Article ID: 1006-8775(2013) 01-0067-13

A QUANTITATIVE STUDY FOR ABNORMAL FREEZING RAINS AND SNOWSTORMS IN SOUTHERN CHINA IN EARLY 2008

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Abstract: A quantitative diagnosis is carried out for the upward branch of a local meridional circulation over southern China (SC) during the abnormal snowstorms with severe freezing rain from 10 January to 3 February 2008. The diagnostic study shows that the upward branch is mainly associated with the zonal advection of westerly momentum and meridional temperature advection instead of the latent heating (which is commonly the dominant factor in many other storm cases). The corresponding weather analyses indicate that (1) the zonal advection of westerly momentum represents the effect of the upper-level divergence on the anticyclone-shear side in the entrance of a 200 hPa westerly jet with a westward deviation from its climatological location over southwestern Japan; (2) the meridional temperature advection represents the interaction between the mid-lower layer (850 to 400 hPa) warm advection over SC (ahead of temperature and pressure troughs with the latter trough deeper than the former in the Bay of Bengal) and cold advection over north China (steered by an underlying flow at 500 hPa); (3) the relatively weak vapor transport (compared to that of spring, summer and autumn) from the Bay of Bengal and the South China Sea to SC and the existence of a temperature inversion layer in the lower troposphere over SC diminish the effect of latent heating. With the significant increase of vapor transport after 24 January, the role of latent heating is upgraded to become the third positive contributor to the upward branch over SC.

Key words: freezing rain and snowstorms; westerly jet; local meridional circulation; temperature advection; vapor transport; inversion layer

CLC number: P458.1.21 **Document code:** A

1 INTRODUCTION

The southern China was seriously influenced by abnormal snowstorms with severe freezing rain from 10 January to 3 February 2008, which led to closure of highways, railway transports and civil aviation flights that caused thousands of travelers stranded on their way home for Spring Festival. This disaster killed about 100 people and resulted in a direct economic loss of more than 150 billions yuan (about US$ 21 billions at that time). Therefore, it deserves attention from the Chinese government and researchers[1]. Tao et al.[2] argued that the air temperatures in Henan, Jiangxi, Hunan, Guangxi, Guizhou, Shaanxi and Ningxia were 4°C lower than normal from 10 January to 3 February. In addition, the air temperature in the regions of middle and lower reaches of the Yangtze, Hanjiang and Huaihe Rivers, south of the Yangtze River basin and eastern part of Southwest China reduced to –8 to 0°C, and the precipitation more than doubled in the drainage area adjoining the Yangtze and Hanjiang Rivers and most of Northwest China, which is coincident with Wang et al.[3].

It is rare that the previous abnormal snowstorms could last as long as this one. Lots of studies showed that this disaster occurred mainly because there was a sustained blocking high in the middle and high latitudes of Asia and the western Pacific subtropical high was strong and northward located, the southern

Received 2011-06-25; **Revised** 2012-11-26; **Accepted** 2013-01-15
Foundation item: National Natural Science Foundation of China (40965001, 41265003); and an open project of State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences (2009LASW-A02)
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branch trough of west wind remained stable and active and a temperature inversion layer appeared in Guizhou and Hunan[1-4], together with the downstream development effect of the Rossby wave[1, 5-7], lower stationary front frontogenesis caused by an upper vortex tongue[1], active Arctic oscillation[3], sea surface temperature anomalies in the tropical western Pacific and western North Pacific[4, 8] and a Ural blocking high that stayed strong and northward in a La Niña climate background. For this freezing disaster in early 2008, however, most of the studies were conducted mainly based on weather and statistic analysis with few focused on quantitative diagnosis. In fact, the precipitation in early 2008 was similar to some rainfall during strong summer Meiyu periods[2] with the characteristics of northward warm and moist air joining in southward cold and dry air in southern China. Therefore, meridional circulation over southern China during this period was quantitatively diagnosed by using the meridional circulation linear diagnosis model[10], which mainly includes dynamic and thermodynamic processes[11]. This model has been applied to simulate the East Asia monsoon, South China Sea monsoon, south China spring drought, and Yangtze River flood for its good performance. These studies showed that the early outbreak of a South China Sea summer monsoon was related to the appearance of early warm advection, and the late Indian summer monsoon was connected to cold advection that disappeared late[11]. They also showed that the primary factors that influence south China spring drought were latent heat, meridional temperature advection and zonal westerly momentum advection[12] and the appearance and spread of low-frequency cyclones in low-latitude regions during the Yangtze River flood period of 1998 were closely related to the effects of condensation latent heat, heating boundary and heat vertical transfer. Moreover, the appearance and spread of high-latitude, low-frequency cyclones were mainly connected to the influences of horizontal westerly momentum advection and temperature advection; a Lake Baikal-Xinjiang low trough and the warm advection ahead of a small trough separated from the westerly were superposed with southwest warm advection at the west of the subtropical ridge in Yangtze River region, which can be used to some extent to forecast autumn flood in the Yellow River and Huaihe River basins. And the forecast of the ending time of autumn flood can take reference from upper-tropospheric cold advection that appears in this region and upper westerly jet streams from South Asia to the north of the Yangtze River basin[15]. In this study, based on the results of meridional circulation over southern China for these abnormal events of interest, which is simulated by a meridional circulation linear diagnosis model and in association with analyzing the influences of physical processes on local meridional circulation, main factors and their influencing systems were determined.

2 DATA AND MODEL

2.1 *Material and methods*

Daily National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR, USA) reanalysis data with 2.5°×2.5° resolution were used in numerical simulation and diagnostic analysis. Upper-level meteorological elements are consisted of horizontal wind, geopotential height, temperature, vertical speed and specific humidity in 13 vertical layers that were at the pressure levels of 1,000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100 and 50 hPa, respectively. Besides, the inputs of model also included sig995 horizontal wind, surface pressure, surface temperature, surface elevation, surface humidity and Gaussian grid surface sensible heat flux, surface latent heat flux and surface net longwave radiation from universal standard time January 1 to February 20 in 2008. The interval of the rainfall dataset was 3 hours with 0.25°×0.25° resolution from TRMM satellite 3B42. In this paper, the coverage of the research area was from 102.5 to 120°E and from 0 to 60°N.

2.2 *Model introduction*

A meridional circulation linear diagnostic model was established by Yuan et al.[10, 11] associated with the conservation equations of zonal quality, momentum and energy in the *p*-coordinate system. The mathematical model is as follows:

$$\frac{\partial}{\partial y}\left(\frac{\overline{\sigma_s}}{\cos\varphi}\overline{\frac{\partial\psi}{\partial y}}+\frac{1}{\cos\varphi}\frac{\partial\overline{\alpha}}{\partial y}\overline{\frac{\partial\psi}{\partial p}}\right)+\frac{\partial}{\partial p}\left(\frac{1}{\cos\varphi}\frac{\partial\overline{\alpha}}{\partial y}\overline{\frac{\partial\psi}{\partial y}}+\frac{f_A\overline{\zeta_a}}{\cos\varphi}\overline{\frac{\partial\psi}{\partial p}}\right)=$$

$$\frac{\partial}{\partial p}\left[f_A\left(-\frac{\partial\overline{\Phi}}{\partial x}+\overline{F_x}-\overline{u}\frac{\partial\overline{u}}{\partial x}-\overline{u'\frac{\partial u'}{\partial x}}-\overline{v'\frac{\partial u'}{\partial y}}-\overline{\omega'\frac{\partial u'}{\partial p}}+\frac{\overline{u'v'\tan\varphi}}{a}+f\overline{v_{HC}}-\overline{v_{HC}}\frac{\partial\overline{u}\cos\varphi}{\cos\varphi\partial y}-\overline{\omega_{ZC}}\frac{\partial\overline{u}}{\partial p}\right)\right]$$

1 2 3 4 5 6 7 8 9 10 ,

$$-\frac{\partial}{\partial y}\left(\frac{R\overline{\dot{Q}}}{pc_p}-\bar{u}\frac{\partial\bar{\alpha}}{\partial x}-\frac{\partial\bar{\alpha}}{\partial y}\overline{v_{HC}}+\overline{\sigma_s}\overline{\omega_{ZC}}-\overline{u'\frac{\partial\alpha'}{\partial x}}-\overline{v'\frac{\partial\alpha'}{\partial y}}+\overline{\sigma_s'\omega'}\right) \tag{1}$$

11 12 13 14 15 16 17

where a local meridional mean value is $\overline{(\ )}=\left[\int_{\lambda_1}^{\lambda_2}(\ )\,\mathrm{d}\lambda\right]/(\lambda_2-\lambda_1)$, λ_1=102.5°E, λ_2=120°E, $(\ )'$ is the average disturbance related to meridional mean value, Φ the geopotential height, α the specific volume, Earth radius a=6,371 km, λ is the longitude, φ the latitude, p pressure, t time, u, v and ω are velocity components at the x, y and p direction, f is the Coriolis parameter, F_x the friction component at x direction, $v=v_{HC}+v_{MC}$, and $\omega=\omega_{ZC}+\omega_{MC}$. Here v_{HC} is the horizontal circumfluent component of v, v_{MC} the component of meridional circulation, ω_{ZC} the component of zonal circulation, ω_{MC} the component of meridional circulation, θ potential temperature, $\sigma_s=\alpha/\theta(-\partial\theta/\partial p)$ static stability, $\dot{Q}/c_p$ non-adiabatic heating rate, gas constant R=287 J/(kg·K), constant-pressure specific heat c_p=1,004 J/(kg·K), $\mathrm{d}x=a\cos\varphi\mathrm{d}\lambda$, $\mathrm{d}y=a\mathrm{d}\varphi$, ψ is meridional circulation function. So v_{MC} and ω_{MC} are calculated as in:

$$v_{MC}=-\frac{1}{\cos\varphi}\frac{\partial\psi}{\partial p}, \tag{2}$$

$$\omega_{MC}=\frac{1}{\cos\varphi}\frac{\partial\psi}{\partial y}. \tag{3}$$

The forcing factors on the right-hand side of the equations are classified as dynamic and thermal factors. Dynamic factors include pressure gradient-force (term No.1), friction (term No.2), zonal advection of mean westerly wind momentum (term No.3), zonal advection of eddy westerly wind momentum (term No.4), meridional advection of eddy westerly wind momentum (term No.5), vertical convection of eddy westerly wind momentum (term No.6), curvature (term No.7), Coriolis force (term No.8), meridional advection of average westerly wind momentum (term No.9), and vertical transport of average westerly wind momentum (term No.10). Thermal factors consist of sensible heat flux $\dot{Q}_{SF}$, latent heat flux $\dot{Q}_{LF}$, latent heat $\dot{Q}_L$ and solar shortwave and atmosphere net longwave $\dot{Q}_R$ ($\dot{Q}$ in term No.11 consists of these factors), average zonal temperature advection (term No.12), mean meridional temperature advection (term No.13), vertical transport of average temperature (term No.14), advection of eddy zonal temperature (term No.15), advection of eddy meridional temperature (term No.16) and advection of eddy vertical temperature (term No.17).

In Eq. (1), v_{HC} and ω_{ZC} can be calculated as known quantities. The previous studies generally assumed that v_{HC} is approximately equal to v_g[11, 12]. However, as the error of v_g in the vicinity of the equator is so large that in this paper v_{HC} is calculated as in:

$$v_{HC}=\frac{\partial\psi_{HC}}{\partial x}. \tag{4}$$

Here ψ_{HC} is the horizontal circulation function, which is based on the Poisson equation:

$$\nabla^2\psi_{HC}=\zeta=\frac{\partial v}{\partial x}-\frac{\partial(\cos\varphi u)}{\cos\varphi\partial y}. \tag{5}$$

v_{HC} is substituted into an input continuity equation and ω_{ZC} on the p isobaric surface is calculated by integrating v_{HC} from tropopause (p_T=50 hPa) to p:

$$\omega_{ZC}=-\int_{pT}^{p}\frac{\partial u}{\partial x}+\frac{\partial v_{HC}\cos\varphi}{\cos\varphi\partial y}\mathrm{d}p. \tag{6}$$

Because Eq. (1) is a linear equation about $\bar{\psi}$, solutions of the equation can be overlaid or resolved. The arithmetic solution of Eq. (1) can be obtained with the central difference and over-relaxation iterative method[16] when local zonal average field is under stable condition[10, 11]. Then the effects of every term on the right hand side of Eq. (1) can be quantitatively determined.

3 CHARACTERISTICS OF PRECIPITATION IN SOUTHERN CHINA DURING EARLY 2008

Based on the datasets of TRMM 3B42, precipitations in the Yangtze and Huaihe Rivers basin, south of Yangtze River and most areas of southern China during January 2008 were all between 50 and 100 mm. They were even more than 100 mm in central part of southern China, south Henan, central Anhui and south Jiangsu (Figure 1a). Precipitation in southern China, the Yangtze and Huaihe Rivers basin and most areas of Northwest China were more than their previous record for the period, which agreed with the conclusion in Tao et al.[1]. It is particularly noted that precipitation in Guizhou, Hunan and Jiangxi provinces in early 2008 was less than that in the same period of previous years (Figure 1b). The research showed that there were temperature inversion layers in Guizhou, Hunan, Jiangxi and Zhejiang during the freezing disaster of early 2008[1-4], which meant that the lower layers of troposphere were very stable, suppressing the development of severe convection and conducing to rainfall reduction. It also indicates clearly that latent heat of condensation may not be the primary factor of influence (quantitative result shown in section 4.2).

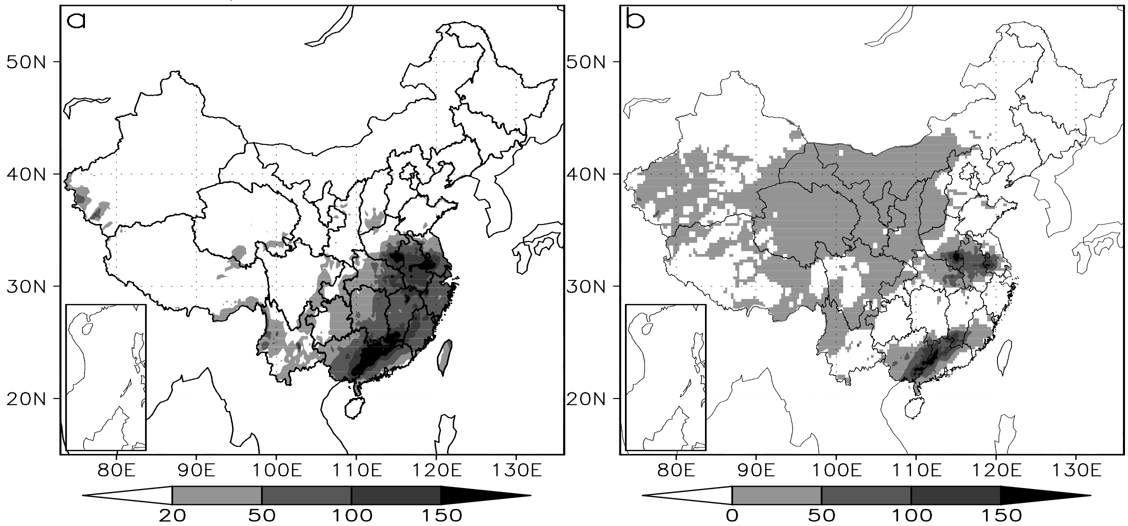

Figure 1. (a) Precipitation and (b) rainfall deviation in China during January 2008, relative to the average value in Januaries 1998 to 2007 (Unit: mm).

Based on the accumulative precipitation of southern China, the icing and snowy weather in early 2008 can be divided into four processes. The first process appeared from 10 to 14 January, in which the rainfall was not large and mainly covered the Yangtze and Huaihe Rivers basin (Figure 2a). The second process happened from 18 to 23 January. Like the first one, rainfall in this period was mild and mainly covered the same basin and Yellow and Huaihe Rivers basin (Figure 2b). The third process took place from 25 to 29 January in which precipitation was the largest and most extensive of the four processes (Figure 2c), with more than 150 mm of rainfall. Precipitation in the fourth process (from 30 January to 3 February) was similar to that in the third one but with weaker intensity and a main coverage of southern China, the Yangtze and Huaihe Rivers basin, South Yangtze River and Yunnan. The locations of these four processes coincided with the center of a 500 hPa updraft for the vertical component of meridional circulation zonally averaged (102.5 to 120°E) in southern China, demonstrating that some signal was conveyed by local meridional circulation.

4 FORMATION MECHANISM ANALYSES BASED ON MERIDIONAL CIRCULATION LINEAR DIAGNOSIS MODEL

Under the condition of the same large-scale background, the phase state of precipitation is mainly influenced by topography and ground layer. During the early period of 2008, the precipitation was mainly freezing rain because there was a hot layer on the cold ground layer in Guizhou, Hunan, Jiangxi and Zhejiang. In southern China, it was mainly rain due to the hot surface. Because of the cold surface, however, it was snow chiefly north of the Yangtze River. In fact, rain, snow and freezing rain are formed from air parcels—rich in water vapor, which are cooled and condensed in uplift, an essential condition for their formation. In the case of the early 2008, the precipitation was characterized by the interaction over southern China between abnormally active, northward warm and moist air and southward, cold and dry air. Therefore, based on a linear diagnosis model, quantitative diagnosis was performed of the rising branch of the meridional circulation of this event in order to determine the main factors for this disastrous weather. To make sure that the model-simulated results were reliable, the performance of the model was first examined.

4.1 *Performance of the model*

The quantitative diagnosis was carried out using in reverse the solution to the linear equation (1). Separate contribution is sought from each of the forcing terms in the r.h.s. of Eq. (1) to ($\overline{\omega_{MC}}$), the vertical branch of local meridional circulation in southern China, and then the greatest contribution is identified for the forcing process and its corresponding weather system. To ensure that the results in this work are reliable, we examined the performance of the model using the methods as follows: $\overline{\omega_{MC\,\mathrm{obs}}} = \overline{\omega} - \overline{\omega_{ZC}}$, calculated with the ω field provided by NCEP and Eq. (6), is assumed to be the "observed" field of $\overline{\omega_{MC}}$. The simulated field of $\overline{\omega_{MC}}$ was the value calculated by substituting $\overline{\psi}$ into Eq. (3) after solving Eq. (1). If the distribution, central position and center magnitude of the simulated field agrees well with those of the observed field, it can be known that the model has good reliability.

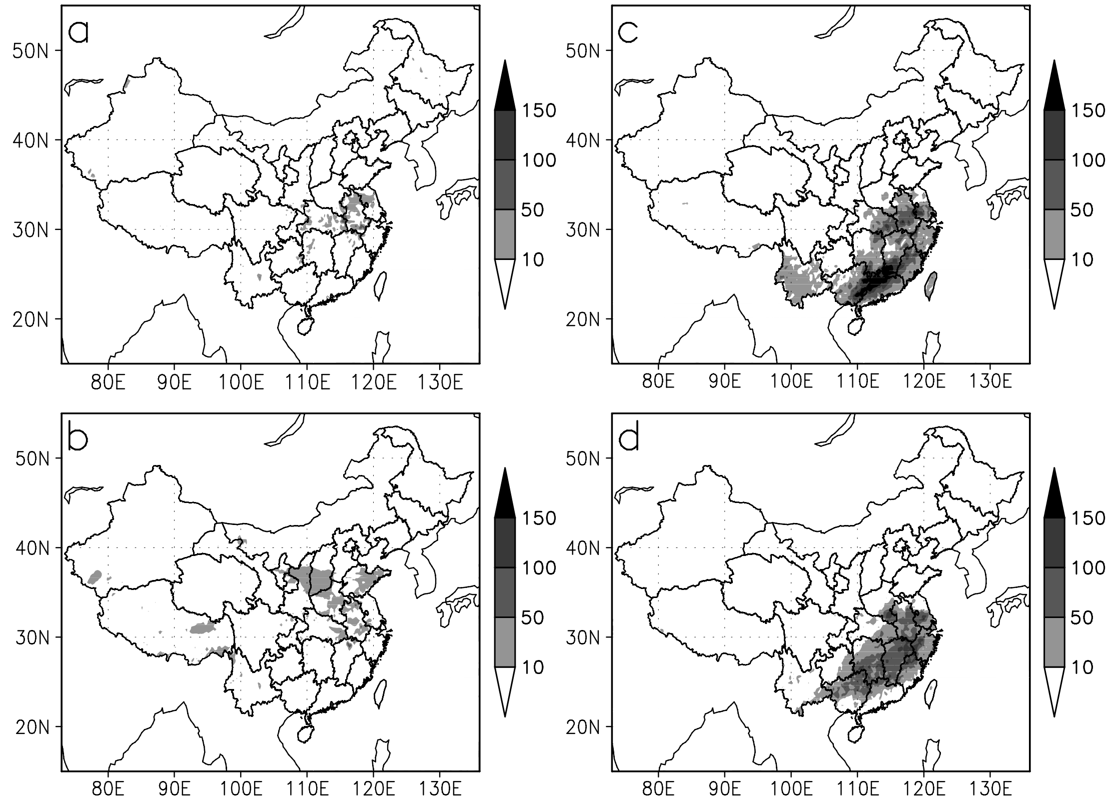

Figure 2. Accumulative precipitations during the first phase (a), second phase (b), third phase (c), and fourth phase (d). Units: mm.

As is shown in Figure 3, the distribution, central position, center magnitude and their changes with time agree between the simulation and the observation, although the intensity of the simulated $\overline{\omega_{MC}}$ is slightly weak, which may be caused by the errors of difference calculation and gradient-wind hypothesis. A lot of studies[11-14] indicated that these errors have no effects on the sequence of individual factors in terms of contribution. Therefore, the model output is reliable.

4.2 *The evolution of vertical velocity and contribution from main physical factors in four processes of rainfall*

Because the geostrophic balance relationship is best relevant in mid-latitudes, the value of the pressure gradient force is equal to the Coriolis force in the inverse direction and their contribution to meridional circulation and vertical branch offsets each other, which coincides with the result of the continuous equation, $\partial\omega/\partial p = -\nabla_2 \cdot \mathbf{V} = -(\nabla_2 \cdot \mathbf{V_g} + \nabla_2 \cdot \mathbf{V_{ag}}) \approx -\nabla_2 \cdot \mathbf{V_{ag}}$, achieved in isobaric coordinates. This signifies that the vertical motion is caused by $-\nabla_2 \cdot \mathbf{V_{ag}}$, the convergence of the ageostrophic wind going through isobars, because the main component of the geostrophic wind was rotary and the divergence of the pure rotational wind was 0 ($\nabla_2 \cdot \mathbf{V_g} \approx 0$). In addition, as the horizontal branch of meridional circulation v is mainly the ageostrophic wind v_{ag}, the pressure gradient and Coriolis force can be ignored when the causes are studied for the vertical branch ω_{MC} of meridional circulation, which is caused by the convergence of south and north wind.

4.2.1 ANALYSIS ON ω_{MC} IN THE FIRST RAINFALL

The area of ascending movement ($\overline{\omega_{MC}} < 0$) of the meridional circulation tilted to the north with height from 10 to 14 January 2008, which distributed from 20 to 37.5°N in the lower and middle layers (Figure 4a) and provided upward movement condition for precipitation in the Yangtze and Huaihe Rivers basin. According to the output of a local meridional circulation model, the zonal advection of average westerly momentum (Figure 4b) and the advection of mean meridional temperature (Figure 4c) are the two greatest contributors to the upward movement (Figure

4a). Upward movements in Figures 4b and 4c are much stronger than those in Figure 4a, which indicate that there are other physical factors that offset their influences. The outputs also suggest that these physical factors are the meridional advection of average westerly momentum (Figure 4d), advection of average latitudinal temperature (Figure 4e) and vertical transport of average temperature and the boundary effect (Figure 4f).

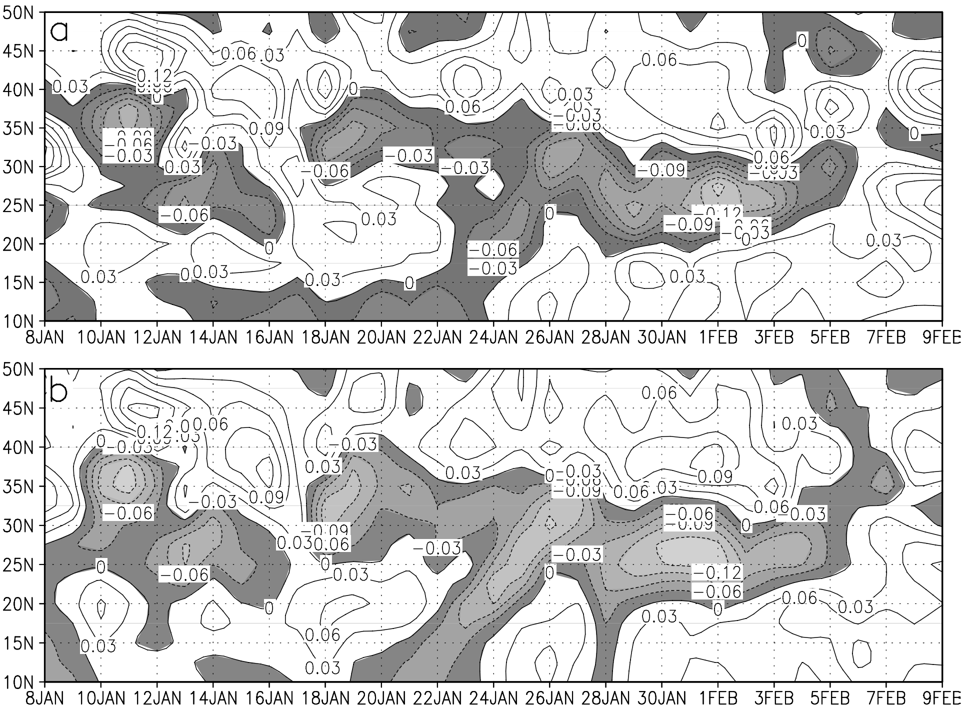

Figure 3. Zonal circulation vertical component ($\overline{\omega_{MC}}$) at 500 hPa in southern China (102.5 to 120°E) in early 2008: (a): observed; (b): simulated.

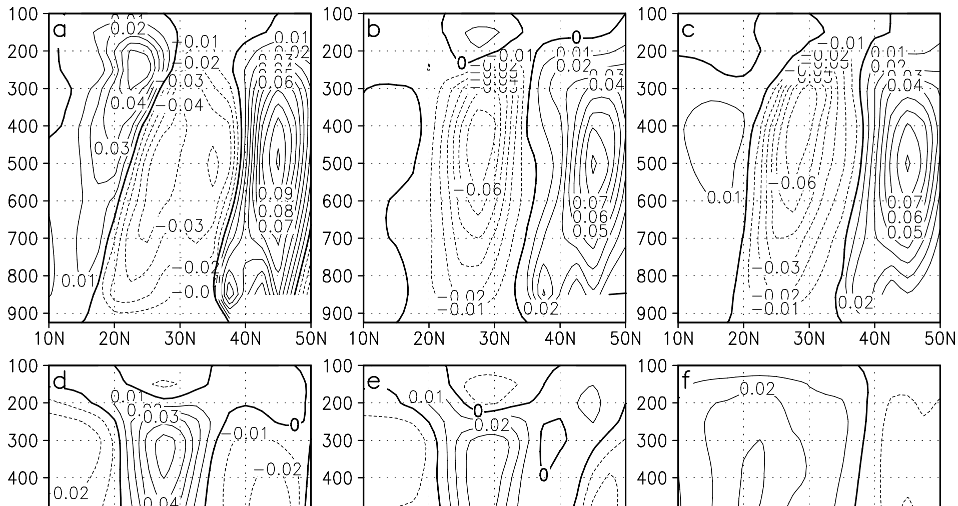

Figure 4. The distribution of meridional circulation of vertical component at the north, south and vertical direction related to the first precipitation phase with the inputs from (a) all factors and open boundary, (b) average westerly momentum zonal advection, (c) mean meridional temperature advection, (d) average westerly momentum meridional advection, (e) average latitudinal temperature advection, and (f) average temperature vertical conveyor and boundary effect.

4.2.2 QUANTITATIVE ANALYSIS OF ω_{MC} IN THE SECOND RAINFALL

In contrast to the first precipitation process, only small variations can be found in the impacted area of the upward branch of the meridional circulation during 18 to 23 January 2008. The area was still located between 20 and 37.5°N and tilted northwards with height but the ascending velocity in the middle level increased with the northward tilt (Figure not given here), which was one of the reasons why the precipitation region in Figure 2b was more northward than that in Figure 2a. Quantitatively comparing the contribution from individual forcings revealed that the ascending movements in the south of China were positively related to the zonal advection of westerly momentum and the meridional advection of temperature, while the zonal advection of temperature, the meridional advection of westerly momentum, the vertical thermal transportation and the boundary effect had negative contribution to this precipitation.

4.2.3 QUANTITATIVE ANALYSIS OF ω_{MC} IN THE THIRD RAINFALL

From 25 to 29 January 2008, the upward branch of the regional meridional circulation strengthened dramatically with southward migration (Figure 5) which resided between 20 and 37.5°N. The scope of the northward tilt of the upward motion was smaller than that of the previous two precipitation processes, which was corresponding to the major precipitation area in Figure 2c. Being the same as those of the first two processes, the zonal advection of westerly momentum and the meridional advection of temperature had the greatest contribution to the upward activities. However, the positive effect of the latent heating of condensation took the third place in this process and the negative effect of the meridional advection of westerly momentum seemed to be little, while the factors of negative effect were the zonal advection of temperature, the vertical thermal transportation and the boundary effect.

4.2.4 QUANTITATIVE ANALYSIS OF ω_{MC} IN THE FOURTH RAINFALL

The fourth precipitation process occurred from 30 January to 3 February 2008, which was similar to the third one. However, during this process the scope of the upward branch of the meridional circulation narrowed and obviously tilted northward with height (figure omitted). And this was the one of the reasons why the heavy precipitation in Figure 2d moved from the center of the southern China to the north of the region and the south of the Yangtze River. In this process, all of the previous factors, ranked by positive contribution, were the zonal advection of westerly momentum, the meridional advection of temperature and the latent heating of condensation. The zonal advection of temperature, the vertical thermal transportation and the boundary effect also played negative roles in this process.

The quantitative analyses of the four processes showed that the factors which are positively related to the upward activities in the southern China are the zonal advection of westerly momentum and the meridional advection of temperature. The positive effect of the latent heating of condensation was not important from 10 to 23 January. And it was not until 25 January to 3 February did it take the third place in positive contribution to the precipitation process. The zonal advection of temperature, the vertical thermal transportation and the boundary effect always had negative effects on the precipitation processes. All of these results were different from those of early diagnosis of regional meridional circulation. Previous studies[11-15, 18] pointed out that the latent heating of condensation often had the greatest effect on precipitation. However, in this work, they are the zonal advection of westerly momentum and the meridional advection of temperature that became the most important factors in this precipitation.

5 WEATHER PATTERNS OF ESSENTIAL IMPACT FACTORS AND THEIR COMPARISONS WITH EARLIER CASES

In this section, the synoptic background will be analyzed in order to ensure that positive impacts are made by the westerly momentum advection and the temperature advection, which is valuable to modeling diagnosis in actual operation. And some detailed comparisons will be made between our quantitative analysis and earlier cases since our results are quite different from those of previous studies.

5.1 *Weather patterns of essential impact factors*

First, the role of the westerly momentum advection was discussed. As we know, the second derivative of any variable has opposite sign, Eqs. (1) and (3) are considered and the vertical velocity at middle troposphere, which is induced by the westerly momentum advection, can be described as:

$$\overline{\omega_{MC}}\Big|_{mid} \propto \frac{\partial}{\partial y}\left[\left(-\bar{u}\frac{\partial \bar{u}}{\partial x}-\bar{v}\frac{\partial \bar{u}}{\partial y}\right)_{upper}-\left(-\bar{u}\frac{\partial \bar{u}}{\partial x}-\bar{v}\frac{\partial \bar{u}}{\partial y}\right)_{low}\right]. \quad (7)$$

The upper westerly momentum advection was stronger than the low-level advection in the impact area of an upper-level westerly jet. It was also stronger than the upper meridional advection of westerly momentum. Thus, Eq. (7) can be simplified as:

$$\overline{\omega_{MC}}\Big|_{mid} \propto \frac{\partial}{\partial y}\left(-\bar{u}\frac{\partial \bar{u}}{\partial x}\right)_{upper}. \quad (8)$$

The sketch map of westerly $-u\partial u/\partial x$ and

$\partial(-u\partial u/\partial x)/\partial y$ is given by Figure 6. It can be seen that the zonal advection of the westerly momentum is $-u\partial u/\partial x<0$ ($-u\partial u/\partial x>0$) at the entrance (exit) of the westerly jet. And the positive/negative center is over the jet axis. Accordingly, there are upward activities with $\overline{\omega_{MC}} \propto \partial(-\bar{u}\partial\bar{u}/\partial x)/\partial y<0$ at the side of the anticyclonic wind shear at the jet entrance and the side of the cyclonic wind shear at the jet exit. For the same reason, there are downward activities with $\overline{\omega_{MC}} \propto \partial(-\bar{u}\partial\bar{u}/\partial x)/\partial y>0$ at the side of the cyclonic wind shear at the jet entrance and the side of the anticyclonic wind shear at the jet exit.

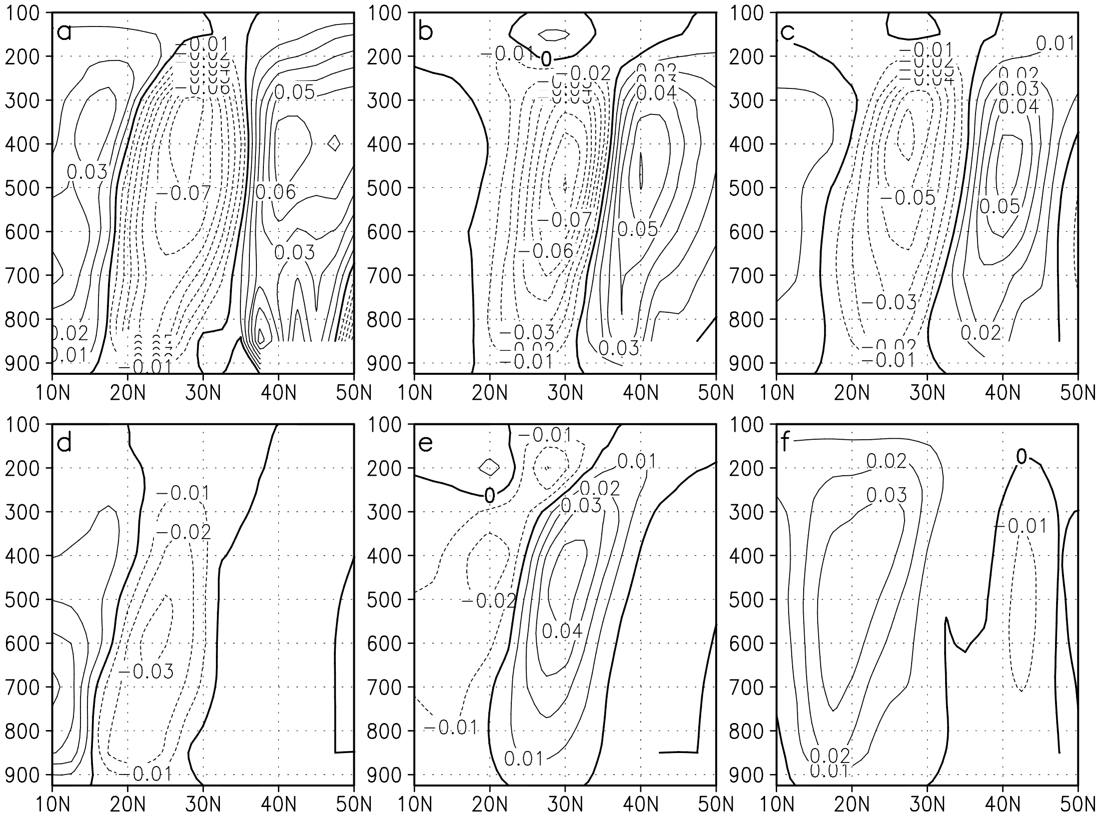

Figure 5. Same as Figure 4 except for the third precipitation process and (d) is for the genesis of latent heating.

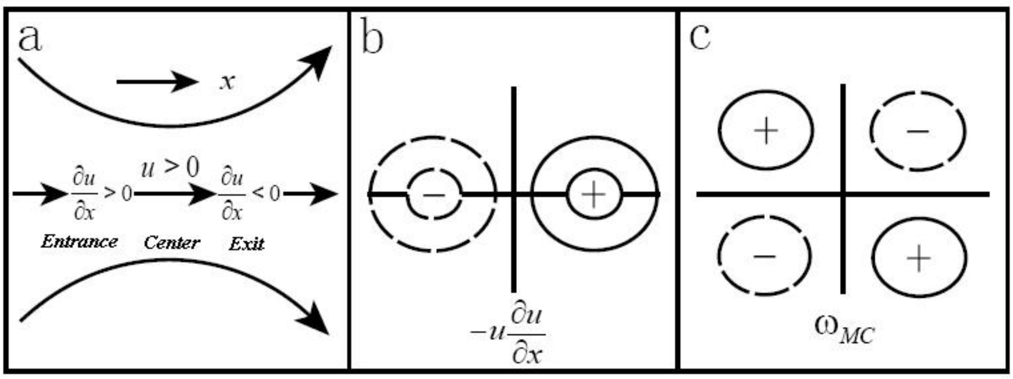

Figure 6. Diagrammatic sketch of the westerly jet (a); the corresponding zonal advection of the westerly momentum ($-u\partial u/\partial x$) (b); vertical motion induced by the uneven distributions of zonal advection of the westerly momentum (c). "+" represents updrafts, "–" represents downdrafts.

The previous analysis showed that the upper level westerly jet is the main reason for the upward activities at the side of the anticyclonic wind shear at the jet entrance and the side of the cyclonic wind shear at the jet exit, and for the downward activities at the side of the cyclonic wind shear at the jet entrance and the side of the anticyclonic wind shear at the jet exit. This result is in accordance with the theory that divergence pumping often exists at the side of the anticyclonic wind shear which was at the entrance of upper-level westerly jets[19-21].

The 500 hPa weather pattern during the period from 10 January to 3 February was that blocking highs alternatively appeared near the Ural Mountains and Lake Baikal, abnormal meridional circulation emerged at mid- and high-latitudes, especially in the Eurasian area[1, 22], and the polar cold vortex moved to the Okhotsk. This kind of synoptic background also occurred at 200 hPa, where a ridge was over the Ural Mountains and a deep trough was over the Okhotsk area (Figure 7a), and there was a ridge over the tropical western Pacific. Thus, the impact of both the trough over the Okhotsk and the ridge over the tropical western Pacific induced the westerly jet to appear in the area around the middle and lower reaches of the Yangtze River and Japan. The center of the jet was over the southwest of Japan which was northward to its mean state (Figure 7a). Most of the southern China was under the control of upper divergence at the side of the anticyclonic wind shear at the westerly jet entrance. This divergence can easily lead to the upward activities over the southern China. This is a finding that is similar to Wu[23].

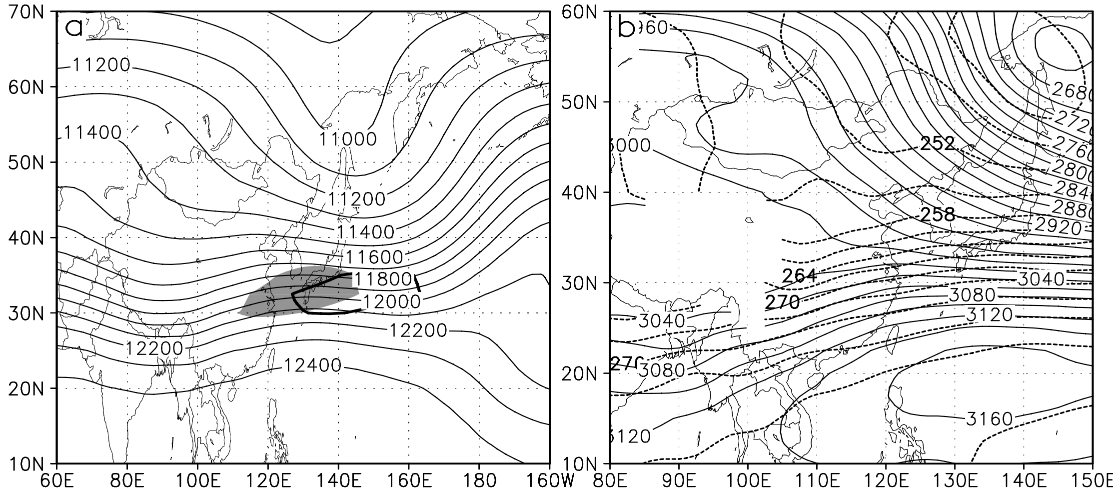

Figure 7. Geopotential height at 200 hPa (a) and 700 hPa (b) during 25 January to 3 February 2008. The interval in (a) is 100 gpm, and the shade represents the wind speed greater than 72 m/s. The thick, black and enclosed line indicates the historical wind speed greater than 72 m/s. The solid lines in panel (b) are the geopotential height with 30 gmp intervals. The dash lines are the temperature with 3 K intervals.

Next, the impact of temperature advection will be discussed. As shown in the 700 hPa geopotential height and temperature (Figure 7b), the ridge of the western Pacific subtropical high (WPSH) was near 15°N, the 3,140 geopotential isoline extended to the west as far as near the center of the Indochina. A geopotential trough was over the Bay of Bengal with a thermal trough (from 500 hPa to 400 hPa), which was much deeper than the thermal one. At this time, most of the southern China was ahead of both troughs. And these parts of China were dominated by the warm advection which was induced by the southwest wind before the trough over the Bay of Bengal and the northwest side of the WPSH. The northern China was affected by cold advection at 500 hPa[21], which was led by a north flow behind the polar vortex over the Okhotsk Sea (Figure 7b). The combined impact of the cold and the warm advection enabled upward activities (Figures 4c and 5c).

As we know, latent heating often results from condensation which is induced by convergence and lifting. In this consideration, both of the water vapor transportation and the convergence and lifting definitely have direct impact on the upward activities over southern China. A horizontal trough developed at 500 hPa over the Mongolia and then moved southward from 8 to 14 January 2008, which guided the low-level cold air to move southward[22]. There was a low trough at 700 hPa near 105°E over East Asia. The Bay of Bengal was controlled by the anticyclone behind the trough and ahead of the ridge. The ridge of the WPSH was near 17.5°N. The 3150 geopotential isoline extended to the center of the South China Sea (figure omitted). This kind of background enabled the warm and wet flow to move along the west side of the WPSH and the cold and dry flow to travel from the north to meet together over the southern China, eventually leading to convergence and lifting. All of these caused the first precipitation process. The location of the WPSH was much southward and eastward and its strength was weaker during the first process, and the northward transportation of the water vapor was not strong. Both of these made the condensation latent heating less important as compared with that during the third and the fourth processes (Figure 8). There was a distinctive adjustment in the 500 hPa atmospheric circulation over the Northern Hemisphere after 16

January: the Ural high and Baikal high appeared in turn, the polar cold vortex moved to the Okhotsk, and abnormal meridional circulation appeared at mid- and higher-latitudes, especially in the Eurasian area. This kind of background sustained till the early February. Under the guidance of the 500 hPa airflow, the southern China was continually attacked by the cold flow from late January to early February[21]. The trough near 105°E weakened and disappeared during 18 to 23 January while another trough built gradually over the Bay of Bengal. The WPSH moved a little bit northward and its ridge resided near 20°N. Over the south of China, a warm and moist airflow from the southern branch trough and the west side of the WPSH met together with a cold and dry airflow from the north. These led to the second precipitation process. Thus, the reason why the condensation latent heating was not as important as those of the third and the fourth processes was similar to that of the first. The cause was that the southern branch trough was weaker, the WPSH was more southward and eastward and its strength was weaker during the second process, which caused the southward transportation of the water vapor ahead of the southern branch trough was not strong (Figure 8). After 24 January, the WPSH strengthened and extended westward, the 3150 geopotential isoline extended to the Indochina, and the southern trough deepened. Thus, the southward transportation of the water vapor strengthened near the west of WPSH and before the southern trough, which led to the heavy precipitation of the third and the fourth processes (Figure 8). Correspondingly, the condensation latent heating became more important in these two processes.

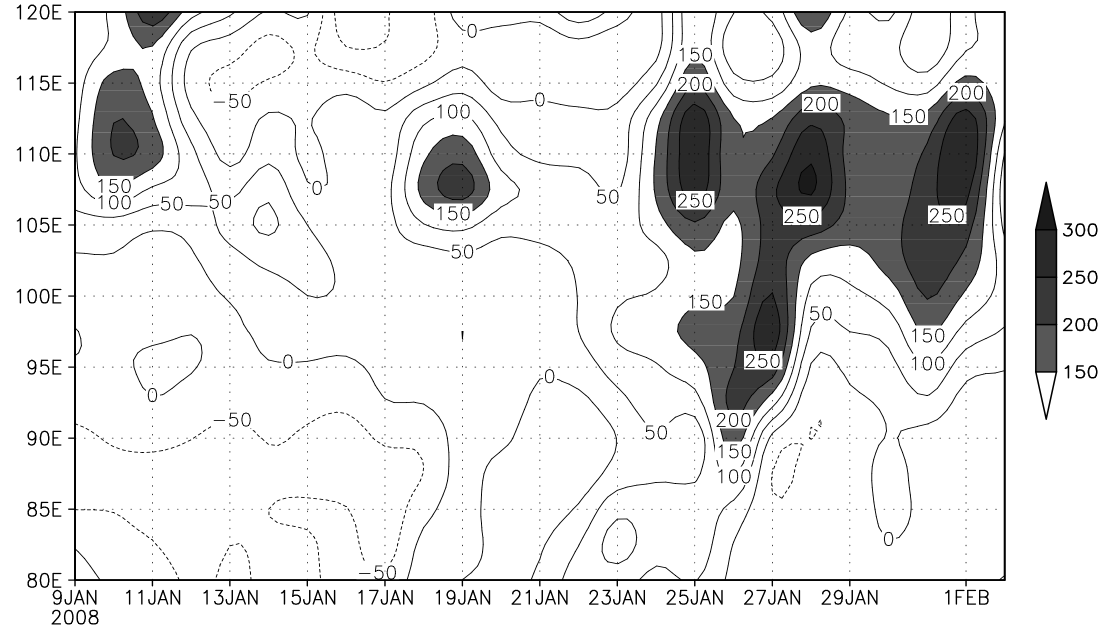

Figure 8. Meridional water flux ($\int_{Ps}^{300\text{hPa}} qv\,\mathrm{d}p$) integrated from the surface to 300 hPa at 22.5°N. The shaded area indicates values larger than 150 kg/(m·s).

From the viewpoint of synoptic background, there are several reasons for the freezing rain and severe snowstorms in the south of China during early 2008. These included an upper-level westerly jet over the southwest of Japan whose location was more westward to the mean state; the cold advection from the north meeting with the warm advection persisted in the southern China; strong water vapor transporting from the South China Sea, which was strengthened by water transportation from the Bay of Bengal; and a temperature-inversion layer caused by the cold surface and a warm hat over the surface in the south of China.

5.2 *Comparisons with earlier cases*

The results from our analysis on the freezing rain and severe snowstorms in section 4.2 are quite different from those of earlier studies[11-17]. Our analysis showed that the zonal advection of westerly momentum was the most important positive factor in this event while the condensation latent heating was an important factor in previous events[11-17]. Why are there such big differences? The flood over the Yangtze River basin in 1998 will be taken as the example[13] in this section. The synoptic background corresponding to the westerly momentum advection and the condensation latent heating will be diagnosed in order to figure out the reason for the differences.

A diagnosis of updrafts during the 1998 flood over the Yangtze River basin[13] indicated that the condensation latent heating in the mid- and lower-latitudes (20 to 35°N) had the greatest contribution. The meridional averages contributed about 45% while the contribution from the meridional advection of the westerly momentum was less than 20%. The analysis on temperature in June 1998 (figure omitted) showed that the temperature-inversion layer did not exist at the mid- and- lower level in East Asia, which helped the convection to develop at this level. The total water transportation at 22.5°N during 1 to 30 June, 1998 (Figure 9a) showed that the transportation from the South China Sea was as strong as 600 kg/(m·s), which was twice as much as the transportation in the 2008 event (Figure 8). The water from the Bay of the Bengal was also strong enough, with the total amount of 500 kg/ (m s) twice as much as the transportation in the 2008 event (Figure 8). The center of the westerly jet resided from the Yangtze-Huaihe River basin to the middle of Japan, and the Yangtze-Huaihe River basin was controlled by upper-level divergence at the side of the anticyclone wind shear at the jet entrance. The maximum wind speed of this jet was less than 40 m/s, which was only 50% of the speed in the 2008 event (Figure 7a). These situations implied that the non-existence of the temperature-inversion layer at mid- and lower- troposphere, the strong water transportation from the South China Sea and the Bay of the Bengal, and the weak westerly jet over the Yangtze-Huaihe River basin to Japan were the reasons why the condensation latent heating did have great positive contributions to the flood while the westerly momentum advection did not. Studies on the 2008 case indicated that the strong westerly jet over southwest Japan at 200 hPa, the existence of the temperature inversion layer and the weak water transportation from the South China Sea and the Bay of the Bengal, instead of the condensation latent heating, were the greatest contributors for the westerly momentum advection.

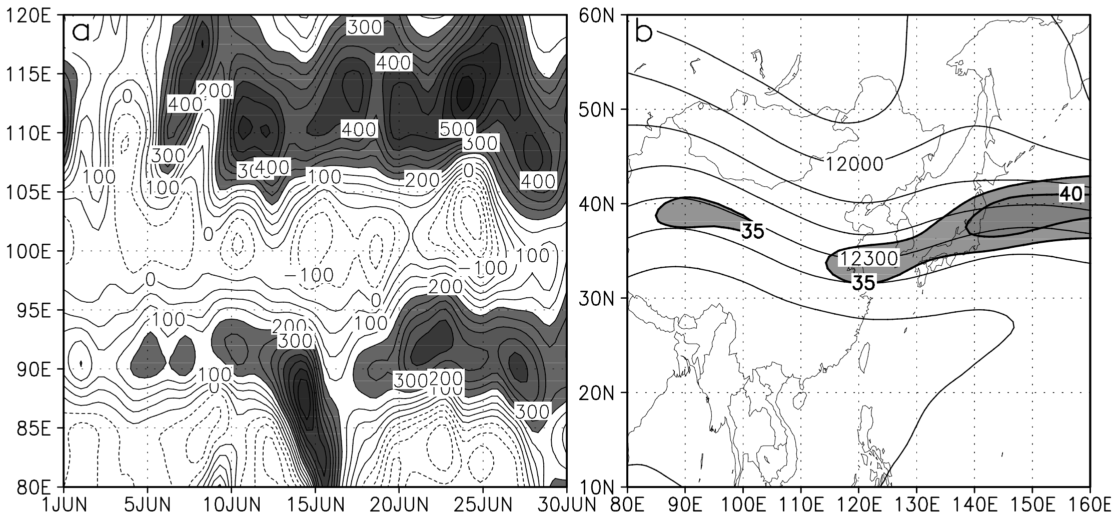

Figure 9. Meridional water flux ($\int_{Ps}^{300\text{hPa}} qv \, \mathrm{d}\, p$) integrated from the surface to 300 hPa at 22.5°N for the period from 1 to 30 June, 1998 (a) and 200 hPa geopotential height and zonal wind fields averaged over June 1998 (b, shaded areas). Other captions are the same as Figure 8.

A number of cases are similar to the case in 1998. Most of them happened in spring, summer and autumn. During these seasons, the lower level in East Asia is controlled by the warm and moist southerly flow, which could obstruct the formation of the temperature-inversion layer but help to transport water vapor from the ocean to the south. The southern branch of the westerly jet at mid- and higher- level weakened and retreated northward. Leading to the condensation latent heating, all of these had a great impact on the precipitation but the westerly momentum advection had a little contribution.

6 CONCLUSIONS

An extreme event with freezing rain and snowstorms happened in south China during early 2008. The synoptic background of this event was similar to the background of some Mei-yu seasons. It was obvious that in the southern China during this event the warm and moist airflow moved northward to meet together with the clod and dry airflow from the north. The NCEP/NCAR reanalysis and an improved linear diagnostic model for regional meridional circulation were utilized to study the upward branch of the circulation. Some conclusions can be obtained as follows:

(1) The four strong precipitation processes in south China from 10 January to 3 February 2008 were related to the control of the upward branch of the regional meridional circulation.

(2) Quantitative studies on the dynamic and thermal factors showed that the results were quite

different from those of the early studies. That was the greatest impact contributed by the westerly momentum advection rather than the condensation latent heating.

(3) There was divergence pumping at the side of the anticyclonic wind shear at the entrance of the upper-level westerly jet whose center resided over the southwest Japan. It was the main reason why the zonal advection of the westerly momentum had positive impacts on the upward branch of the meridional circulation in south China.

(4) For the mid- and lower-troposphere (850 to 400 hPa), most of the southern China was located in front of a Bay of Bengal trough, and was dominated by the warm advection induced by the southwest wind ahead of the trough over the Bay of Bengal and on the northwest side of the WPSH. Meanwhile, the northern China was affected by cold advection. The combined impact of the cold and warm advection was the major reason why the meridional temperature advection had positive impacts on the upward branch of the meridional circulation in south China.

(5) The weak transportation of water vapor from South China Sea and the Bay of the Bengal and the existence of a temperature-inversion layer weakened the lift of convergence at surface. As a result, the condensation latent heating just had a little impact on the upward branch of the meridional circulation in south China. After 24 January, the water transportation strengthened and the impact of the condensation latent heating was upgraded to the third place.

Acknowledgement: The authors are grateful to the anonymous reviewers and editors of *Journal of Tropical Meteorology*, and also would like to thank Professor LIU Xi-ming for his valuable comments and suggestions.

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Citation: FU Min-ning, ZOU Hai-bo, WU Jun-jie et al. A quantitative study for abnormal freezing rains and snowstorms in southern China in early 2008. *J. Trop. Meteor.*, 2013, 19(1): 67-79.