The Water Vapor Transport Model at the Regional Boundary during the Meiyu Period

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ABSTRACT

The water vapor transport model at the regional boundary in the Meiyu period is put forward through diagnostic analysis. The numerical simulation on the water vapor transport at the boundary of China in the heavy rainfall period during June-July 1998 shows that the feature of water vapor transport in June is different from that in July. The main body of the water cycle that forms the torrential rain in the Yangtze River Valley is made up of water vapor transport at the western and southern boundaries of the China region in June, whereas the water vapor flow at the western boundary in middle Tibet turns out to be the main body of water vapor sources in July. The water vapor transport at the western boundary of the Tibetan Plateau and the southern boundary of China plays an important role in the torrential rain in the Yangtze River Valley. The temporal and spatial distribution characteristics of water vapor flow at the regional boundary and their theoretical model would provide the scientific proof for the heavy rain forecasts in the Yangtze River Valley.

Key words: water vapor flow, torrential rain, Yangtze River Valley, Meiyu period

1. Introduction

In the summer of 1998, another exceptionally serious flood happened along the whole Yangtze River, the Nenjiang River and Songhua River Valleys since 1954. The temporal and spatial features of the water vapor transport that contributed to the catastrophic flood and their connection with the water vapor source/sink structure of the rain belt in the Meiyu front system are important scientific problems that are drawing more and more attention of scientists. In particular, the water vapor transport features in the torrential rain process from the second dekad of June to the last dekad of July are the key factors for the formation of the flood. They are related to the source of water vapor supply to form the maximum rainfall in the two torrential rain processes during rainfall period.

The dynamic variations of water vapor in the atmosphere including transport, phase change, and various adjustments, are always realized through various scale circulations. Wu (1990) studied the contribution of various atmospheric movements to water vapor transport and its budget. He pointed out that the Hadley cell plays an important role in the water vapor transport from the subtropics to the equator and from the winter hemisphere to the summer hemisphere. However, tropical planetary waves bring the water vapor from the tropics to the subtropics. During the transitional period from spring to summer, because of the thermal difference between land and sea as well as the topography impact of the Tibetan Plateau in East Asia, the planetary wind belt is likely to shift with season, which would result in the sudden changes of large-area, surface-dominant wind direction, namely the outbreak of the summer monsoon. Meanwhile, the outbreak, prevailing direction, advancing or retreating of the summer monsoon also have inter-annual changes accompanied by the inter-annual changes of relevant water vapor transport, rain belt, and its intensity. The Meiyu front system is a special key rainfall system of East Asia. Obtaining clear knowledge about the connection between the water vapor supply source of the Meiyu front system and its carrying system, as well as the temporal and spatial changes of water vapor transport channel, are important steps to explore the formation mechanism of flood in China.

Liu (1997) and Xu et al. (2002a) put forward that

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significant differences exist in the situation of water vapor transport over different boundaries of Mainland China because of the different distances of various calculation domains from the coast and their different latitudes. From the point of view of climatological averages, water vapor over China mainly comes from the southern boundary. The annual water vapor input from the southern boundary is about 42 percent of the total. A certain amount of water vapor also comes from the western and northern boundaries, which account for 12 and 22.5 percent of the total respectively. Zhou et al. (1998) investigated the distribution and transport of the water vapor source/sink in August 1994 for the Asian monsoon area. They found that the western Pacific (120°–133°E)and the Bay of Bengal are climate water vapor source areas.

Fei et al. (1993) analyzed the transport and flux of water vapor during different Meiyu periods in the Yangtze River and Huaihe River Valleys. They pointed out that the water vapor for South China precipitation mainly comes from southwest Indian monsoon flow and southeast monsoon flow before the Meiyu, while it comes from southwest Indian monsoon flow during the Meiyu period. Zhang (2001), Xu et al. (2000a) and Wang et al. (2000) investigated the relationship between water vapor transport from the Indian monsoon and that over East Asia in Northern Hemisphere summer. He found that more (less) water vapor transport corresponds to less (more) water vapor transport over East Asia and less (more) rainfall in the middle and lower reaches of the Yangtze River.

This paper aims to investigate the water vapor source features in the China area and the East Asia Meiyu front system during the key period (June and July) of the heavy rainfall in the Yangtze River Valley in 1998, as well as the impact of the water vapor transport at the regional boundaries, especially the water vapor transport via the Tibetan Plateau, on the formation of local torrential rain in the Yangtze River Valley.

Utilizing composite analyses on radar echo charts in the central plateau, satellite water vapor pictures, remote sensing TBB time-longitude sections, and dynamic evolution of satellite cloud pictures, the dynamic processes of the cloud system from the source area of the plateau are traced during the torrential rain of Wuhan in July. It is found that mesoscale cumulus convective systems in the central plateau are continually developed and move out of the plateau, being directly related to the heavy rainfall of the Yangtze River Valley. Figure 1 shows the cloud picture at 0800 LST 20 July 1998 in which the mature convective

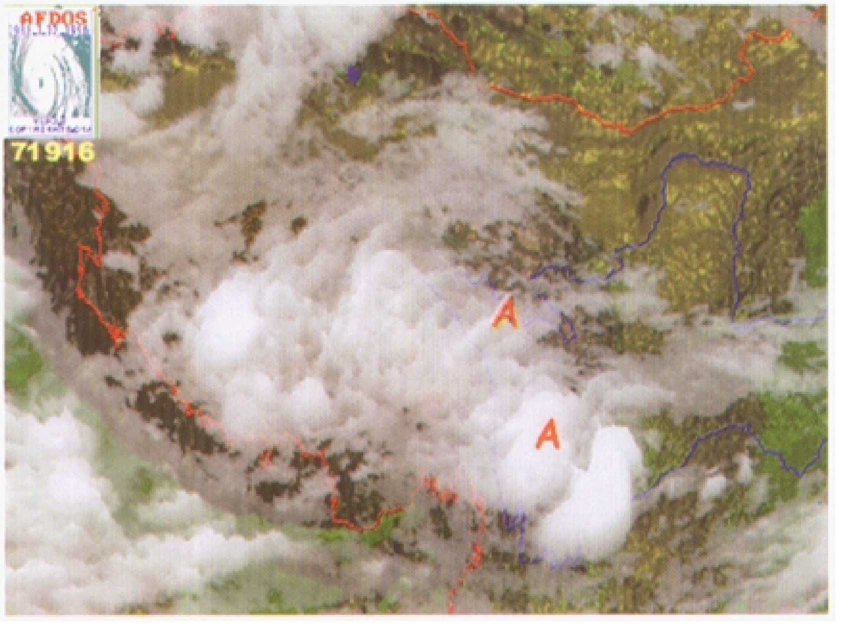


Fig. 1. The satellite cloud picture at 0800BT 20 July 1998 ('A' represents the active cumulus convective system over the plateau).

clouds possess a shape similar to popcorn. Hence they are called popcorn clouds (Wang et al. 2000 and Xu et al. 2002a). The successive dynamic pictures show that the popcorn convective system, originating from the plateau, are continually developed, mature, and move eastward, forming the heavy rainfall of the Yangtze River Valley. In detail, earlier at 1800 LST 19 July 1998, the mesoscale convective clouds grow up to a mesoscale cloud cluster system and begin moving eastward. The exceptional torrential rain occurred while the cloud cluster system was passing Wuhan. Figure 2 gives the time-longitude section of the cloud track described by TBB at intervals of three hours during the period of heavy rainfall (the middle and last dekad of July). It shows that a continuous convective cloud zone begins from the central plateau on 19 July and develops strongly while moving eastward to the middle and lower reaches of the Yangtze River around 22 July, i.e., the main body of the convective cloud cluster tends to move eastward from the plateau to the middle and lower reaches of Yangtze River, where the convective clouds are significantly developed. This process corresponds to the period of the exceptional heavy rainfall in July. The cloud system track possesses a similar feature during the period of exceptional heavy rainfall in the middle and last dekad of June.

2. Areas that affect water vapor transport of the East Asia monsoon

The Tibetan plateau, Indian Ocean, Bay of Bengal, and South China Sea are the key areas for monsoon water vapor transport affecting abnormal climate such as flood and drought in China. The composite connection features disclose that there are significant interactions between the plateau and many other factors including the South Asia monsoon. In the spring of flood years for the Yangtze River Valley, there is a prominent southerly water vapor transport zone from the tropical Indian Ocean (90°–130°E), the Bay of Bengal, and the South China Sea. The southwesterly water vapor flow turns to the east in the southeast of the plateau, forming the westerly water vapor transport zone. As well, the water vapor transport mechanism is closely associated with the plateau, monsoon, and subtropical high. Figure 3a shows the average water vapor flux vector field from 1958 to 1995. It indicates that the high value areas of southerly water vapor transport that affect flood in China are located from the Philippines through the South China Sea, to the west to Somalia in East Africa, the Arabian Sea and the Indian Ocean to the west, from the Bay of Bengal via

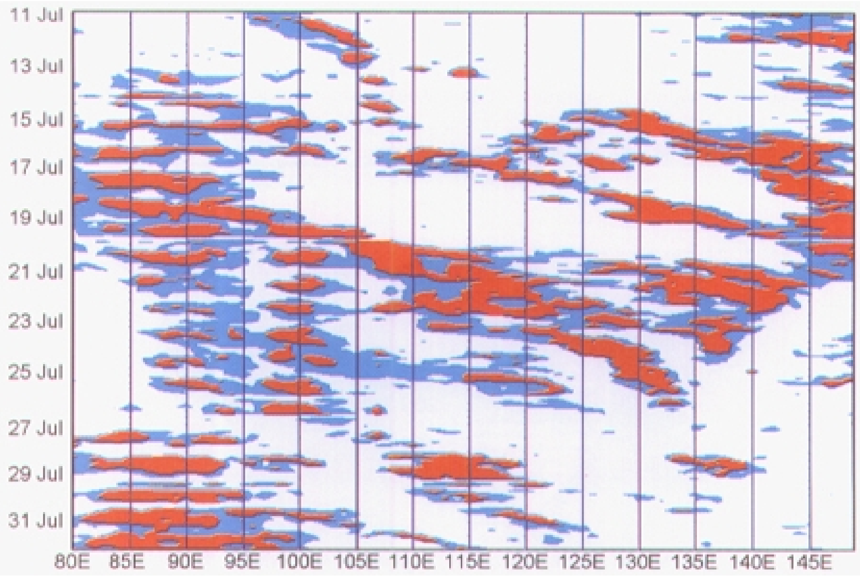


Fig. 2. The time-longitude section of the temperature of cloud top along 30°N.

Eastern Tibet to the east to the Yangtze River Valley of China, and finally, the Japanese islands (shaded areas). of which the shape is like a big triangle. Meanwhile. the water vapor channel related to the outbreak of the Asian monsoon, the abnormal water vapor source structure over the plateau, the interaction between Tibetan dynamic factors and the water vapor flow of the East Asia monsoon, and the function of mid-low latitude oceanic heat sources all appear in this area. Namely the interactions between Tibet and the monsoon as well as its members all occur in the Big Triangle area, which is shaded in Fig. 3a. Figure 3b gives the average cloud top temperature (TBB) for seven days during the exceptional heavy rainfall of the last dekad of June 1998. The area within the dashed lines represents the stronger convective region, of which the shape primarily corresponds to the plateau and the monsoon "big triangle" area described in Fig. 3a (Xu, et al., 2002b). Consequently, the southerly water vapor transport feature describes the tele connection between Tibet and the lower latitude oceanic heat source, latent heat source, and water vapor source on different time and space scales.

Based on the climate-averaged water vapor features in the Big Triangle area in Fig. 3a, we can see that the Tibetan area is an important water vapor source or a milestone on the western boundary for the Meiyu in the Yangtze River Valley in summer. The interaction between the dynamic effect of the plateau and the monsoon water vapor flow at the southern boundary forms the strong transport of water vapor from Tibet to the Yangtze River Valley. The water vapor transport belts from the western and southern boundaries make up the main input of water vapor flow into the Yangtze River Valley in summer. The main output of water vapor flow is at the eastern seashore of China. The water vapor transport features in the above Big Triangle area can be described as a conceptual model shown in Fig. 4. We can conclude that the water vapor transport from the western (Tibet) and southern boundaries play an important role in the torrential rain process of the Yangtze River Valley. Furthermore, the characteristics with the main input at the western and southern boundaries and output at the eastern boundary also describe the water vapor transport features in the Big Triangle influence on area of the plateau and the Asian monsoon in Fig. 3a.

3. Water vapor transport features at the boundaries of the region

There are significant seasonal changes in the budget of water vapor over the mainland of China. Statistics shows that the maximum net input of monthly water vapor appears in May, June, and July from the point of view of the whole country. During this period, the summer monsoon reaches its peak in South China

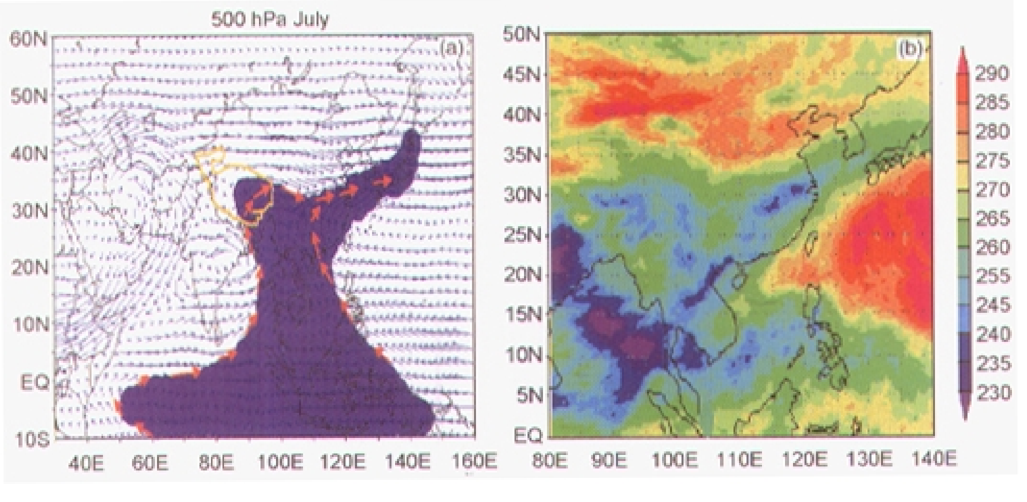


Fig. 3 (a) The averaged (from 1958 to 1995) 500 hPa water vapor transport features in summer based on the NCEP/NCAR reanalysis data; (b) The averaged temperature of cloud top for the last dekad of June 1998 (values within dashed lines are below 255 K).

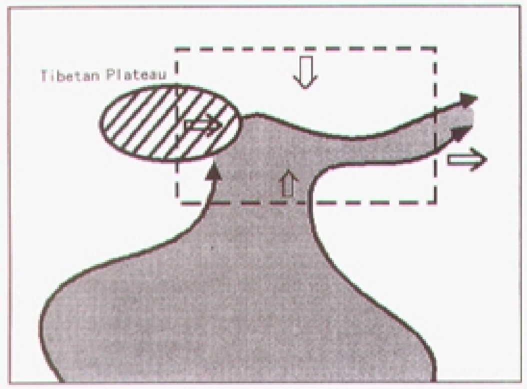


Fig. 4. Water vapor transport model at the boundaries of region.

first, and then the Meiyu begins in the Yangtze and Huaihe River Valleys and starts to affect North China. When the summer monsoon reaches its peak in middle China, southwesterly or southerly flow brings large amounts of water vapor into the China area. The water vapor fluxes in various months calculated in this paper with the reanalysis data of NCEP/NCAR are also different. In June, the southwesterly transport of water vapor from the Bay of Bengal and Arabian Sea becomes intensified. The southeasterly transport of water vapor at the western boundary of the subtropical high from the South China Sea is also very significant. Namely, the three water vapor transport channels from the South China Sea, Arabian Sea, and Bay of Bengal are all very apparent. These three branches of water vapor flow of the summer monsoon in July are somewhat different from those in June. In particular, the two southwesterly channels from the Indian Ocean and Bay of Bengal become the main body of water vapor sources at the boundaries. The plateau becomes an important turning point for water vapor transport of the Meiyu in East China, which transports water vapor to the east from Tibet (figure omitted).

Figure 5 describes the difference between the water vapor flux in June and July 1998 and that of flood years. The figure shows that in June 1998, the water vapor flow from the Arabian Sea turns to the north after climbing over the Plateau, and merges with the water vapor flow from the South China Sea into a kind of southwesterly flow. This forms a strong westerly water vapor transport channel over South China, which is different from the usual situation. During the formation process of heavy rainfall in the Yangtze River Valley in July 1998, the strong westerly water vapor flow from the Tibet turning point was more significant. Consequently, the interaction between the dynamic-thermal function of the plateau and the monsoon in the flood process in 1998 in the Yangtze River Valley is different from that in usual flood years. The characteristics that southerly water vapor flow travels over the plateau and turns to the east are more apparent. The above water vapor flow feature may be one of the important factors causing the abnormal East Asian water cycle and the flood of China in 1998.

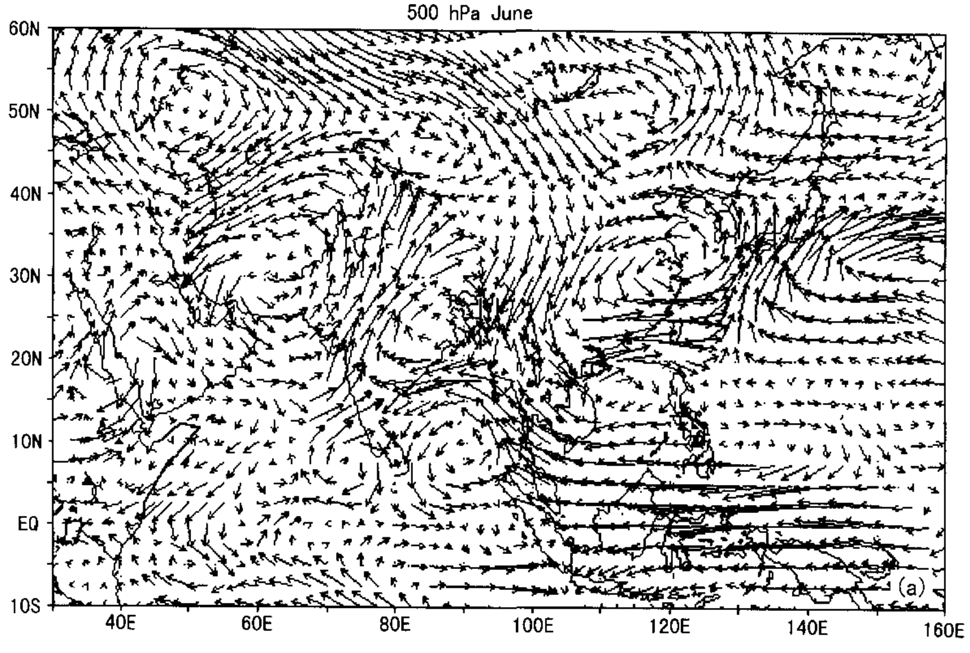
Figure 6 shows the temporal variation of the total amount of water vapor transport of the whole layer along the western (S_1: 90°E), eastern (S_3: 130°E), southern (S_2: 20°N), and northern (S_4: 40°N) boundaries of the domain relevant to the diagnosis in this paper. From Fig. 6a, we can see that the input (at the western boundary) and output(at the eastern boundary) amount are close to each other in May, but in June and July, the total input amount at the western boundary is generally larger than the output amount at the eastern boundary. Furthermore, the total input amount at the southern boundary in May, June, and July is respectively larger than the output amount in the corresponding month at the northern boundary. The composite of Figs. 6a and 6b indicates that the main input part of water vapor transport in the torrential rain period in China in 1998 is from the southern and western boundaries with the main output part at the eastern boundary.

The method used to calculate the water vapor flux at the lateral boundary of the whole layer is as follows:

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix} = \begin{pmatrix} \sum\limits_{k=1}^{T}\sum\limits_{j=1}^{N} q_{1j}(k)u_{1j}(k)/N \\ \sum\limits_{k=1}^{T}\sum\limits_{i=1}^{M} q_{i1}(k)v_{i1}(k)/M \\ \sum\limits_{k=1}^{T}\sum\limits_{j=1}^{N} q_{Mj}(k)u_{Mj}(k)/N \\ \sum\limits_{k=1}^{T}\sum\limits_{i=1}^{M} q_{iN}(k)v_{iN}(k)/M, \end{pmatrix} \quad (1)$$

with zonal grid point $i = 1, 2, \cdots, M$, meridional grid point $j = 1, 2, \cdots, N$, and vertical level $k = 1, 2, \cdots, T$.

The above regional water vapor dynamic features show that the water vapor in the Big Triangle area of the East Asian monsoon in the heavy rainfall area in 1998 enters from western and southern boundaries. *The transport model with the eastern boundary as the* main output boundary is very significant. The numerical experiment in this paper is constructed to investigate the water vapor transport features at the western boundary in middle Tibet and the southern boundary of the South China Sea and West Pacific, as well as



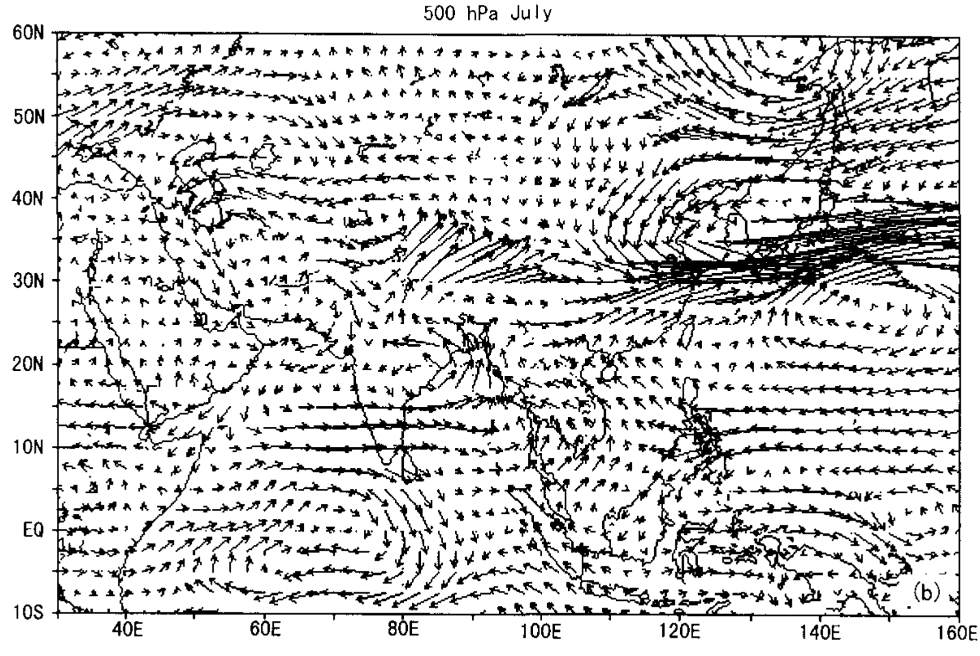


Fig. 5. 500 hPa difference field between water vapor flux field in 1998 and climate averaged water vapor flux field. (a) June; (b) July.

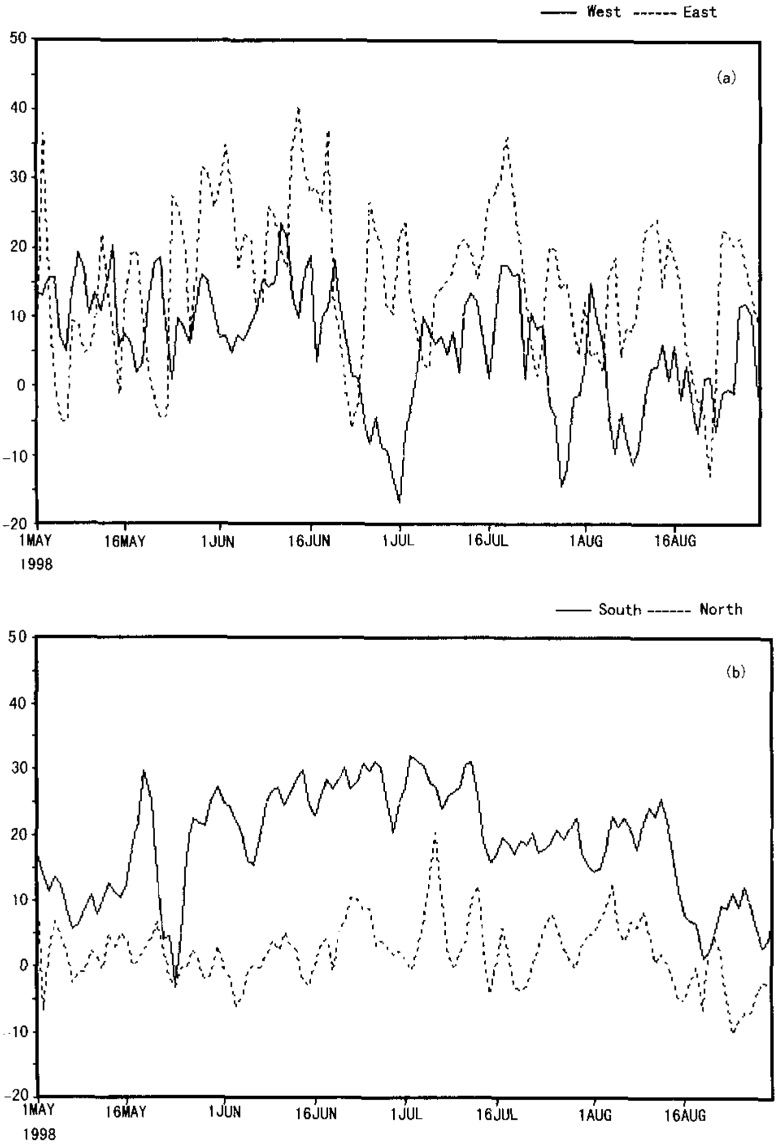


Fig. 6. The temporal variation of the total amount of water vapor transport in the whole layer along the regional boundaries in 1998. (a) West (S_1) and east (S_3) boundaries of the domain; (b) South (S_2) and north (S_4) boundaries of the domain.

their affecting mechanism on the flood in the Yangtze River Valley in 1998.

4. Numerical experiment

The model employed in this paper is RegCM2 (Giorgi et al., 1993a, b). The vertical coordinate is σ. The physical processes include the radiation transfer process, land surface process, boundary layer and cloud physical process. The horizontal domain of the model covers 3000 km×5000 km. There are fourteen vertical levels. NCEP/NCAR reanalysis data are adopted to provide the initial and boundary condition.

The frequency of the data is twice a day (0000 UTC and 1200 UTC) with a resolution of 2.5° × 2.5°. A total of 50 model-days' integration is carried out from 0000 UTC 10 June 1998 to 0000 UTC 30 July 1998.

To confirm the above diagnostic results, namely the abnormal features of water vapor flow at the boundaries of the China region during the period of torrential rain in 1998, the following schemes are designed:

Scheme 1(control experiment):

With the reanalysis data as the initial and boundary data, the model is integrated for 50 model days covering the intensive heavy rain phase in the Yangtze River Valley in 1998 (from the second dekad of June to the third dekad of July).

Scheme 2:

Considering the impact of the water vapor channel at the southern boundary of the China region on the flood in the Yangtze River Valley in 1998, the model is integrated for 50 model days. The reanalysis data are still used as the initial and boundary data. However, the water vapor input at the southern boundary of China is cut off, namely the input amount of water vapor and its tendency at the southern boundary are set to zero.

Scheme 3:

Considering the impact of the water vapor channel at the western boundary in middle Tibet and at the southern boundary of China on the flood in the Yangtze River Valley in 1998, the model is integrated for 50 model days. The reanalysis data are still used as the boundary data. However, the water vapor inputs at the southern and western boundaries are cut off, namely the input amount of water vapor and its tendency at the southern and western boundaries are set to zero.

4.1 *The impact of water vapor input at the southern boundary*

Comparing the result of scheme 2 (Figs. 7c and 7d) with that of the control experiment (Figs. 7a and 7b), we can see that the heavy rain belt in the second and third dekad of June would change significantly without the water vapor input at the southern boundary of China. The rain belt shrinks. The intensity of the rainfall gets weakened. However, the rain belt in July changes little in its extent and intensity. This may indicate the changes of water vapor transport channel at the regional boundaries in the flood period of June and July 1998. This conclusion may be somewhat different from the water vapor transport status of the climate-averaged water vapor source.

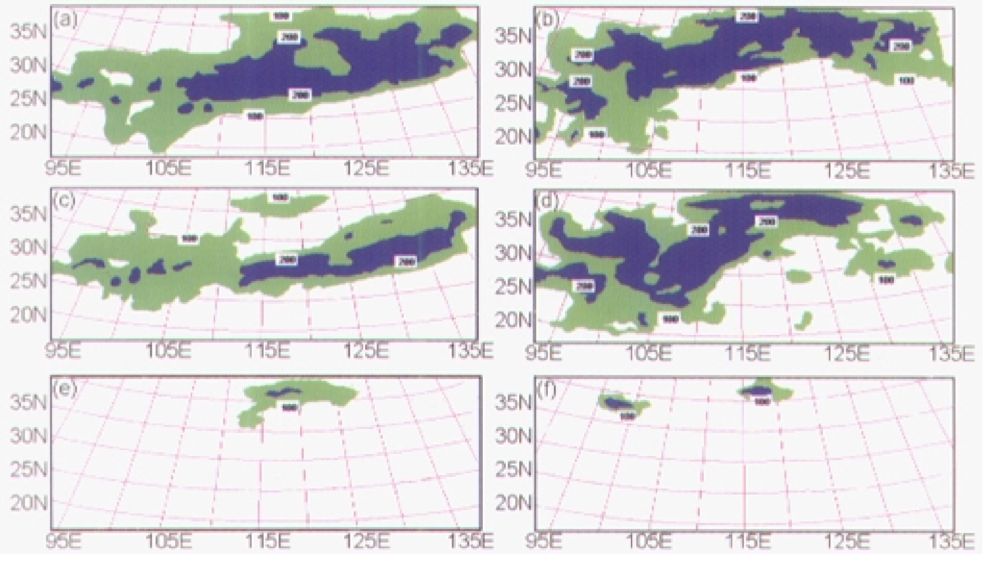


Fig. 7. Total rainfall in the numerical experiments: (a) 10–29 June in the controlling experiment, (b) 30 June to 29 July in the controlling experiment, (c) 10–29 June in the sensitivity experiment (scheme 2), (d) 30 June to 29 July in the sensitivity experiment (scheme 2), (e) 10–29 June in the sensitivity experiment (scheme 3), (f) 30 June to 29 July in the sensitivity experiment (scheme 3).

4.2 *The impact of water vapor input at the western and southern boundaries*

Without the water vapor input at the western boundary in middle Tibet and at the southern boundary of China, significant changes would happen in the rain belt in the last dekad of June and July. Figures 7e and 7f show that the intensity and extent of the rain belt in the Yangtze River Valley decreased significantly. The rainfall center of the rain belt shifts to 40°N. Apparently, the numerical results show that the water vapor input at the western boundary in middle Tibet and at the southern boundary of the China region is a key factor of the water vapor source and its regional water cycle in the torrential rain in the Yangtze River Valley in 1998. This result suggests that the affecting mechanism of water vapor flow and its input intensity at the western boundary in middle Tibet and at the southern boundary of the China region on the water cycle in the Yangtze River Valley need to be understood to disclose the cause of the 1998 summer flood in the Yangtze River Valley.

5. Conclusions

Through the analysis on the water vapor transport channel features during the rainfall period in June and July 1998 as well as numerical simulation on the water vapor input at the boundaries, the following conclusions are obtained:

Through diagnostic analysis, the characteristics of water vapor transport at the boundaries of China in the Meiyu period are put forward. Namely, the main input of water vapor transport is at the western boundary in middle Tibet and at the southern boundary in lower latitudes of the South China Sea and the West Pacific. The main output of water vapor transport is at the eastern boundary in the West Pacific. The input and output features of water vapor transport at the boundary of the region coincide with the Big Triangle mode for water vapor transport in the monsoon region.

Differences exist between the features of the water vapor transport channel in June and in July, when the torrential rain happened in 1998. In June, the southwesterly water vapor flow originating from the Bay of Bengal and transferred at Tibet is very significant. Furthermore, the southwesterly water vapor transport in the South China Sea at the southwestern boundary of the subtropical high in the West Pacific is more significant. In July however, the main body of water vapor at the boundary of the region consists of two branches of southwesterly water vapor flow from the Indian Ocean and the Bay of Bengal respectively.

The numerical simulation results also disclose the significant changes in the water vapor source of the rain belt and its channels in the Yangtze River Valley in the torrential rain period in the last dekad of June and the last two dekads of July. In the middle dekad of June 1998, the main body of the water cycle that forms the torrential rain in the Yangtze River Valley is made up of water vapor transport at the western and southern boundaries of the China region, in which the water vapor transport in the South China Sea and the West Pacific is very significant. In July, the water vapor flow at the western boundary in middle Tibet turns out to be the main body of water vapor source.

The diagnostic and numerical simulation results show that the water vapor channels at the western boundary in middle Tibet and at the southern boundary of the China region are key factors that should not be neglected in the formation process of torrential rain in the Yangtze River Valley during the Meiyu period. The impact of water vapor flow from the plateau on the Yangtze River Valley is especially significant. Since the boundary of the region is far from the rainfall area in the Yangtze River Valley, the temporal and spatial distributions of water vapor flow and the water cycle features in East Asia are also important respects and key factors for the forecast of continuous torrential rain in the Yangtze River Valley.

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梅雨期区域边界水汽输送模型及其数值试验

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摘　要

通过诊断分析，提出梅雨期中国区域边界水汽输送特征模型，即高原中部区域西边界与低纬南海、西太平洋南边界为水汽输送流入主体，西太平洋东边界为水汽“流出”主体。数值模拟研究表明：1998年洪涝特大暴雨过程6月与7月份水汽输送通道特征存在差异，6月中下旬长江流域暴雨过程以西边界与南边界水汽流共同输送为主体，其中南海西太平洋区域水汽输送显著，7月份水汽输送过程以高原中部区域西边界“水汽流”为主体。因此，高原中部区域西边界与中国区域南边界的水汽输送对长江流域特大暴雨的形成均具有重要的作用。区域边界水汽流的时空特征分析及其理论模型将为长江流域暴雨预报提供科学依据。

关键词:水汽流, 暴雨, 长江流域, 梅雨期