A Preliminary Analysis of Features and Causes of the Snow Storm Event over the Southern Areas of China in January 2008*

WANG Donghai†(王东海), LIU Chongjian (柳崇健), LIU Ying (刘 英), WEI Fengying (魏凤英), ZHAO Nan (赵 南), JIANG Zhina (姜智娜), LI Ying (李 英), CHEN Juying (陈菊英), WANG Yafei (王亚非), SHI Xiaohui (施晓晖), and XU Xiangde (徐祥德)

State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081

(Received March 13, 2009)

ABSTRACT

Four successive freezing rain/heavy snowfall processes occurred in the southern part of China from 11 January to 2 February 2008 (named "0801 Southern Snow Disaster" hereafter), during which a large-scale blocking circulation lasted for a long time over the mid-high latitudes of the Euro-Asian continent. This severe event is featured with a broad spatial scale, strong intensity, long duration, and serious damage. During the event, the blocking situation in the mid-high latitudes maintained quasi-sationary, but weather systems in the lower latitudes were active. Abundant water vapor was supplied, and favorable weather conditions for ice storms were formed over the large areas across the southern part of China.

The results in this paper demonstrate that the significant factors responsible for the abnormal atmospheric circulation and this severe event include: 1) the very active Arctic Oscillation (AO), which helped the permanent maintenance of the planetary-scale waves; 2) the continuous transfer of negative vorticity from the upstream region around 50°E into the blocking area, which caused the blocking situation reinforced repeatedly and sustained for a long time; and 3) the active air currents south of the Tibetan Plateau, which ensured abundant moisture supply to the southern areas of China.

The 0801 Southern Snow Disaster was accompanied by extremely severe icing. In this paper, the data from Cloud-Profile Radar onboard the satellite CloudSat are used to study the dynamic and microphysical features of this event. The results show that there existed a melting layer between 2 and 4 km, and ice particles could be found above this layer and in the layer near the ground surface. Surface temperature kept between –4°C and 0°C with relative humidity over 90%, which provided the descending supercooled waterdrops with favorable synoptic and physical conditions to form glaze and ice at the surface via freezing, deposition and/or accretion.

Causes of the event might be, as a whole, traced back to the planetary-scale systems. The study on the polar vortex anomaly in this paper reveals that changes in the polar vortex in the stratosphere preceded those in the troposphere, especially in early December 2007, while the intensification of the polar vortex in the troposphere delayed dramatically until middle January and early February of 2008. This implies that changes in the polar vortex in the stratosphere may be a precursor of the ensuing severe event and a meaningful clue for extended forecasts of such a disaster.

Key words: snow storm event, low temperature, freezing rain, ice storm

Citation: Wang Donghai, Liu Chongjian, Liu Ying, et al., 2009: A preliminary analysis of features and causes of the snow storm event over the southern areas of China in January 2008. *Acta Meteor. Sinica*, **23**(3), 374–386.

1. Introduction

Worldwide extreme weather/climate events are getting more and more frequent. Plenty of literature and data (Easterling et al., 2000; Karl et al., 1991; Manton and Eral, 2001; Wang and Gong, 2000) reveal that a variety of devastating weather/climate events occur frequently over the world. For example, the most serious drought since 1940 occurred in 1998 in the central-western part of the United States, with

*Supported jointly by the Basic Research Project of the State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, and the National Natural Science Foundation of China under Grant Nos. 40633016 and 40875029.

†Corresponding author: wangdh@cams.cma.gov.cn.

crop yields dropping by 38%, and the year 1998 was the warmest year that China experienced in the last one hundred years. Moreover, it is likely that such disastrous events will become more severe. Their causes, implications and countermeasures are a current subject of concerns. Among them is the successive snow storm event with severe freezing rain in the southern areas of China in January 2008, named "0801 Southern Snow Disaster" hereafter, which cost US$22.2 billions and over 130 total fatalities.

In this paper, the features and causes of this event are examined on the basis of a variety of data sources. The paper is laid out as follows. A brief description of the event is given in Section 2. Detailed features and potential causes are discussed in Section 3. A summary and further discussion is given in Section 4.

2. A brief description of the snow storm event

The unusual precipitation and temperature distributions over the period from 11 January to 2 February 2008 in China are shown in Figs. 1–3. Distinct negative temperature anomalies appeared over most parts of China, especially in central-northern Guangxi, eastern Guizhou, entire Hunan, and central-eastern Hubei provinces (Fig. 1). Changes in the area (25°–35°N, 105°–120°E) mean precipitation, temperature, maximum and minimum temperature averaged daily over the period from 11 January to 2 February 1951–2008 are shown in Fig. 2. The general evolution trend of

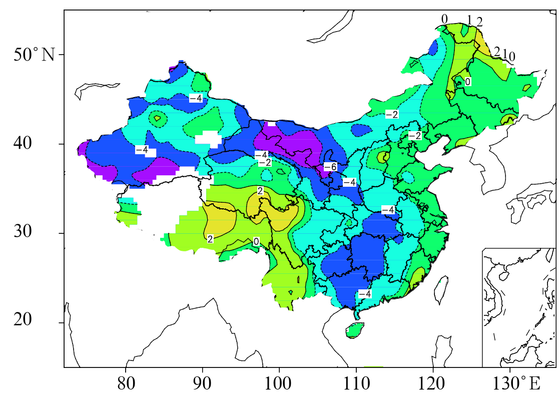

Fig. 1. Temperature anomalies (°C) for the whole China averaged over the period from 11 January to 2 February 2008. The anomalies are relative to the mean between 1971 and 2008.

temperature and maximum/minimum temperature anomalies is almost invariant. Nonetheless, temperature anomalies in 2008 reach a minimum. Positive precipitation anomalies (Fig. 3) show up in most of the southern areas of China. In fact, record-breaking meteorological observations are reported in many places in the southern part of China during the snow storm event in January 2008, such as the lowest temperature in the same period in history in Hubei Province, the longest duration of freezing rain in Jiangxi Province since meteorological data became available in 1959, the disastrous snow storm event with the longest duration and deepest snow cover in the recent 50 years in Jiangsu Province, the most persistent snowfall since the meteorological records commenced in Anhui Province, and the newly-recorded longest duration of sustained freezing rain causing the maximum thickness of electric wire icing in Guizhou Province, and so on.

Particularly, it is noticed that beginning from 11 January, average temperature in the area dropped by over 10°C with daily low down to the range from −4°C to 0°C and daily mean retaining around –1–0°C (Fig. 2b). This kind of weather condition is advantageous for freezing weather to develop in the presence of precipitation. Compared with historical data in the same period, precipitation in early 2008 is two to three times or more than that in the past (figures omitted) in a lot of southern areas of China. The average amount of precipitation during the snow storm period across the whole China is the largest since 1951.

In fact, the whole event consists of four separate precipitation processes (see Fig. 2e) from 1) 11 to 15 January, 2) 18 to 22 January, 3) 25 to 29 January, and 4) 31 January to 2 February 2008. Cold air intrusion in every latter process was supplemented and superposed upon the former one after a very short interval.

3. Main causes leading to the snow storm event

A significant scientific problem has arisen from the abnormal maintenance of the sustained low-temperature snowy weather with severe freezing rain in the southern areas of China. The event may involve

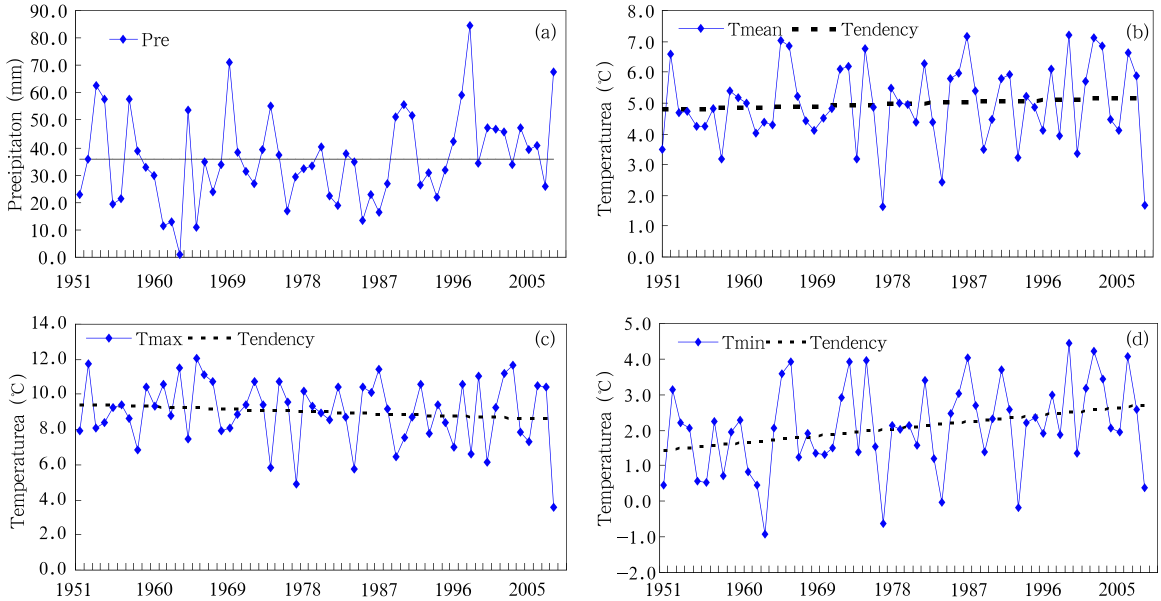

Fig. 2. Changes in the area (25°–35°N, 105°–120°E) mean precipitation (a, in mm), temperature (b, in °C), maximum (c, in °C) and minimum temperature (d, in °C) averaged daily from 11 January to 2 February between 1951 and 2008.

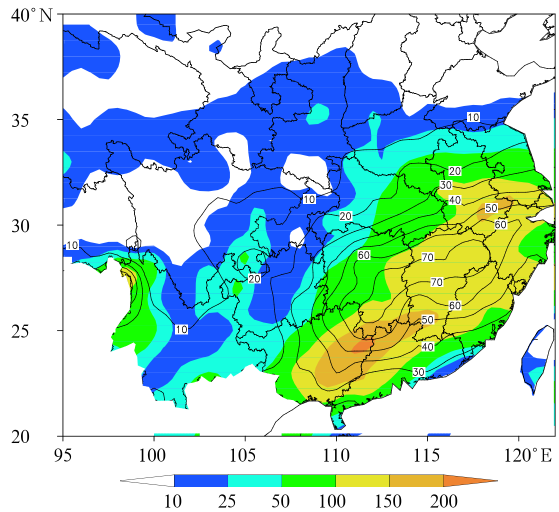

Fig. 3. The accumulative precipitation from 0000 UTC 11 January to 0000 UTC 3 February 2008 (shaded, mm), and the climate mean accumulative precipitation in the same period over 1971–2000 (solid, mm).

several fundamental dynamic/thermodynamic factors, including the polar vortex changes reflected in the AO index variability, continuous intrusion of cold fronts into the areas from the north, abundant water vapor or precipitation superposed by cold air mass, as well as stable inversion layer in the lower troposphere very close to the surface.

3.1 Changes in the polar vortex and AO index

The 0801 Southern Snow Disaster is a large-scale weather and climate event which involves some global factors such as the polar vortex and the Arctic Oscillation (AO). The polar vortex is a key circulation system that influences weather in China. The extension or contraction of the polar vortex in winter is closely related to the variation of temperature across China, and changes in the polar vortex area in mid-winter over Asia have a crucial impact on the temperature distribution in China (Liu, 1986; Li and Liu 1986). On the other hand, the AO activities reflect, to a great extent, abnormal polar vortex changes in the full column of the atmosphere, and these two variations are equal to each other to some extent. Previous investigations show that the temporal variation of AO is related to the interaction between the synoptic and quasi-stationary waves in the Northern Hemisphere, which is mainly confined in the troposphere and drives the AO through generating the longitudinal momentum fluxes. The AO of 10–20 days is associated with such forcings. In winter, the quasi-stationary waves over the mid-high latitudes can propagate upward into the stratosphere and interact with the polar vortex over there, causing the AO of 30–60 days. Such an interaction is bidirectional, i.e., the E-P fluxes generated by the quasi-stationary waves can force the latitudinal currents to affect the AO, and then changes in the latitudinal currents associated with the AO can in turn affect activities of the waves (quasi-stationary or weather waves). Figure 4 provides a good example concerning the aforementioned double-scale (10–20-day and 30–60-day) oscillations in the troposphere and stratosphere.

However, the vertical structure of the polar vortex or the AO shows a very distinct anomaly during the 0801 Southern Snow Disaster (more accurately, since October 2007) as seen in Fig. 4. This includes mainly: 1) the amplitude of changes in the polar vortex in the stratosphere enhanced dramatically with its period extending; 2) the phase change of the polar vortex in the stratosphere was substantially opposed to that in the troposphere, which is important since the AO is usually regarded as being barotropic; 3) changes in the polar vortex in the stratosphere were ahead of those in the troposphere. Especially, the polar vortex got strengthened since December 2007, while the intensification of the polar vortex in the troposphere delayed obviously until mid-January and early February of 2008. This suggests that the changes of the polar vortex in the stratosphere may precurse its variations in the troposphere and the subsequent severe weather event.

From mid-January 2008, the AO was in the highly positive phase, suggesting that both the subtropical high and the polar low were abnormally intensified, which led to the abnormally strong westerlies and the prevailing zonal currents in the middle latitudes. The subtropical jet weakened dramatically and the polar jet strengthened significantly. At this time, there existed extremely strong downdrafts over the subtropics and middle latitudes and particularly strong updrafts over the higher latitudes, causing the southerlies to be distinctly strong, which favored the northward transport of the warm and humid air from the lower latitudes and guaranteed the abundant moisture supply for the 0801 Southern Snow Disaster.

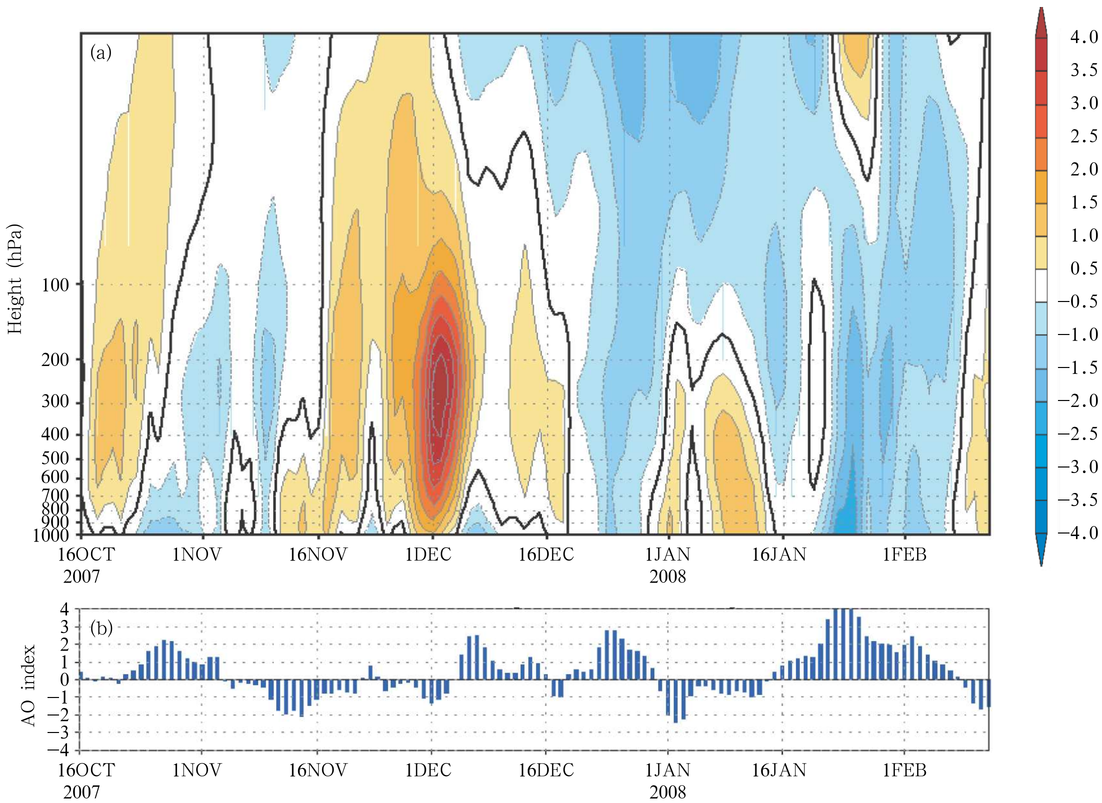

Fig.4. Normalized geopotential height anomalies at different pressure levels (a) and the corresponding AO index (b) between October 2007 and February 2008 (from http:// www.cpc.noaa.gov).

3.2 Abnormal patterns of the general circulation over the Northern Hemisphere

The extremely anomalous atmospheric circulation during this event is clearly demonstrated in the 500-hPa height anomaly field (Fig. 5). Surprisingly, in the mid-high latitudes, a height anomaly dipole is found between 40° and 160°E, with strong positive height anomalies situated at the mean trough zone and strong negative anomalies at the mean ridge area. That is, the blocking high during this event occurred in the area where a low-pressure trough used to stay, and the low pressure zone occurred in the high ridge area, showing a fully reversed phase positioning in space.

Figure 5 also shows the multi-year (1958–2006) 500-hPa geopotential height field averaged only for the period from 11 January to 2 February. Normally, cold surge weather events take place under the steering of the height distribution pattern as presented in Fig. 5. Generally, such a height pattern lasts 5 days or so. That is, the blocking situation in higher latitudes maintains for about a week. However, such a pattern in Fig. 5 remained, more or less stronger for about 20 days during the 0801 Southern Snow Disaster. Therefore, the successive southward intrusion of cold fronts continued for 20 days or so, resulting in the lasting freezing weather.

3.3 The steady maintenance of the blocking high

As mentioned above, the circulation pattern shown in Fig. 5 stayed for about 20 days during the 0801 Southern Snow Disaster. However, it was stronger sometimes and weaker at other times (see Fig. 6), corresponding to the four precipitation processes, during which temperature fluctuated as well (see Fig. 7). According to previous studies, the long-term maintenance of a blocking pattern can be attributed to the upstream vorticity forcing (Berggren et al., 1949; Shutts, 1983; Luo, 2005), which is expressed as

$$J_P = -J(\varphi_s, \nabla^2\varphi_s)_P,$$

where φ is streamfunction, ∇^2 is Laplace Operator, s represents the synoptic scale waves with the latitudinal wave numbers of 6–18, and P for the planetary scale waves with the latitudinal wave numbers of 0–4.

Figure 8 shows the 500-hPa streamline field and vorticity forcing of synoptic-scale waves averaged over the period of 11 January to 2 February 2008. It is seen that strong negative vorticity forcing in the upstream area appeared around 50°E so that negative vorticity was continuously transferred into the blocking area. This might be the reason why the blocking pattern can be maintained for such a long period in the longitudes between 60°–100°E, and why cold fronts from the north intruded incessantly into the southern part of China.

3.4 Mid-low latitude weather systems and the moisture supply

As seen from the large-scale circulation background, the continuous heavy precipitation was essentially caused by the blocking high in the north and

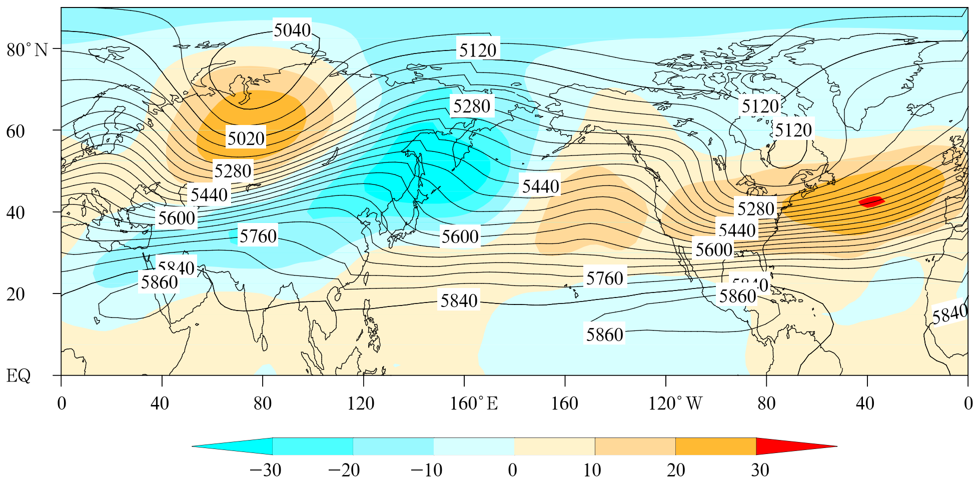

Fig. 5. The averaged 500-hPa geopotential height over 1958–2006 (solid, unit: gpm) and the 500-hPa height anomalies (gpm) in the Northern Hemisphere from 11 January to 2 February 2008 (shaded, relative to the mean between 1958 and 2006).

the western Pacific subtropical high in the south as well as the trough in the southern branch of the westerlies over the Bay of Bengal, all of which coexisted and maintained stationarily. In fact, the subtropical high over the western North Pacific in January 2008 was located 3–7 longitudinal degrees north of its normal position (13.3°N) since 1958 (Fig. 9). It is also noticed that water vapor carried by the southwesterly flows in the northwestern part of the subtropical high was accumulated over the southern part of China (Fig. 10). The trough in the southern branch of the westerlies over the Bay of Bengal migrated gradually

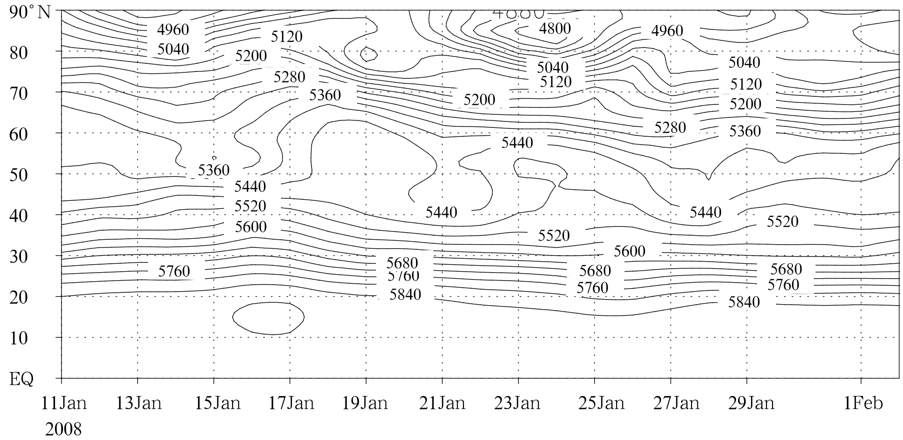

Fig. 6. Evolution of 500-hPa geopotential height (gpm) averaged between 45°E and 100°E.

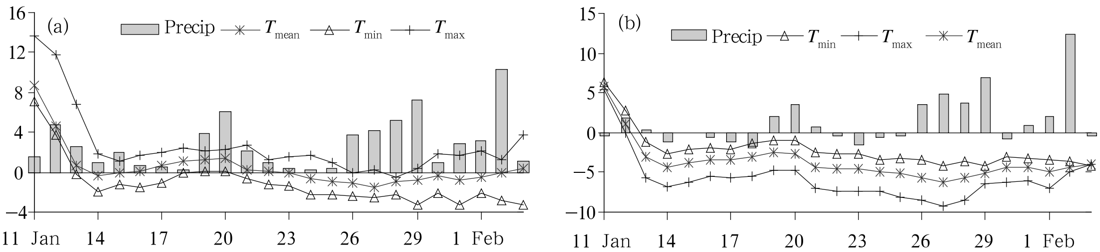

Fig. 7. (a) Evolution of the daily precipitation (mm), daily maximum/minimum temperature, and daily-averaged temperature (°C) from 0000 UTC 11 January to 0000 UTC 3 February over the region (25°–35°N, 105°–120°E). (b) As in (a), but for their anomalies computed relative to the climatology of 1971–2000.

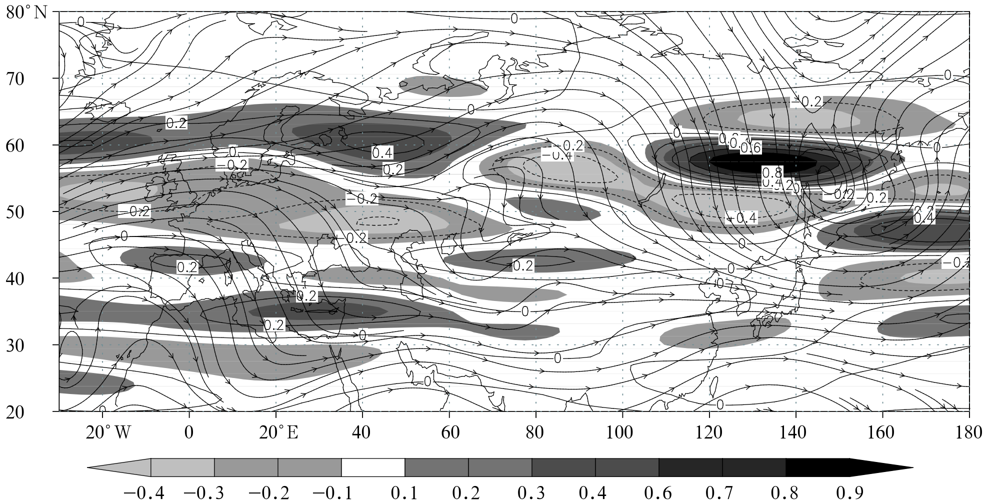

Fig. 8. The 500-hPa averaged streamline field and mean vorticity forcing of the synoptic-scale waves (shaded, unit: $10^{-20}s^{-2}$) over the period of 11 January to 2 February 2008.

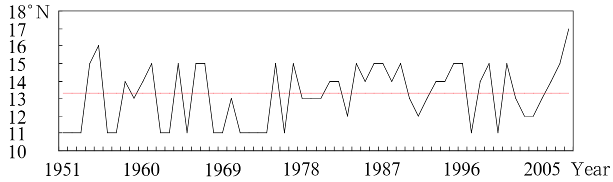

Fig. 9. Changes in the latitudinal position of the subtropical ridge between 1951 and 2008.

eastward and got strengthened (Fig. 11). The four freezing rain/heavy snow processes experienced different stages of water vapor transport, during which some moisture was even transported from over the Qinghai-Tibet Plateau (Fig. 12). The abnormal intensification and northwestward extension of the subtropical high (see also Fig. 10) facilitated the moisture transport a lot.

In addition, the distribution of precipitable water retrieved from the ground-based GPS data (Fig. 13) between 1600 UTC 19 January and 0400 UTC 1 February demonstrates that the area-averaged GPS precipitable water (Fig. 13a) in Yunnan Province was significantly correlated with the snowfall (figure omitted) in the later periods in the areas of 1) Yunnan, Guizhou, and Guangxi; 2) Anhui, Jiangsu, Zhejiang, and Shanghai; and 3) Hunan, Hubai, and Jiangxi. The correlation coefficients between the GPS precipitable

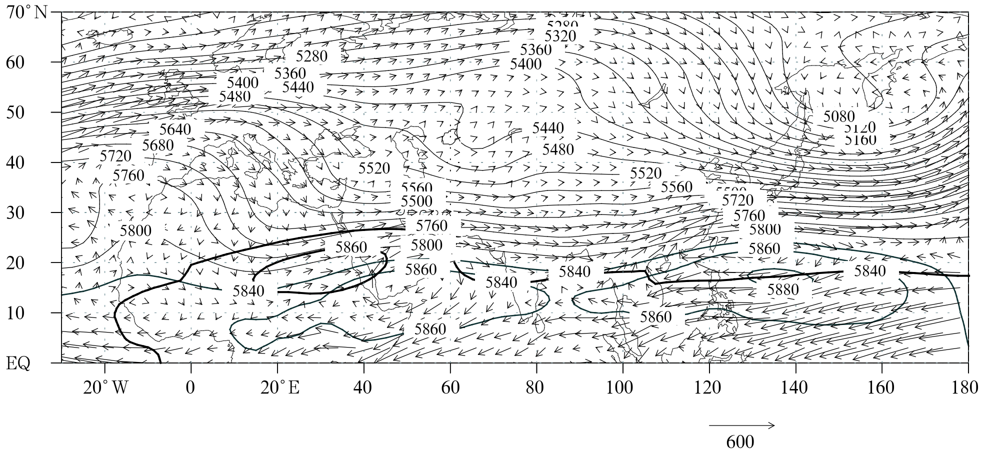

Fig. 10. The 500-hPa geopotential height field (solid, unit: gpm) and vertically integrated (surface to 100 hPa) water vapor flux (vectors, in kg m^{-1} s^{-1}) averaged over the period of 11 January to 2 February 2008. Thick lines stand for the climate mean lines of 5860/5840 gpm over the period of 1958–2006.

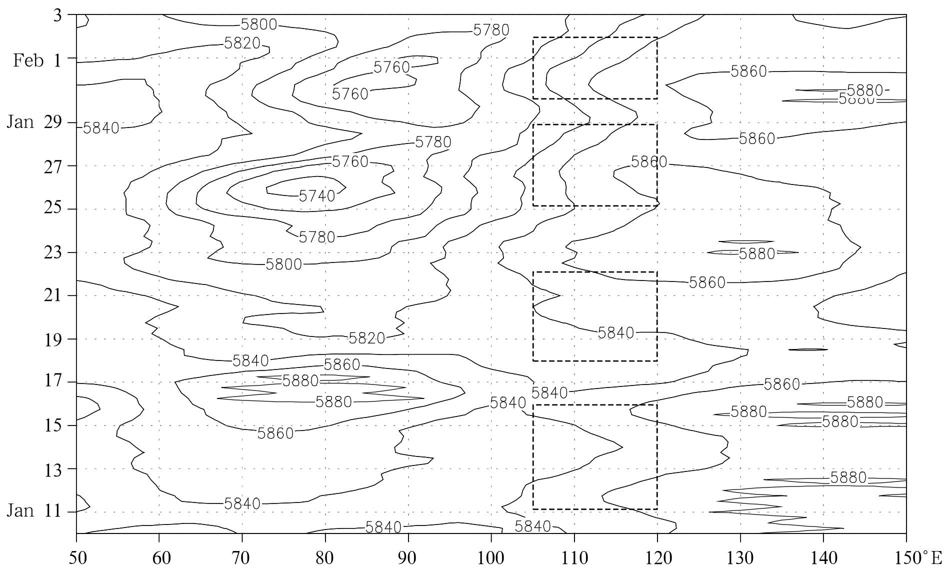

Fig. 11. Evolution of the 500-hPa geopotential height averaged over the latitudes (15°–25°N) between 10 January and 3 February 2008.

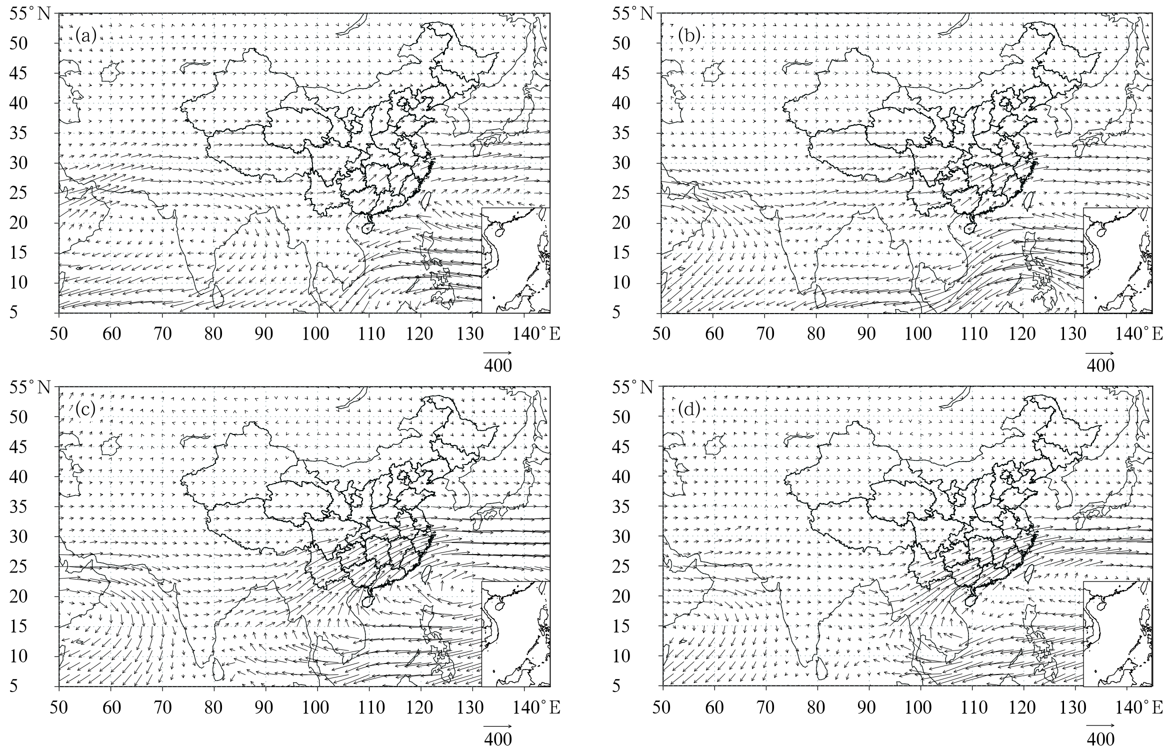

Fig.12. The vertically (surface to 100 hPa) integrated moisture flux field (vector, in kg $m^{-1}s^{-1}$) during each of the four precipitation processes: (a) 10–16 January; (b) 18–22 January; (c) 25–29 January; and (d) 31 January-2 February.

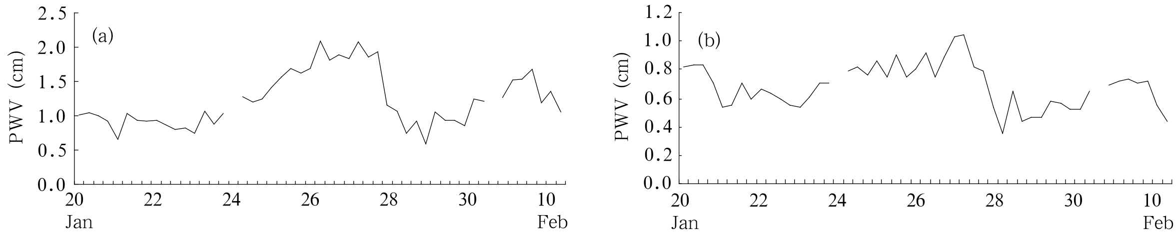

Fig. 13. Evolution of the GPS retrieved precipitable water from 0000 UTC 20 January to 1200 UTC 1 February over (a) Yunnan and (b) Sichuan.

water in Yunnan and the subsequent snowfall in the above three areas at a lead time of 24 h were 0.6781, 0.8198 and 0.6302, respectively, all exceeding the significance level of 0.001. The correlation coefficients between the GPS precipitable water (Fig. 13b) in Sichuan and the precipitation in the three areas were 0.5154, 0.5926, and 0.4442, respectively, all exceeding the 0.01 significance level. This implies that the moisture condition over the regions such as Yunnan and Sichuan may signify to some extent the subsequent precipitation situation in the downstream areas.

3.5 Cloud microphysics and the large-scale freezing weather

The most amazing and puzzling feature of this event is the hazardous weather associated with sustained heavy ice accumulation. Commonly, freezing rain events develop when a warm, moist layer of air overruns a colder air mass beneath to form an inversion layer. The favorable conditions for heavy ice events include warm air overrunning a near-stationary front that is generally oriented west-east (Brooks, 1920).

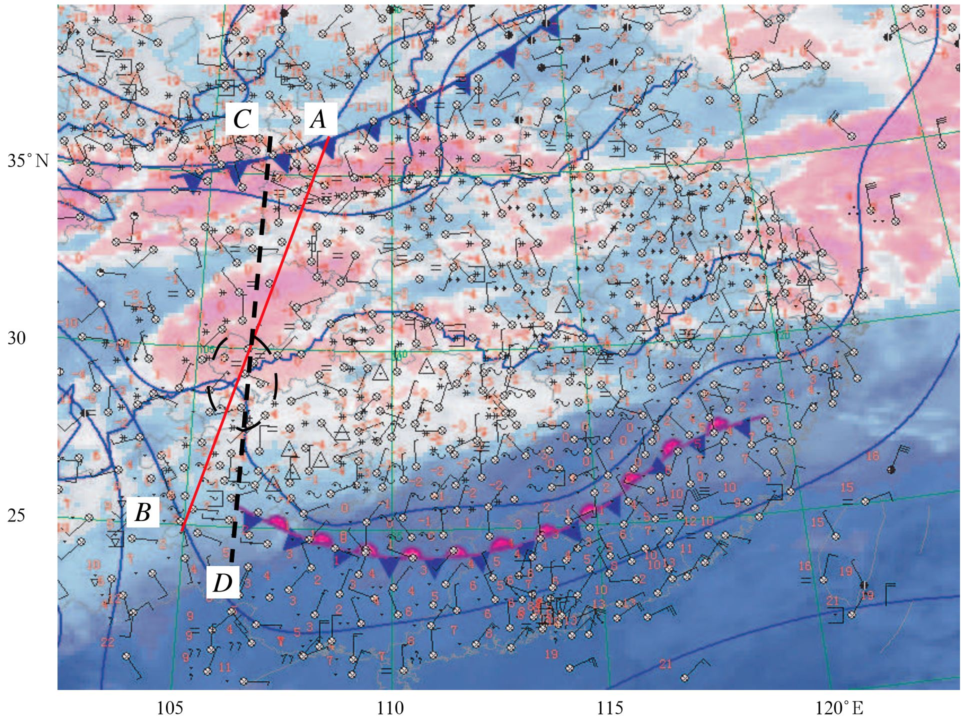

Fig. 14. The surface weather chart at 1800 UTC 27 January 2008. Line *AB* denotes the CloudSat scanned path.

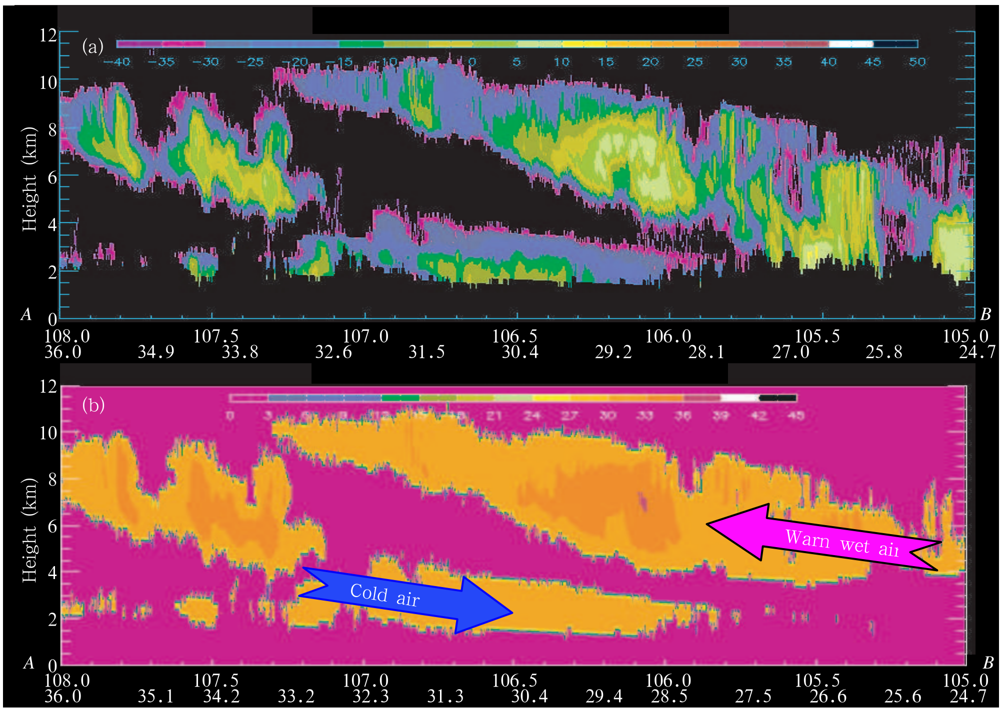

Fig. 15. Vertical cross sections of radar reflectivity (a, unit: dBz) and ice water content (b, unit: g m^{-3}) at 1800 UTC 27 January 2008, as observed from the CloudSat.

For example, across most states of the United States, the layer being overrun has top temperatures approximately colder than −10°C in the case of glaze. Similarly, the well-known west-east oriented near-stationary southern China front played a crucial role in the weather processes of January 2008. The vertical structure of the atmosphere during this event was also quite unique, which led eventually to a devastating ice accumulation covering large areas in the southern part of China.

The 3rd precipitation process (25–29 January 2008, see Fig. 7a), which is the most disastrous episode during the 0801 Southern Snow Disaster, is now taken as an example and to be discussed in detail. Particularly, we are now in the position to analyze in depth the microphysical structure of the cloud-breeding freezing rain using data from the Cloud Profiling Radar (CPR) onboard the new satellite CloudSat.

Figure 14 shows the surface weather chart at 1800 UTC 27 January 2008, over which the FY-2C infrared image is superposed. This is when the CloudSat was passing across Guizhou Province (indicated by line AB). The image suggests that there existed two cloud series: one was associated with the trough in the southern branch of the westerlies over the Bay of Bengal and the clouds there had higher temperature; the other was the plateau trough cloud series with lower temperature. From Fig. 15 (which is the cross-section along the line AB in Fig. 14), it is found that the strongly developed warm and humid air currents climbed up along the cold front, which moved downward and southward, wedged under the warm air mass, and formed two cloud bands at the altitudes distinctly different from each other. Meanwhile, it is seen that there were plenty of ice particles in the layers near the ground (see Fig. 15b), which could adhere directly and instantly to the surface or objects with lower temperature. Thus, this is one of the important causes for the ice accumulation on the surface and objects like trees and wires.

Compared with the case of 1800 UTC 27 January 2008, icing regions are found to have expanded and the cold-air-intrusion locations at the lower levels moved southward further at 0600 UTC 28 January, as shown in Fig. 16. The cross-section of temperature and horizontal wind fields (Fig. 17) taken along the nearest

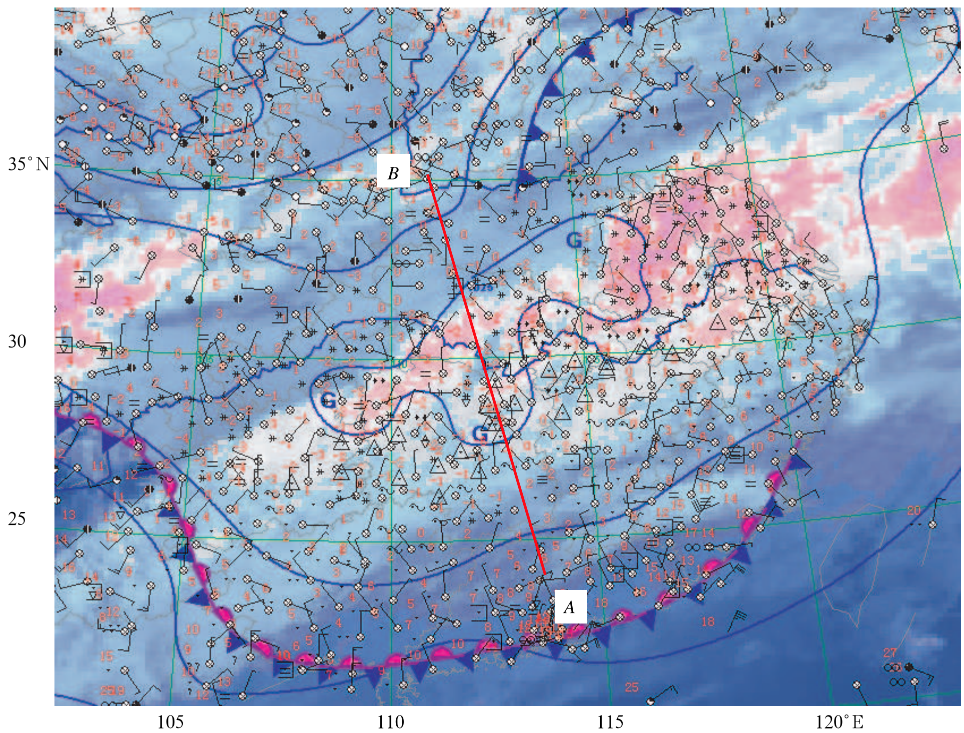

Fig. 16. The surface weather chart at 0600 UTC 28 January 2008. Line AB denotes the track scanned by Cloud Sat at that time.

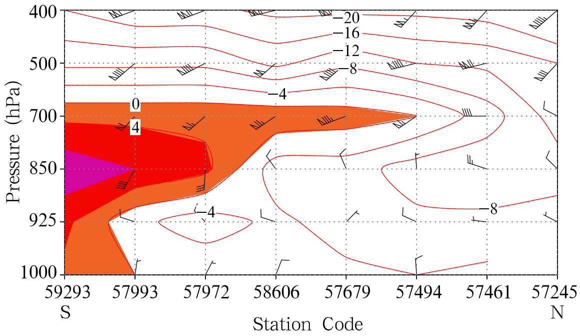

Fig. 17. The vertical cross section of the soundings at 0000 UTC 28 January 2008 along the line *AB* in Fig. 16 from south to north. Isothermal lines are in red. Areas larger than 0°C are shaded, and barbs denote the observed winds (A full wind bar is 4 m s^{-1}).

CloudSat track at 0000 UTC 28 January (i.e., line *AB* in Fig. 16) shows that a strong inversion layer lived in the middle levels. This was caused by the strong warmer southerlies that continuously transferred moisture into the middle and lower reaches of the Yangtze River and the cold air of relatively small velocity that invaded gradually from the north, making the surface temperature there drop to below 0°C (Fig. 18).

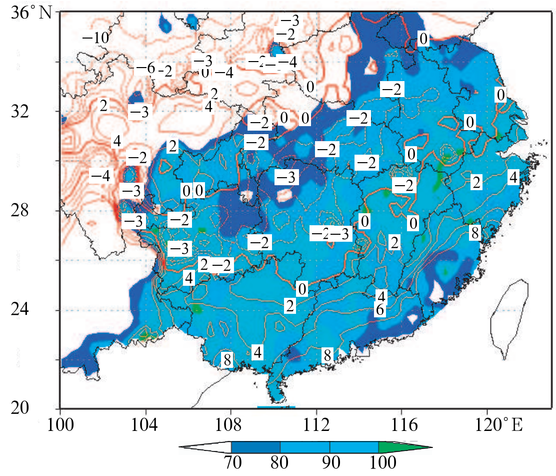

Fig. 18. Distributions of surface air temperature (contours, °C) and relative humidity (shaded, %) at 0600 UTC January 2008.

During the 3rd episode, the Ural blocking high was steadily developing at the higher latitudes while the western Pacific subtropical high got intensified and extended westward at the lower latitudes, which caused cold fronts from the north to intersect with the warm moist air over the southern areas of China.

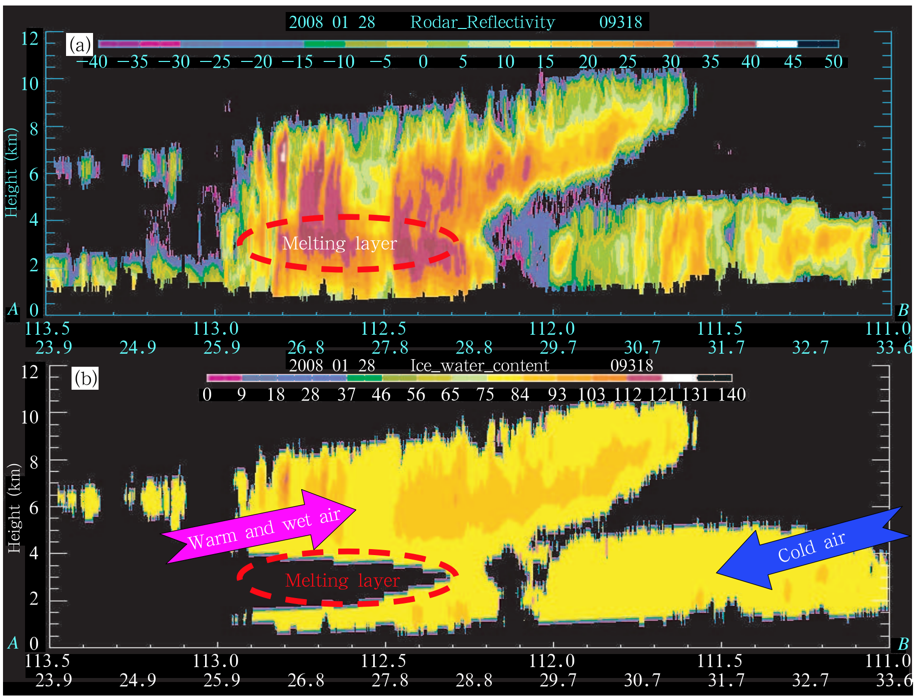

Fig. 19. As in Fig. 15, but for 0600 UTC 28 January. Areas circled by thck dashed red lines denote the melting layers of icing rain or snow.

Therefore, the very beneficial conditions for heavy precipitation in those areas were developed. As a matter of fact, heavy precipitation began to hit the southern areas of China from 25 January (see also Fig. 7a). Southeast Guangxi, entire Guangdong, and parts of Fujian provinces were caught by moderate to heavy rainfall, and then the rain belt gradually marched northward, resulting in the torrential snow during 28–29 January in the areas of southern Henan, eastern Hubei, Anhui, Jiangsu and northern Zhejiang, where the snow cover was found as deep as 20–50 cm on 28 January. At the same time, large-scale freezing rain events emerged in Jiangxi, and much of Guizhou and some parts of Hunan were still under the control of freezing rain.

Meanwhile, the near-stationary southern China front reached the coast of the South China Sea at 0600 UTC 28 January, thus causing larger damage-hit areas including, for example, the central-eastern Guizhou, Hunan, northern Jiangxi, southern Anhui, northern Jiangsu, etc. At this moment the satellite CloudSat happened to be passing across the icing area of Hunan. Figure 19 shows the vertical profile of the cloud radar reflectivity (Fig. 19a) and the corresponding ice water content (Fig. 19b) at 0600 UTC 28 January. It can be distinctly seen from Fig. 19 that there was a melting zone between 2 and 4 km above the surface at 26°–29°N and no ice particles existed in the corresponding inversion layer, where the temperature was higher than 0°C and strong southerly winds were prevailing. Active warm moist air from the south, climbing along the near-stationary southern China front, occupied the whole atmospheric column above 700 hPa. It overran the relatively weak cold air below. As a result, falling ice crystals aloft with low temperature first passed through the inversion layer before striking the surface, so the ice crystals got melted within the inversion layer closely related to the melting layer, as seen in Fig. 19. Subsequently, as falling further through the cold air layer beneath, the melted water droplets froze and changed into freezing rain upon contact with the surface or any objects. Hence, the existence of the inversion layer is critical to the formation of freezing rain. For example, only snowfall could be observed at 29°N since there was no inversion layer existing over there.

Since the satellite CloudSat was launched, advantageous data were available to identify the melting layer feature (Stephen et al., 2002). Especially, the CloudSat products of reflectivity combined with ice water content (Fig. 19) can be easily used to judge the existence of a melting layer and thus the possibility of lasting freezing rain, based on the information on the unique features of the melting layer (its intensification, thickness, anomalies, etc.).

4. Summary

The 0801 Southern Snow Disaster is a weather/climate event that rarely happens in the southern part of China. An abnormal synoptic feature during this event is the dramatically anomalous blocking condition maintained steadily over the region where the climate-averaged low is located, leading to the successive intrusion of cold fronts from the north into the southern part of China for a long period of time. Meanwhile, warm and moist air from the southwestern seas, were very active, owing to the abnormal intensification and northwestward extension of the subtropical high, providing abundant water vapor for the heavy snowfall/severe glaze. In addition, the well-developed inversion layer during this event grew and maintained persistently under favorable conditions of the near-stationary southern China front, which stimulated eventually the catastrophic freezing rains.

This study finds that the key factors causing the 0801 Southern Snow Disaster include: 1) the unusually active AO, which was very advantageous to the stable maintenance of the planetary-scale waves; 2) the successive transfer of very strong negative vorticity from the upstream areas around 50°E into the blocking high. This caused, time and again, the re-intensifying of the blocking condition already on the verge of collapsing, so the blocking situation could be maintained for a long time; 3) the active trough in the southern branch of the westerlies over the Bay of Bengal, south of the Tibetan Plateau, which guaranteed the abundant moisture supply to the southern areas of China; and 4) long-term existence of particular synoptic, dynamic, and physical conditions which were favorable for the genesis and development of ice storms.

REFERENCES

Berggren, R., B. B. Bolin, and C. G. Rossby, 1949: An aerological study of zonal motion, its perturbation and break-down. *Tellus*, **1**, 14–37.

Brooks, C. F., 1920: The nature of sleet and how it is formed. *Mon. Wea. Rev.*, **48**, 69–73.

Easterling, D. R., J. L. Evans, P. Y. Groisman, et al., 2000: Observed variability and trends in extreme climate events: A brief review. *Bull. Amer. Meteor. Soc.*, **81**, 417–425.

Karl, T. R., G. Kukla, V. N. Razuvayev, et al., 1991: Global warming: evidence for asymmetric diurnal temperature change. *Geophys. Res. Lett.*, **18**: 2253–2256.

Li, X. Q., and Z. X. Liu, 1986: The North-Semisphere and partition 500 hPa polar vortex area indexes. *Meteorological Monthly*, Supplement (2), 69–83. (in Chinese)

Liu, Z. X., 1986: Calculation of the North-Semispheric polar vortex intensity indexes and its relationship with changes in temperature in China. *Meteorological Monthly*, Supplement (2), 84–89. (in Chinese)

Luo, D. H., 2005: A barotropic envelope Rossby soliton model for block-eddy interaction. Part I: Effect of topography. *J. Atmos. Sci.*, **62**, 5–21.

Manton, M. J., and J. Eral, 2001: Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. *Int. J. Climat.*, **21**, 269–284.

Shutts, G. J., 1983: The propagation of eddies in diffluent jetstreams: Eddy vorticity forcing of blocking flow fields. *Quart. J. Roy. Meteor. Soc.*, **109**, 737–761.

Stephens, G. L., D. G. Vane, R. J. Boain, et al. 2002: The Cloud Sat mission and the A-Train. *Bull. Ame Meteor. Soc.*, **83**(12), 1771–1790.

Wang, S. W., and D. Y. Gong, 2000: Enhancement of the Warming Trend in China. *Geophsy. Res. Lett.*, **27**(16), 2581–2584.