig. 8, the warm layer ($T \geqslant 0$°C) over Guizhou, Hunan, and Jiangxi dwelled between 800 and 600 hPa. After 22 January, the temperature within the warm layer rose up and became over 4°C while the height of the warm layer center went down gradually. On 25 January, the warm layer center was found at 750 hPa ($T \geqslant 6$°C) and inside the warm layer there blew the southwesterly wind. When the southwest flows between 800 and 600 hPa got intensified, the temperature at the relevant levels in the warm layer increased obviously with great correspondence. The warming effect of warm advection was significant, and could be used as a criterion in forecasting freezing rain. Inside the cold layer below 800 hPa was northeast or northerly wind with the speed of 2–4 m s^{-1} and the relative humidity was above 90%. Beginning from 23 January, temperature of the cold layer dropped sharply, and the lowest ($T \leqslant -6$°C) appeared at 900 hPa on 27 January. The analysis discovers that, when strong and persistent northeasterly wind gusts, the cold advection strengthens, temperature of cold layer drops, and the freezing rain reinforces. For instance, on 27 January, the freezing rain was the heaviest, but the warm layer was not the strongest.

In summary, the higher the temperature in the warm layer and the lower the temperature in the cold

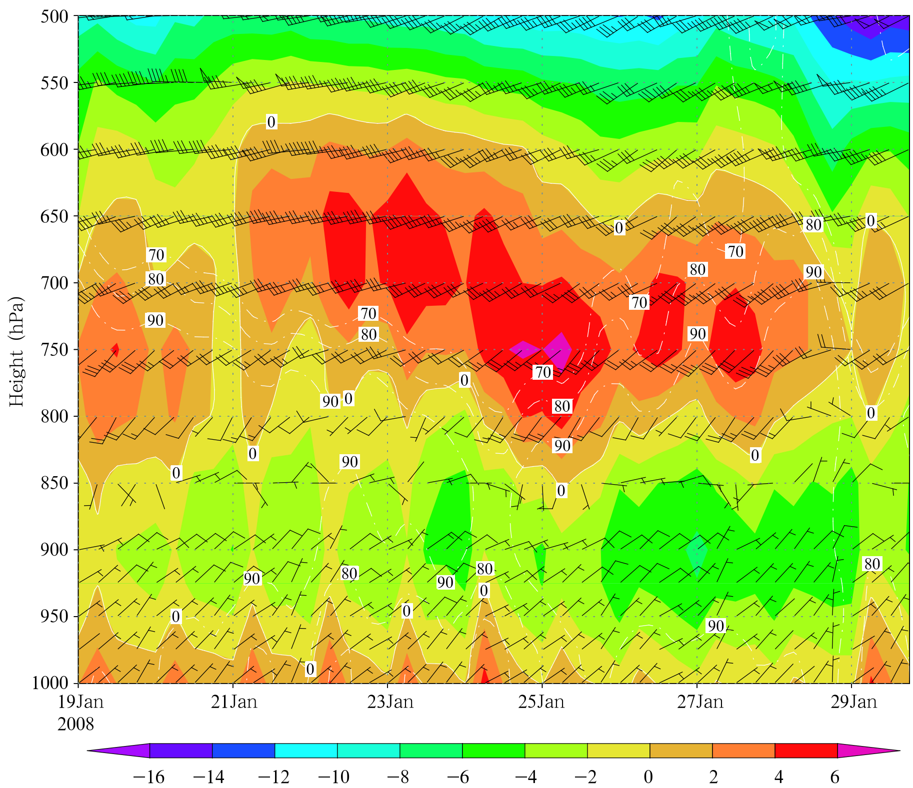

Fig. 8. The height-time evolution of mean temperature (shaded areas; °C), wind (barbs), and relative humidity (white dotted lines; %) over the region 26°–28°N, 105°–116°E around Guizhou, Hunan, and Jiangxi during 19–29 January 2008.

layer, the more severe the freezing rain is. This is very important for forecasting typical freezing rains.

The distribution of inversion areas (figure omitted), defined as the regions surrounded by the contour of $T = 0°C$ at 700 and 850 hPa, shows that the inversion covered Guizhou, Hunan, and Jiangxi from 10 January to 2 February and moved to the south gradually in the process of the whole event. The regions in the first three periods expanded gradually but got smaller in the fourth one slowly. The changing tendency of inversion area corresponded well with the development of the freezing rains.

3.3 Causes of the snowstorm

3.3.1 Overview

During the exceptional freezing rain and snow disaster in early 2008, snowstorms attacked China from the north to the south. The most severe blizzards occurred in the third and fourth periods of the event. Unusually heavy snowstorms rarely seen in history overwhelmed southern Jiangsu, central Anhui, and northern Zhejiang.

The blizzard during 25–28 January was the most severe during the four periods, along with the freezing rain of the largest coverage. The snowstorm to the south of Huaihe River lasted for four days, dominating the south of Jiangsu and the north of Zhejiang and surrounding areas with the largest scale and strongest intensity in history. The snow duration created a new record in Jiangsu since the initial establishment of observation in 1961. Forty-two stations in the Jiangsu Province reported snowstorms and the coverage was so large that it ranked the second since 1961, only inferior to the case on 18 January 1984 with 49 stations reporting blizzard. Until 0800 BT 29 January 2008, compared with the historical data, the maximum depth of snow broke the records in 23 cities or towns and one station found it the same as the historical file.

By 0800 BT 2 February 2008, the snow depth was 20–35 cm in the central and southern parts of Anhui, southern Jiangsu, northern Zhejiang, central Hunan, and northern Jiangxi. Some isolated places in the middle parts of Anhui and Hunan and northern Jiangxi even measured 35–40 cm. Meanwhile, the extremely heavy snow with fairly strong intensity controlled a great many parts of Zhejiang Province and the snow depth in much of the northern part broke the 50-yr record.

The rain and snow lasted for 28 days from 10 January to 6 February 2008 in Anhui Province, exceeding those in 1954 (16 days) and 1969 (16 days). This is the snowfall with the longest duration recorded ever since measurement was started.

3.3.2 The influential systems

Figure 9a presents the time-longitude variations of the average relative vorticity at 500 hPa over 30°–33°N from 25 January to 2 February 2008. There were

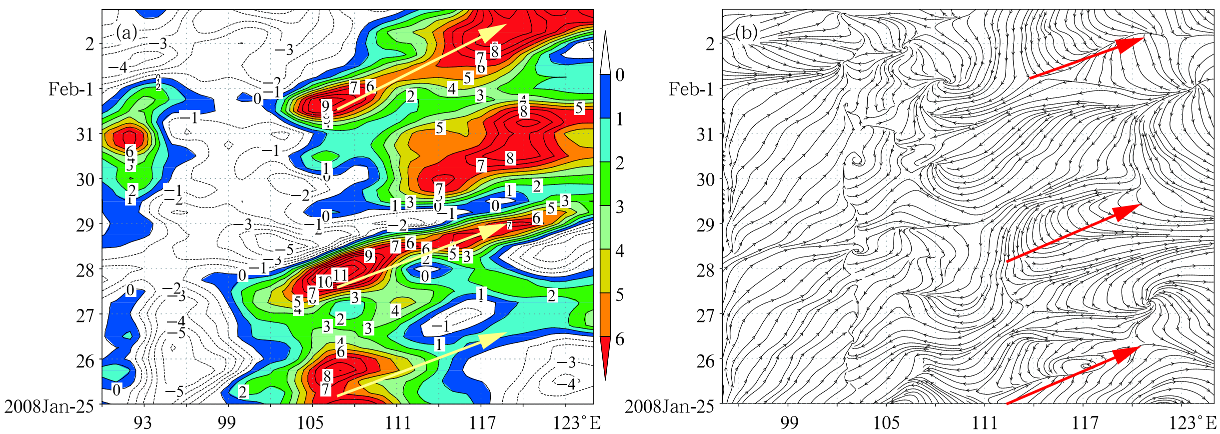

Fig. 9. Time-longitude variations of the relative vorticity (10^{-5} s^{-1}) at 500 hPa averaged over 30°–33°N (a) and the stream field at 850 hPa along 30°N (b) from 25 January to 2 February 2008.

three positive vorticity areas spreading eastward from the Sichuan Basin to coastal regions in the east of China. Thus, the cyclonic vortex or the shear developed and the vertical motion reinforced, causing the rain and snow around the Yangtze River. During 25–26 January, the positive vorticity at 500 hPa developed over the Sichuan Basin. On 26 January, though the vorticity reduced its intensity while traveling eastward, the cyclonic circulation at 850 hPa strengthened (Fig. 9b), which resulted in the snowstorm in central Anhui, central and southern parts of Jiangsu with 6-h precipitation amount up to 5–6 mm in the 12 h from 0200 to 1400 BT on 26 January. During 27–28 January, positive vorticity areas expanded greatly with the relative vortictiy of the center reaching 11×10^{-5} s^{-1} and spreading eastward. When getting to the area of 115°–120°E, the relative vorticity weakened a little, but still with a value of 7×10^{-5} s^{-1}. Meanwhile, the shear lines at 850 hPa maintained. Therefore, during the period from 0800 BT 27 January to 1400 BT 28 January, central Anhui and southern Jiangsu got dominated by blizzard, and the 6-h precipitation reached 8–13 mm. From 31 January to 1 February, another positive vorticity area developed eastward, and then weakened for some time while shifting eastward, but intensified again near 114°E, and correspondingly at the low level there existed the convergence of northwesterly and southwesterly winds, which made the north of Zhejiang (to the north of 30°N) caught by blizzard too during 0800 BT 1 February to 1400 BT 2 February with the 6-h precipitation of 5–9 mm reported. The evolution of the positive vorticity areas over 105°–120°E was similar to the evolution of the cyclonic circulation at 850 hPa over 30°N. The development and eastward spreading of the positive vorticity corresponded well with the historical unusual snowstorm cases.

3.3.3 The moisture condition

The condition for snowstorms is the same as that for torrential rains, i.e., ample moisture, intense updraft and long persistence. In the real-time weather forecast, the divergence of moisture flux is an important physical parameter for analyzing the formation of precipitation.

Based on the height-time variation of the average divergence of moisture flux over the central Anhui in 31°–33°N, 116°–119°E (Fig. 10a), intense convergence of moisture flux was found between 700 and 500 hPa when the 6-h precipitation of heavy snow was larger than 5 mm during 0200–1400 BT 26 January in the central Anhui Province. When the moisture flux convergence sharply enlarged from -4×10^{-11} to -10×10^{-11} (g cm^{-1} hPa^{-1} s^{-1}) between 2000 BT 26 and 0800 BT 27 January, a snowstorm with 6-h precipitation of 5–9 mm occurred in the next 24 h. When the moisture flux divergence intensified to the largest and then weakened, the intensity of snow reduced rapidly. The snowstorm was seen at the time when the convergence of moisture flux was the largest.

Similar evolution in the average moisture flux divergence and similar relationship with the snowstorm were found in the south of Jiangsu (31°–33°N, 118°–121°E).

However, the height-time variation of the average moisture flux divergence over the north of Zhejiang (30°–32°N, 119°–121°E) (Fig. 10b) are slightly different from that in the central Anhui. The large convergence center resided in 500–400 and 900–700 hPa respectively while it was divergence in the layer of 700–500 hPa. The heavy snow appeared when the convergence of the moisture flux in the layers of 900–700 and 500–400 hPa strengthened sharply and the divergence in 700–500 hPa developed similarly.

The changes of the moisture flux divergence in the three areas mentioned above are consistent with the evolution of the average moisture flux divergence over 20°–30°N, 100°–120°E (figure omitted).

3.3.4 The vertical motion

Since the calculation of vertical motion is not precise enough, we only analyze it qualitatively. The height-time evolution of average vertical velocity over the central Anhui (31°–33°N, 116°–119°E) is given in Fig. 10a. When the vertical motion initially reinforced in the layer of 600–300 hPa, heavy snow with 6–h

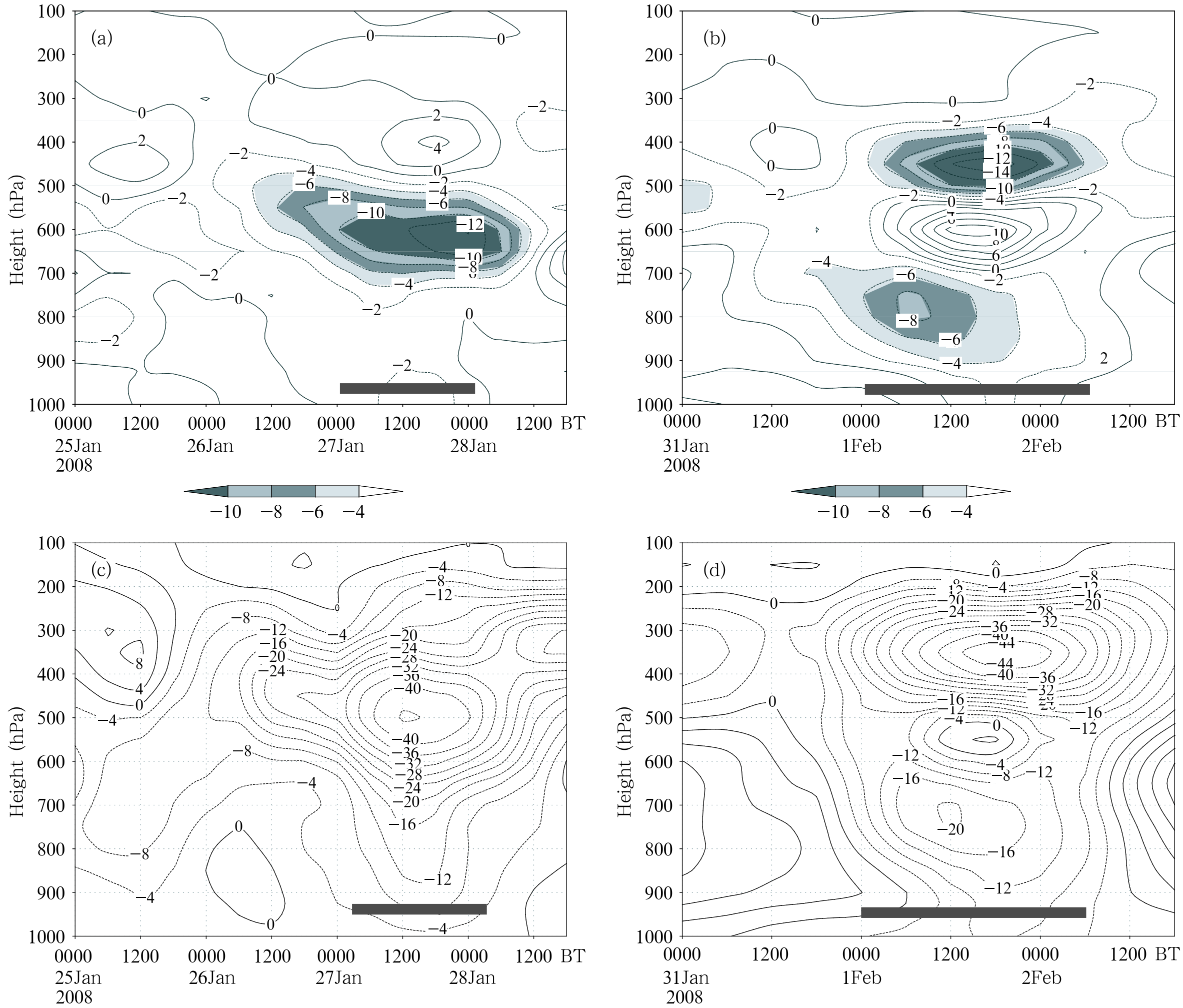

Fig. 10. Height-time variations of the moisture flux divergence (a, b; 10^{-11} g cm^{-1} hPa^{-1} s^{-1}) and the vertical velocity (c, d; 10^{-2} Pa s^{-1}) averaged over the central Anhui Province (a, c) and the north of Zhejiang Province (b, d) from 25 January to 2 February 2008.

precipitation of 5–6 mm was seen during 0200–1400 BT 26 January. When the updraft strengthened sharply, with the intensity of the center reaching -42×10^{-2} Pa s^{-1} and its range extending into the whole layer, the heavy snow intensified rapidly, resulting in the 6-h rainfall of 5–9 mm from 0800 BT 27 to 0800 BT 28 January. The strongest updraft corresponded well with the heaviest snow.

The evolution of average vertical velocity as well as its relationship with the heavy snow in the south of Jiangsu (31°–33°N, 118°–121°E) was similar to the process mentioned above.

In the height-time variation of average vertical velocity over the north of Zhejiang (30°–32°N, 119°–121°E) (Fig. 10d), a blizzard occurred when the updraft near 700 hPa reached its peak and that at 350 hPa, i.e., the updraft related to the upper level frontal zone, strengthened, but the downdraft occupied the level of 550 hPa.

Similarly, the changes of vertical motion in the three areas are basically coherent with the evolution of average upward motion over 110°–120°E (figure omitted).

4. Conclusions

During the cryogenic freezing rain and snow event at the beginning of 2008, the atmospheric circulation patterns were stable. The strong and stable center of the polar vortex was located in the northern part of the Eastern Hemisphere. The circulations in high and low latitudes were out-of-phase over Eurasia. The stable ultra-long wave provided the circulation background for the long-lasting freezing rain and snowstorm event. The cold air mass from polar areas and warm air mass from the tropical ocean confronted each other for a long time, which was considered as the main reason for this event.

The blocking high in the west of the Baikal was strong and stable. Besides, the trough (vortex) over central and western Asia was steady and vigorous while the trough over the east of North Africa stayed stable too. The subtropical high over West Pacific was intense with westward and northward departures.

The dominant wind at 700 hPa was southwesterly and there were shears and vortexes at 850 hPa during the event. The evolution of relative vorticity in the mid troposphere shows that eddies were generated over the Tibetan Plateau and the positive vorticity propagated eastward to the coastal regions of eastern China.

The subtropical frontal zone was puissant, and the north-south temperature gradient was large. The southern branch trough was active and the southern frontal zone went with great intensity and little shift. The quasi-stationary fronts over South China and the Yunnan-Guizhou Plateau remained stable while the warm air mass over the tropical ocean behaved actively. The inversion layer stayed steady and the melting layer was thick.

The first period of the event was featured with the interaction of the strong cold fronts and the warm air mass whilst the other three were with the standing quasi-stationary fronts over South China and the Yunnan-Guizhou Plateau as well as the cold air intrusion from the north in diffusion or infiltration ways.

When the positive vorticity over the Sichuan Basin propagated eastward to the coastal regions of eastern China, the affected area was prone to heavy snows. The water vapor flux convergence in the mid troposphere was also favorable for the record-breaking snowstorm event. These are the main reasons for the snowstorms at the beginning of 2008.

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