Analysis of the Structure of the Temperature Field in Relation to the Persistent Snowy and Cold Weather in South China in Early 2008*

ZENG Mingjian[1,2†](曾明剑), LU Weisong[1](陆维松), LIANG Xinzhong[3](梁信忠), WU Haiying[2](吴海英), PU Meijuan[2](濮梅娟), and YIN Dongping[2](尹东屏)

1 *Nanjing University of Information Science and Technology, Nanjing* 210044, *China*

2 *Jiangsu Provincial Meteorological Observatory, Nanjing* 210008, *China*

3 *University of Illinois at Urbana-Champaign/Illinois State Water Survey, IL* 61820, *USA*

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ABSTRACT

In early 2008, a persistent cold and snowy weather process occurred in South China. Severe freezing rain (FR) and blizzards hit the region, which was not seen in the past 50 years. This work studied the disaster at its most severe stage (25 January–2 February 2008) and addressed the reason for the occurrence of three rainfall types and particularly the FR that resulted from the temperature inversion and low surface temperature. Evidence suggests that the south-to-north distribution of rainfall, FR, and snowfall was determined by the surface temperature conditions and the stratification features of the northward-tilting front in the mid-lower troposphere over different parts of South China. Under the above frontal conditions, the temperature inversion in the mid-lower troposphere and the cold ground temperature took place and the FR formed. The temperature layer (> 0°C) inside the inversion in this region depended on necessary intensity, depth, and height of the inversion, i.e., the depth of the inversion can be neither too thick or low nor too thin or high. For those too thick and low (too thin and high) inversions, the precipitation fell as rain (snow and ice pellets). In the early 2008 case, the 0–6°C layer occupied 650–850 hPa, below which was the sub-freezing level with temperature < 0°C. With the presence of the low sub-freezing level, FR or ice damage could occur even at the 0–1°C surface temperature condition. Besides, even in the absence of a suitable inversion, a low ground temperature might have made ice-covered water and supercooled drops or water from melted ice freeze rapidly into ice at the surface, and the ground ice maintained and accumulated, which resulted in the severe disaster.

Key words: South China, persistence, freezing, temperature structure

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1. Introduction

As a main disastrous event, low temperature and snowy weather in winter, *inter alia* the icing and blizzard, greatly concern theoretical and operational meteorologists as well as the government and public. These events can cause severe damage to transportation, communication, power supply, and building work, and greatly affect the social scope. For example, the freezing rain (FR) and blizzard that hit southern China in 2008 cut off the power supply to a significant extent. Flights were cancelled and most highways were closed in many southern provinces, causing unprecedented difficulties in transportation in the peak time close to the Chinese Spring Festival. This situation occurred due to the blizzard and the low temperature in provinces of Jiangsu, Zhejiang, Anhui, and Hubei, and to the FR over Jiangxi, Hunan, and Guizhou.

Past studies of blizzards are concentrated on the Tibetan Plateau, Northwest and Northeast China, and other extensive areas of northern China. The study by Wang and Xu (1979), for example, is devoted to the snowy weather of China based on the analysis of the blizzard event hitting Silin Gol League of Inner

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†Corresponding author: swordzmj@yahoo.com.cn.
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Mongolia in October 1977. In the study of the dynamic stability for a blizzard event from the perspective of conditional symmetric instability (CSI) and local symmetric instability (LSI), Wang and Ding (1995) discovered different mechanisms for snowfall in different centers of the snow belt. Wang and Cheng (2000) and Cai and Wang (2007) explored the dynamic mechanisms of a plateau blizzard by means of CSI and nonlinear symmetric instability theories. Zhang et al. (2007) researched the synoptic characteristics of a blizzard related to cold return-flows in North China. Some other investigations (e.g., Deng et al., 2000; Hu and Zhou, 2005; Wang et al., 2006; Jia et al., 2007; Sun Xingchi et al., 2007; Yang et al., 2007) documented the mechanisms and properties of a blizzard in North China in aspects such as atmospheric circulation, affecting weather systems, terrain effect, thermal/moisture conditions, and climatic features by means of diagnosis and numerical modeling. Overall, the study of northern China blizzards is more systematic and comprehensive while only a small number of studies on the southern China counterparts are performed based on experience, synoptic analysis, and physical diagnosis (Zeng et al., 2002; Chen and Xu, 2003; Chen, 2007).

The FR disasters in China are distributed mainly in Guizhou and, to a less extent, in Hubei, Hunan, Jiangxi, Anhui, and the Liaodong Peninsula. Chen et al. (1993) and Lu et al. (2004) made a case study of a northern China FR by analyzing the weather condition and vertical temperature distribution. In their study of a snowfall event in Beijing, Zhao et al. (2002) showed that the heavy coating of ice is most likely related to the extremely low surface temperature on that particular day. Guizhou is a province where the FR occurs most frequently. Meteorologists there have gained rich experiences in their operational practice in forecasting FR. A short-range climate prediction model (Xu, 2001), the space/time patterns and circulation analysis (Xu and Luo, 2003), the conditions for FR occurrences associated with the structure of the Yunnan-Guizhou stationary front (Du et al., 2007), and the interpretation of numerical products (Gu, 2001) havebeen constructed, performed and obtained. However, the above studies are confined to a single station or a limited region, without considering an FR event covering an area of thousands of square kilometers. Research of such a disaster began earlier in other countries. For instance, Okada (1914) investigated an FR event in Germany by use of surface observations, indicating that the ice-covered water substance can occur and is frozen at the surface when there is a layer close to saturation with temperature $> 0°$C, a sub freezing layer beneath, and a large enough rising motion. In their numerical study of an eastern Canadian FR event caused by a cyclone, Szeto et al. (1999) discovered an inversion layer with a sub-freezing layer over the FR region, where melted snow is re-frozen or frozen into supercooled raindrops, and they concluded that the inversion depth determines the precipitation type.

Chinese researchers (Sun Jing et al., 2007) identified a close relationship between temperature and the types of condensates distributed in cloud through microphysical modeling of two snowfall events in northern China. Stewart and King (1987) showed that different condensates (snow, ice pellets, and FR) in the inversion and lower sub-freezing layer are partially size-dependent. In addition, The'riault et al. (2006) investigated, by use of a model, the strength and depth of the inversion, the depth of the sub-freezing layer and the surface temperature for different types of precipitation. Tremblay and Glazer (2000) successfully modeled a few FR events in western Europe and North America. Cortains (2000) took a statistical approach to observing the conditions of FR that occurred in the Great Lakes region of North America, indicating that the advection and vertical motion of warm and moist air in a strongly baroclinic system may lead to the FR formation. The above studies follow the classic theory of the mechanism for FR formation in a "melting ice process." In contrast, Huffman and Gene (1988) proposed a "warm cloud" mechanism for FR formation, that is, with the intracloud temperature at 0–-10 °C, FR can be produced by coalescence among supercooled cloud droplets without the warm-layer melting and sub-freezing-layer freezing, a mechanism that is again demonstrated by Rauber et al. (2000) and Bernstein (2000). It follows that FR formation depends on some necessary atmospheric conditions, microphysical mechanisms, and vertical temperature structure. Moisture and surface temperature play an important role in the formation of FR.

As to the 2008 snowy weather spell, Ding et al. (2008) focused on the main characteristics of the disaster and its relation to climate change. A number of researchers (e.g., Wang Donghai et al., 2009; Yang et al., 2008; Wang Yafei et al., 2009; Tao et al., 2010) have performed studies on the large-scale circulation background, weather processes, and FR emerging conditions. The 2008 disastrous weather event is marked by persistent rainfall, FR, and snow distributed longitudinally from southern to northern China. Detailed analyses are still lacking regarding the different types of temperature/humidity structures, their difference and linkage in conjunction with the geographic position and topography of the precipitation zones. The present paper attempts to analyze and address proplems in these aspects.

The data employed are the 9210 system–offered soundings and surface observations from 2000 BT (Beijing Time) January 25 to 2000 BT February 2 2008, together with the 4 times daily global 1°×1° reanalysis data from NCEP in the same period.

2. The weather pattern and observations

Ding et al. (2008) indicated that the 2008 cold FR weather in southern China is not an isolated event. It occurred in the La Niña year-related climate background under joint effects of continuous cold air intrusion from the north and warm and moist air from the South China Sea (SCS) and the Bay of Bengal (BOB). During the disaster, the general synoptic pattern remained almost constant so we can illustrate the situation using the synoptic charts at 0800 BT 27 January. The upper-air and surface situations in Fig. 1 were constructed by reanalysis of the data at that time.

The 500-hPa geopotential height contours in Fig. 1a show that there is a strong blocking high in the east of the Urals, and airflows west of the high are separated into two branches: one in the south and the other in the north. The northern-branch flow, when reaching high latitudes, moves into China with northerlies to the east of the blocking high; whereas the southern-branch flow goes southward, detouring the Tibetan Plateau into the BOB where it becomes warm and moist and migrates from the southwest across the Hengduan Mountains into Guizhou and the neighboring provinces. Moreover, the subtropical high is vigorous enough to stretch its western end of the 588-dagpm ridge line into the central–western SCS, such that warm and wet air enters South China along the western side of the subtropical high. As shown by the arrows in Fig. 1, the three airflows meet and "confront each other" in the Yangtze River basin and to its south. The 700-hPa winds have prominent features with southwest jet streams at 12–25 m s^{-1} entering eastern China from the eastern Indian Peninsula across the BOB and the Hengduan Mountains. The 850-hPa temperature field (shaded) shows that cold air invades China from the western part of the Republic of Mongolia towards the eastern and then southern parts of China. In West China, cold air, after crossing the Qinling Mountains, penetrates southward along the eastern fringe of the Tibetan Plateau, staying in the northern part of the Yunnan–Guizhou tableland. In the central–eastern region of China, the cold air meets with southern warm and wet air, staying to the south of the Yangtze River. As seen on the surface map (Fig. 1b), the mainland as a whole is under the control of a continental cold high centered on the western Republic of Mongolia, with the 0°C contour of surface temperature maintained from the eastern littoral–the Wuyi Mountains–north of the Nanling Mountains to the eastern N–S Hengduan ranges. This situation is responsible for the anomalous weather spell of the so-called "summer climate prevailing in winter." Three types of precipitation, i.e., rainfall, FR, and snowfall, are distributed in order from south to north (Fig. 2). The wavy lines outline the FR zone in the period for which statistics is made. Rainfall areas lie to the south and east, but snowfall areas are largely to the north. The main part of the FR zone covers much of Guizhou, central–southern Hunan, and central Jiangxi Province, with FR weather also occurring in Hefei of Anhui and northwestern Guangxi.

3. Different types of precipitation over South China

Intense rainfall is typical in summers of southern China, but it occurred in the extremely cold season in early 2008, with three precipitation types including rainwater, FR, and snow, a distribution that is similar to the FR and snowfall events around central–western U.S. on Valentine's Day in 1990 (Czys et al., 1996). FR is produced from different mechanisms related to differing vertical temperature structures. The structure associated with the 2008 event is discussed below.

Guiyang is among the most heavily hit regions. Hence, we prepare a vertical cross-section of temperature passing through the neighborhood of Guiyang based on the reanalysis data at 0800 BT 27 January, when the most severe FR occurred. The section runs along 26°N, passing roughly through northern Yunnan, central Guizhou and Hunan, central–southern Jiangxi, and central Fujian (Fig. 3a). In this section, the most prominent feature is a slantwise "pear-shaped" cold zone ($t \leqslant 0$°C) around 105°–117°E in the lower troposphere. The cold zone has two cores, one at 850 hPa with $t \leqslant -6$°C around Guiyang (east of 106°E) and the other at 925 hPa with $t \leqslant -8$°C west of 112°E (the Lingling area of Hunan). The mid–lower troposphere over the cold zone exhibits a strong inversion, with temperatures of 0–6°C in the warm layer. To the west of the cold region (in Yunnan), a

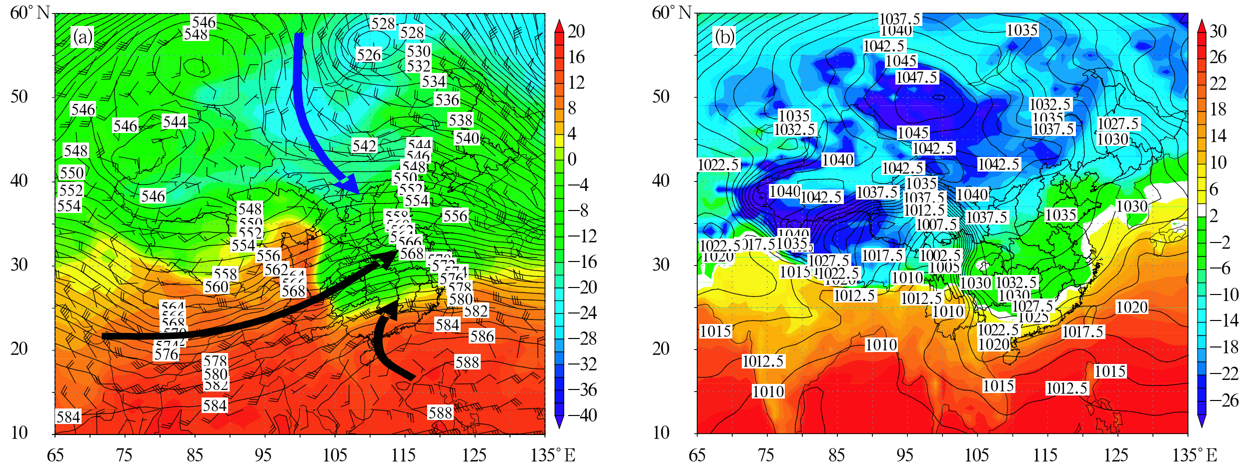

Fig. 1. The synoptic situation at 0800 BT 27 January 2008 with (a) 500-hPa height (dagpm), 700-hPa wind (m s^{-1}), and 850-hPa temperature (shaded; °C) and (b) sea level pressure (hPa) as well as 2-m height temperature (shaded; °C).

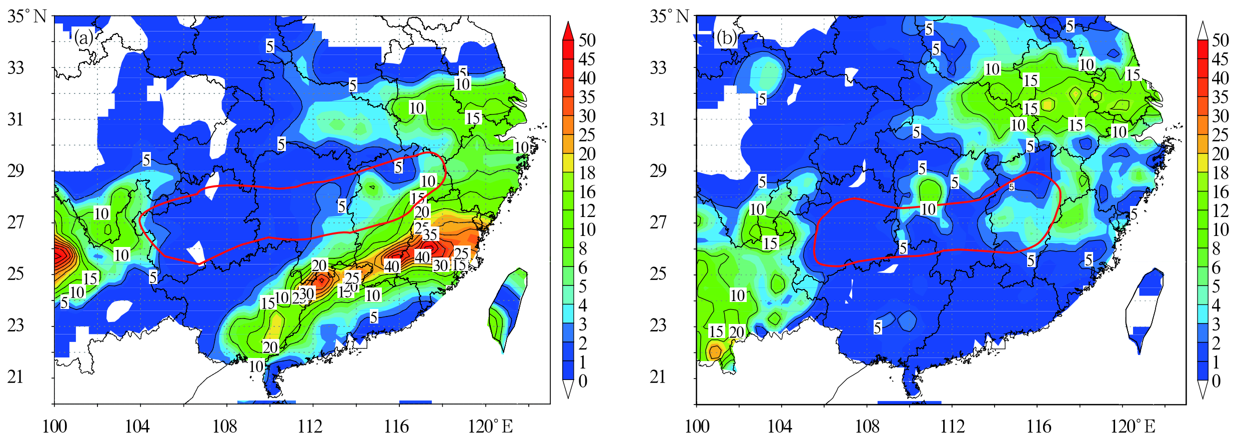

Fig. 2. The 24-h precipitation at 0800 BT (a) 27 and (b) 28 January 2008. Wavy lines delineate the FR zone.

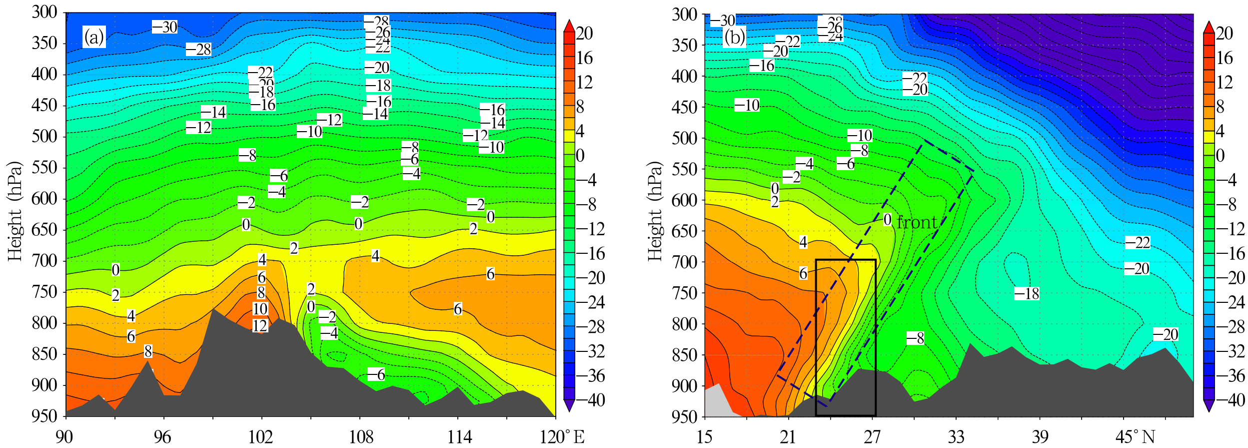

Fig. 3. Vertical cross-sections of temperature fields (°C) valid at 0800 BT 27 January 2008 along (a) 26°N and (b) 107°E.

consistent unsteady stratification structure is seen, and to the east (Fujian), a weak inversion layer with temperature > 0°C below 650 hPa exists. At 0800 BT 27 January (Fig. 2a), the "pear-shaped" cold zone relates entirely to the FR zone, while a convective shower occurs in Yunnan to the west and light rain presents in Fujian to the east. The precipitation types bear a close relationship to the stratification properties. Evidently, the unsteady stratification (> 0°C below and < 0°C above) is responsible for the rainfall, with stronger convection corresponding to more unstable stratification. The FR occurs over a region with temperature > 0°C at higher levels and < 0°C in the sub-freezing layer at low levels.

Figure 3b shows that, longitudinally, there is a "warm tongue" stretching upwards from south to north like a wedge placed slantwise into the pile of cold air running southward, leading to a frontal zone tilting northward and backward between the tongue and cold air from the surface to ~550 hPa (denoted by the blue dashed frame). The slant zone displays a stronger temperature inversion in the vertical direction, and inside the inversion from 24° to 28°N (the black frame), there is a region with > 0°C temperatures above a sub-freezing layer (< 0°C), corresponding to the S–N FR zone centered over Guiyang, except that the S–N dimension of this temperature inversion region is larger than the observed FR belt. The in situ data show that the area south (north) of this region received light rain (snow or ice pellets), implying that there are three types of precipitation over the S–N belt centered in Guiyang and they are in different horizontal positions of the slant front. However, at ~700 hPa, the inversion layer at these positions is featured with different strengths, depths, and heights for different precipitation types. In the south, the warm (cold) layer is deeper and lower (thinner), and in the north, the warm (cold) layer is thinner and higher (deeper). The conditions in Guiyang (as the center) are between the above two situations. Do these results imply that the inversion height, depth, and strength really determine the precipitation type?

To answer this question, a height–station cross-section is made from the station temperature data associated with rain, FR, and snow from south to north at 0800 BT 26 and 0800 BT 27 January 2008.

In Fig. 4, the stations inside the rainfall zone A are mostly in South China (south of the Nanling Mountains), including two stations in Fujian; the stations inside the FR zone B are those covering the areas east of Guiyang, on the north side of the Nanling Mountains, and Guizhou, Hunan, and Jiangxi south of the Yangtze River; the stations in the snowfall zone C are those along the Yangtze River to the east of Chongqing. All of these stations are arranged in order from west to east with the Ganzhou station coded 57993 being at the end of the zone B near to create a sectional distribution of temperature with height

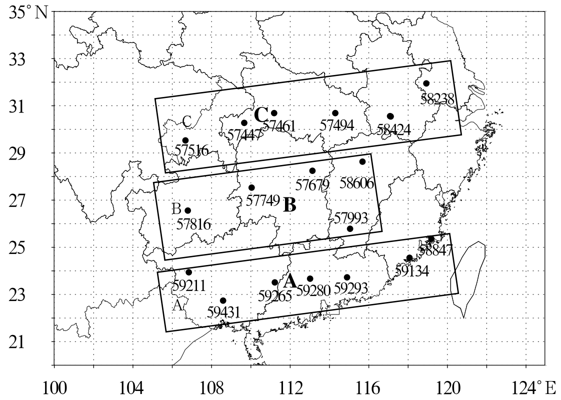

Fig. 4. Zones A, B, and C related to rainfall, freezing rain, and snowfall, respectively. Dots denote the stations, and station numbers are marked below the dots.

(Fig. 5).

In Fig. 5a, a constant 0°C isothermal stratification exists throughout the mid–lower troposphere at one zone-A station in Guangdong (Heyuan, 59293). Over other stations, temperature cores of > 10°C around 850 hPa are capped by cold air, thus constituting an unstable stratification. Inversion stratifications are found in the near-surface layer with temperature > 3°C. No rainfall is found at station 59293 and only light rain occurs at other stations. The stations in zone B show an inversion with > 0°C temperatures in the middle troposphere (near 700 hPa) and < 0°C temperatures in the lower troposphere, and the cold center has a temperature lower than –9°C. It is noted that the warm layer is extremely deep and low over station 57993 (Ganzhou of Jiangxi Province), with > 0°C temperatures occupying 650–900 hPa, except a thin cold layer around 925 hPa (immediately with a warm layer below), leading to light rain at Ganzhou. FR is observed at other stations on the same day. It seems that a deep and low warm layer and higher near-surface temperatures are unfavorable for FR genesis. Greater differences in the stratification are found between stations in zone C. At station 57516 (Chongqing), no clear stratification is observed in the mid–lower troposphere (similar to an isothermal structure), except for a thin layer of unstable stratification in the near-surface layer. Station 57447 (Exi of Hubei) is in a cold region of weak inversion. Stations 57461 (Yichang) and 57494 (Wuhan) have cold centers at 850 hPa, forming a more intense inversion with temperature < –3°C at 700 hPa. The stratification over station 58424 (Hefei) is similar to that of zone B, with a warm core (> 0°C) at 700 hPa. The temperature condition is analogous over Nanjing (58238) to that over Wuhan. The observations show that light rain takes place in Chongqing and snowfall is observed at Exi around 0800 BT 26 January. Icing is reported on power lines in Yichang, while light snowfall is seen in Wuhan and Nanjing, with FR occurring in Hefei. Evidently, the inversion itself is not the sufficient condition for FR, but the strength, depth and altitude of inversion act as the main factors to determine the pretipitation types.

At 0800 BT 27 January (Fig. 5b), the stratification has changed slightly compared to the condition the day before. The inversion domain of zone B extends eastward. The temperature over station Ganzhou (57993) drops to < 0°C below ~900 hPa. The original warm layer becomes thin, and the warm center rises upward, with FR happening over Ganzhou at that time. It is obvious that the height of the warm layer acts as one of the causes of the FR genesis. In Hefei of zone C, the strength of the warm area is reduced, with the central temperature decreasing to about –1°C, thus terminating FR. It follows that an inversion layer (> 0°C) serves as a necessary condition for FR.

The above analysis indicates that the early 2008 event is an FR episode produced under an condition similar to the classic "melting ice" process. It is the atmospheric vertical temperature structure that directly affects the precipitation types. Water from melted ice crystals passing through an inversion layer and liquid water in clouds falling into the sub-freezing layer below the inversion become ice-covered water substance or supercooled water drops falling onto ground. FR is probable when this occurs. However, whether FR is thereby formed in the end or if a disaster emerges after freezing on the ground depends strongly on surface temperature, as indicated in relevant references. In fact, FR is observed mainly in Guizhou, Hunan, and Jiangxi, while snowstorms are observed in Hubei,

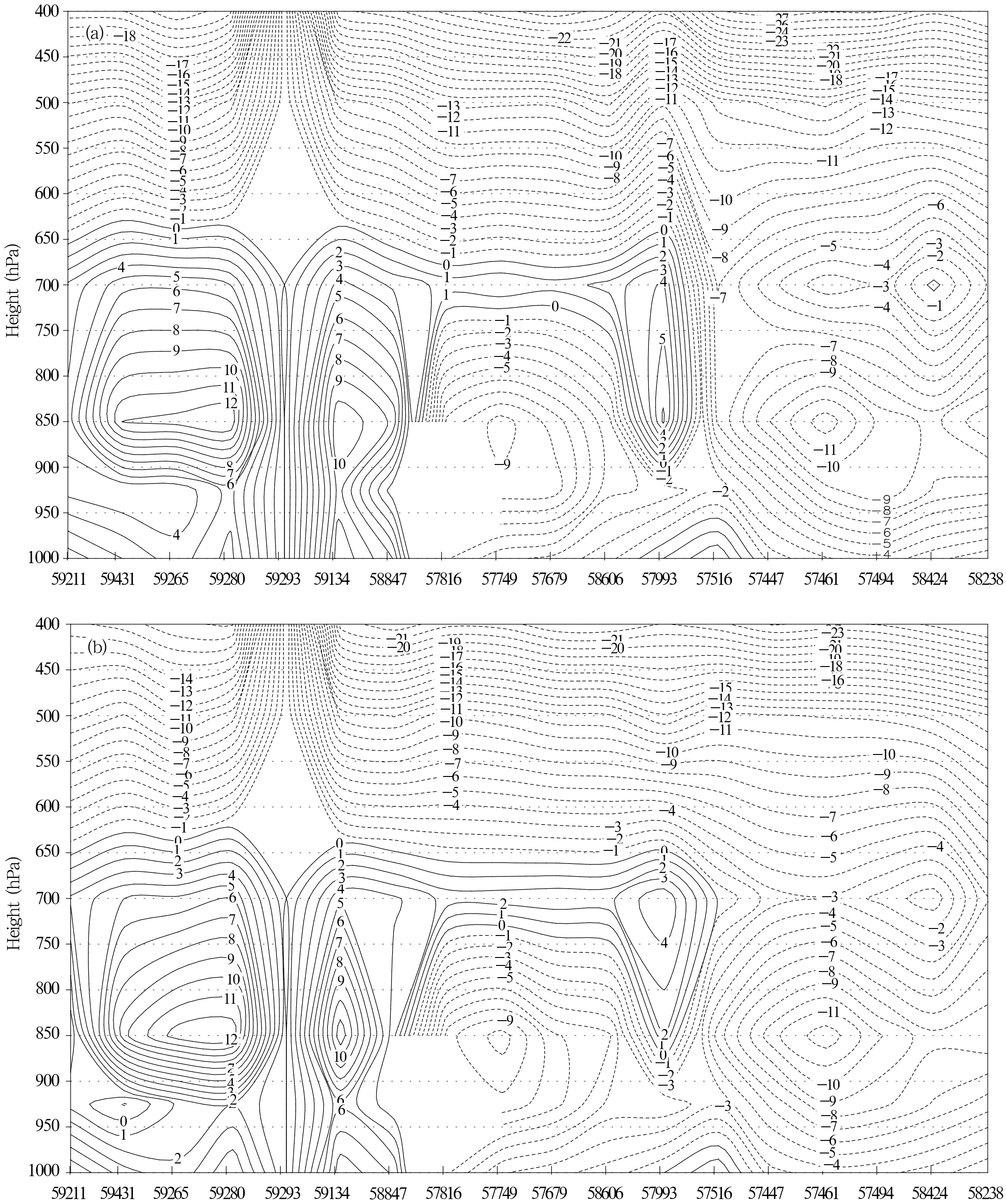

Fig. 5. Height–station profiles of temperature at 0800 BT (a) 26 January and (b) 27 January 2008.

Anhui, and Jiangsu. Then, why do severe freezing calamities also occur in Hubei, Anhui, and Jiangsu where the dominant precipitation type is snowfall? Figures 6a and 6b provide the time-dependent daily lowest surface air temperature and ground surface temperature over the stations in the same order as in Fig. 5.

Figure 6a shows that during the cryogenic disaster, the daily lowest surface air temperature is higher than 0°C at all stations in zone A (rainfall regions); in zone B (FR region), it is lower than 0°C at all stations except Ganzhou (57993) of 0–1°C. In particular, the lowest surface air temperature at Guiyang is below –4°C throughout the day. For zone C (snowfall region), the minima are below 0°C (excluding Chongqing, 57516) eastward from Exi (57447).

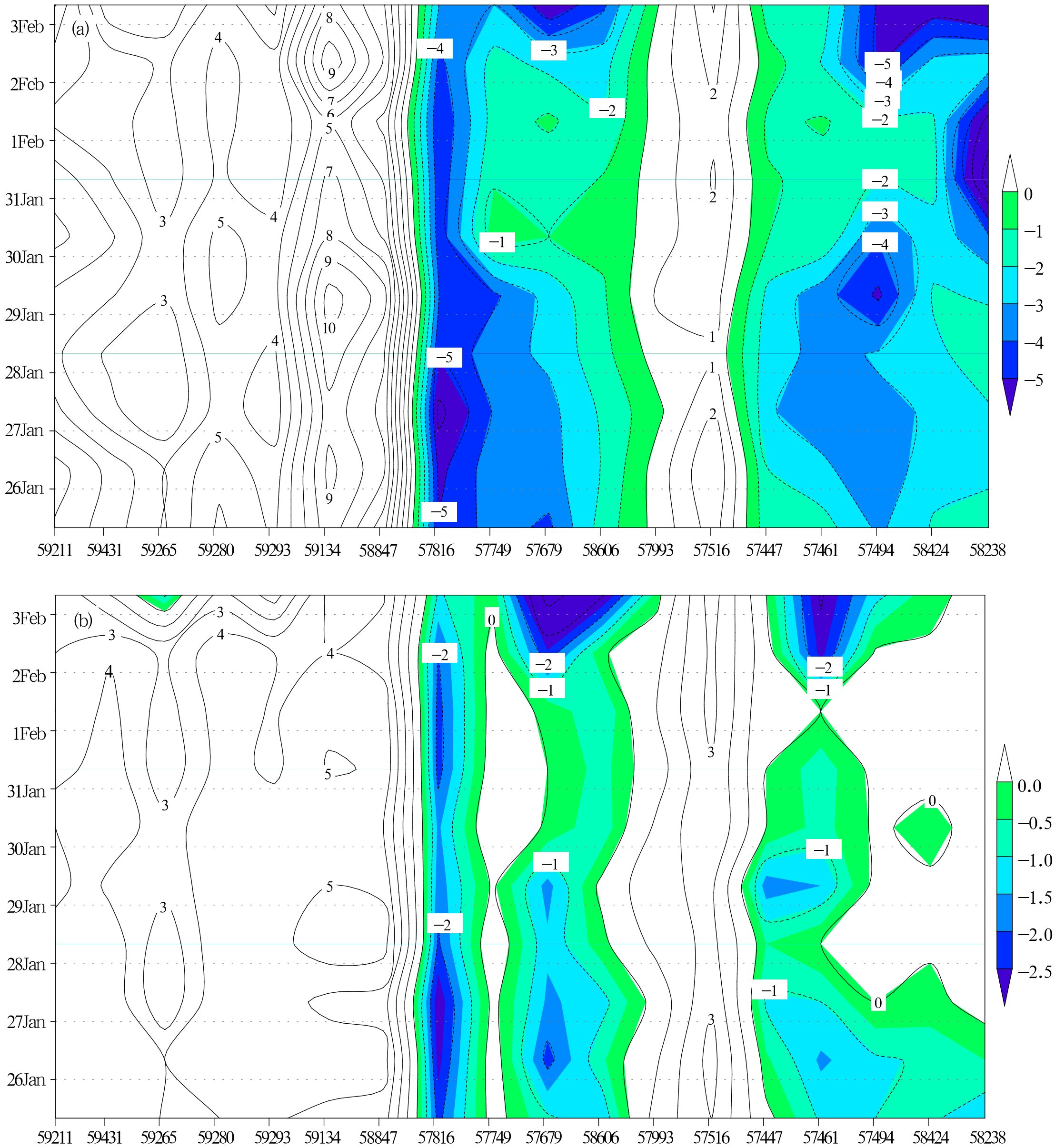

Fig. 6. Evolution of daily lowest (a) surface air and (b) ground surface temperatures (°C).

Figure 6b shows the daily lowest ground surface temperature, with a distribution similar to that of Fig. 6a. The daily lowest ground surface temperature ranges within 0–1°C at Huaihua (57749) and Exi (57747). It follows that FR genesis is closely associated with surface air temperature or ground surface temperature. The linkage is that a colder surface (< 0°C) allows the ice-covered water substance and supercooled waterdrops at the ground or melted snowflakes to freeze rapidly into ice pellets that may be maintained for some time. In the blizzard-stricken region, the smashed ice melting due to daily temperature rises and/or car emissions, which gets frozen rapidly at night, causes an icy disaster. This illustrates the reason for the occurrence of severe freezing damage in Anhui, Jiangsu and especially in Hubei where only blizzards take place and there is no appropriate inversion layer. In addition, even if the surface temperature is not below 0°C but is close to 0°C, the ice-covered water and supercooled drops could freeze after they fall to the ground. In such a case, the freezing/icing is weak in intensity and short in duration as observed.

The above analyses indicate that the FR process occurs when there exist atmospheric inversion and suitable ground surface temperature associated with a tilting frontal zone in the mid-lower troposphere, and the inversion layer is of appropriate intensity, depth, and height, i.e., the warm layer has to be warmer than 0°C, neither too deep or low nor too thin or high. If the inversion layer is too deep or low, water from melting ice crystals falling through the warm layer or the in-cloud liquid water that is dropping will fall as rain onto ground because there is no time to freeze into ice-covered water substance or supercooled drops. This accounts for the occurrence of the rain to the south of the solid black frame shown in Fig. 3b. If the inversion is too thin or high, ice crystals will fall as snow or ice pellets because they have no time to melt and fall into the cold layer. This is the case to the north of the black frame in Fig. 3b. A lower surface temperature allows the ice-covered water substance or supercooled waterdrops to quickly freeze into ice pellets on the ground. These ice pellets accumulate and could also cause a disaster. As shown for this event, the 0–6°C inversion layer is between 650 and 850 hPa, with a < 0°C sub-freezing layer below. With such a sub-freezing layer, FR is possible even at a surface temperature of 0–1°C. This fact differs from the modeling results of The'riault et al. (2006) regarding the condition that surface temperature must be under 0°C, but it conforms to the North American FR statistics described by Cortains (2000) and Cortains et al. (2004).

We analyzed the distribution of rainfall, FR, and snowfall in association with the air temperature and ground surface temperature intensity. In fact, although the vertical and horizontal temperature distributions are a result of the weather systems and their interactions, the topographical role in causing the snowy and FR weather should not be neglected, considering that the FR belt is distributed mainly in Guizhou, Hunan, Jiangxi, east of the S–N Hengduan ranges, and north of the Nanling Mountains. The topographic role will be discussed in a separate article.

4. Conclusions

Based on the analysis of the synoptic situation, precipitation types, temperature stratification, and surface temperature strength, we addressed the persistent adverse weather event in early 2008 over a large area of southern China, particularly with respect to the conditions of FR occurrence. The following conclusions are drawn:

(1) The rainfall, FR, and snowfall distributed in a south-to-north direction are related to different temperature stratifications of the front, the northward tilting of the front in the mid-lower troposphere, and the surface temperature intensity as well.

(2) In the tilted frontal background, the temperature inversion and suitable surface temperature have facilitated the FR genesis, with the inversion layer having appropriate strength, depth, and height. The temperature in the warm sector of the inversion must exceed 0°C. The warm layer of the inversion should be neither too deep or low nor too thin or high. In the case of a too deep and too low inversion, the water from melting ice crystals falling through the inversion layer or intra-cloud water falling downward cannot be frozen into ice-covered water or supercooled drops because of the absence of enough space for low temperature, leading to rain falling onto the ground. In the case of a too thin and too high inversion, ice crystals have insufficient time to become water before entering the < 0°C layer, so they appear as snow or ice particles.

(3) In the absence of an appropriate inversion, a cold surface allows ice-covered water substance and supercooled drops falling to the ground or melting snow to be frozen into ice, which could be maintained to form a disaster.

(4) The 0–6°C inversion from 650 to 850 hPa is required, with a < 0°C sub-freezing layer below. In that case, FR or ice disaster is likely to occur even if the surface temperature range is 0–1°C.

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