THE CHARACTERISTICS OF SUMMER MONSOON AND TRANSPORT OF MOISTURE IN A HEAVY RAIN OVER SOUTH CHINA IN 1994

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Received 10 March 1997, in revised form 8 May 1997*

ABSTRACT

The trajectory of atmospheric particles and material lines on an isentropic surface are computed using the Lagrangian method. It is shown that the 1994 heavy rain in South China was closely linked to the summer monsoon, especially the tropical monsoon in East Asia, which plays a decisive role. The method is useful in tracking the source area and evolution of water moisture and analyzing the transporting part of airflow for water moisture.

Key words: heavy rain, Lagrangian method, monsoon

I. INTRODUCTION

In June through July, 1994, an unusually serious floods disaster occurred in the south of China, which was marked by long duration and large intensity of precipitation. By the middle decade of June in a normal year, the subtropical high has already moved northward to push the rainfall belt over the basins of the Changjiang and Huaihe Rivers to form the yearly rainy season there. It rains relatively less in South China. Instead of being in its usual location, the rain belt was mainly active in regions south of the Changjiang River and the south of China in June 1994, with the rainfall centered over Guangdong, Guangxi and parts of Jiangxi. After the middle decade of July, the rain concentrated in the north of China and the Northeast Plain, accompanying the second northward movement of the subtropical high. Sustained processes of heavy rain were still present in the south of China as a result of effects of tropical circulation systems in the easterly south of the subtropical high. Due to successive appearance of heavy rains, a serious flood disaster occurred in the summer of 1994 over the area of interest.

In this paper, the role of the Indian southwest monsoon and the East Asian summer monsoon corresponding to the June–July heavy rain in South China is analyzed from the point of flow field, the integral variation of the trajectory of air particles and material lines is studied using the Lagrangian method and how the summer monsoon transports water moisture is revealed.

II. DATA AND METHOD OF COMPUTATION

An objective analysis is done with the data provided by the Guangzhou Regional Meteorological Center to have information on 2.5×2.5 mesh grids within a domain of 0 – 50° and 30 – 160°, which is divided into 11 vertical layers of 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa. The potential equivalent temperature is computed for each of the grids to derive isentropic data on 15 layers, and then Lagrangian integration for the trajectory is sought with data being transformed from isobaric to isentropic form.

[1] This work was funded by the National Natural Science Foundation of China.

The trajectory method is a traditional way of computation of the source area and the material diffusion and transportation process. Lu and Lei (1991) contributes in the Lagrangian method for studying the general circulation by addressing the issue of isentropic surfaces, arguing that the material lines are traceable in the troposphere in the order of days. As the entropy in the real atmosphere is close to conservation, three-dimensional motion of the airflow is shown in computed trajectory on the isentropic surfaces. The evolution of the material line on the θ_{se} surface is a good indicator of the variation of the atmosphere, because it has better approximation of the conservative atmosphere and more realistic integration by taking account of water moisture.

The computation of trajectory with the material lines involves data transformation, integral equations and schemes, data fitting and the control of stability[2]. Using the data fitting method, the variation of the trajectory of air parcels in large-scale motion is described with fine-scale motion as the error. In integrating the trajectory of initial material lines using the isopleth, more points are being added to the process to maintain the density of points on the lines for studying the evolution of isopleth.

III. CHARACTERISTICS OF LARGE-SCALE CIRCULATION

The heavy rain in June–July 1994 in the south of China is divided into three stages by the evolution of circulation patterns, i.e. 13–17 June, 14–21 July and 22–28 July.

In the middle decade of June 1994, the subtropical high was anomalously more to the south, with the western ridge point west of 110°E and the ridge between 110°E and 130°E around 15°N. A strong southwesterly airflow was active west of the high. Fig.1 is the variation of mean zonal winds at 500 hPa with time and latitude from 105°E to 115°E. It is obvious that the subtropical high ridge was largely south of 15°N prior to 17 June and it didn't cross the 25°N until 20 June. It is located more southward as compared with the normal year.

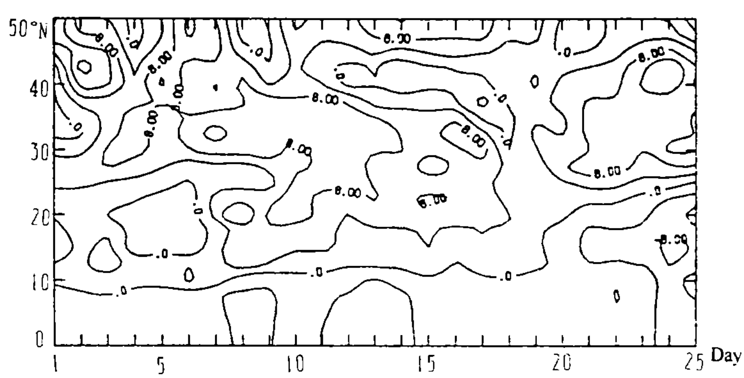

Fig.1. Variation of zonal wind (m/s) at 500 hPa between 105°E and 115°E with time and latitude in June 1994

By the first decade of July 1994 (Figure omitted), the subtropical high had moved north and east, with the ridge crossing 33°N. The line was steadily refrained between 33°N and 35°N from then on until well into the late decade of July. The tropical synoptic systems within the easterly south of the subtropical high and the Indian southwest monsoon were the two phenomena that affect the south of China throughout July 1994.

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2 Cheng Xinxi, 1995. The Lagrangian analysis and diagnostics of anomalous variation of the general circulation, a postgraduate thesis in evaluation of the M.D. qualification at the Air Force Institute of Meteorology.

Fig.2 is the mean flow field at 850 hPa. In Fig.2a that gives the mean field from 13 to 17 June, and the most remarkable feature is that there is a southwesterly airflow traveling eastward over the middle- and lower-latitude regions of the Indian Peninsula, the Bay of Bengal and the Indochina Peninsula, with the mean westerly at 15.3 m/s at 15°N over the region of India. The monsoon was active over the Bay of Bengal and a low trough was a long-lasting feature there. The Indian southwest monsoon was separated into two sections over the southeastern part of the Bay of Bengal, the first being diverted into the northeastern India where it was cyclonic to contribute to a monsoon depression over the north of the nation echoing the Indian monsoon trough, the second being flown into the south of China. Consequently, the South China Sea and southern part of China were affected by a strong southwesterly airflow at the northwest edge of the subtropical high of West Pacific.

The other main airflow was the cross-equatorial current around 100°E, which intrigues upon increase itself the intensification of the South China Sea monsoon.

There had been the southerly cross-equatorial airflow (Fig.3) since 3 June between 90°E and 110°E. It was so strong and stable that it affected the regions of the South China Sea and West

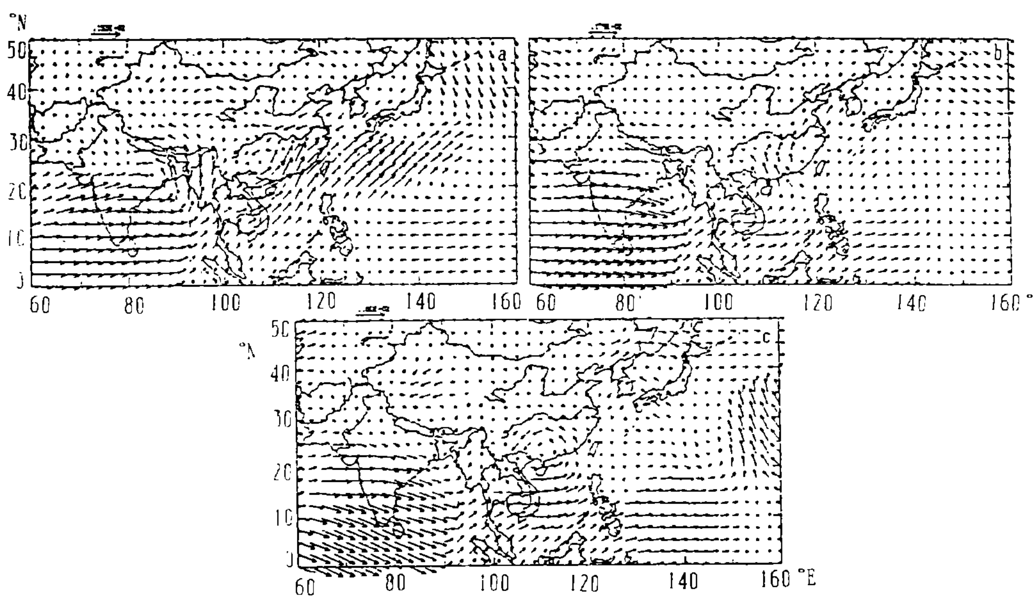

Fig.2. Average flow field at 850 hPa for 13–17 June (a), 15–19 July (b) and 24–28 July (c).

Pacific. Examining the average over the years, it is not hard to find that in the first and middle decades in June the airflow is normally less than 2 m/s in the regions while it reached 4.8 m/s over the second pentad and 6.2 m/s over the third pentad, around 100°E in 1994. The southerly was steadily over 4 m/s from 8–16 June, at 7.7 m/s on 9 June and 7.5 m/s on 13 June. It shows that there was very active tropical monsoon in East Asia around 100°E in contrast to poorly-defined, sometimes breaking-off, cross-equatorial current at 125–130°E over Sulawesi and around 150°E over the central equatorial Pacific. In unusually wet periods over the south of China in 1994, the cross-equatorial flow differs much from the average year in terms of both intensity and location as far as the channel is concerned. A tropical summer monsoon over the Indochina Pen. through the South China Sea, merged by monsoon systems from the Bay of Bengal and the Sea, becomes a major zone of southwesterly. It is found that the June heavy rain was

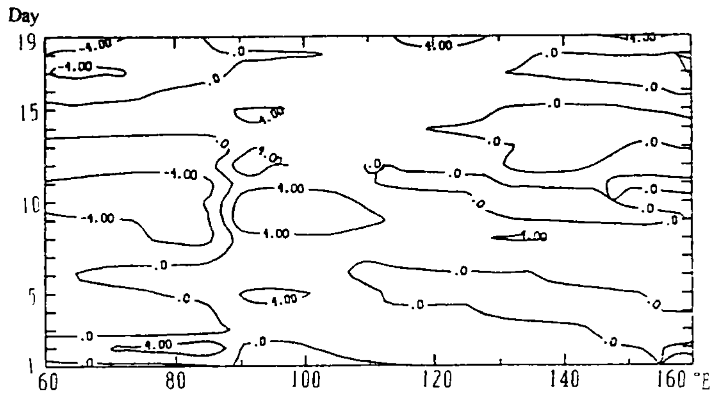

Fig.3. The longitudinal distribution of meridional wind components (m/s) along the Equator at 850 hPa from 1 to 25, June 1994.

resulted from the joint influence by the southwest monsoon of India and tropical monsoon of East Asia.

The Indian southwest monsoon remained as strong as ever before in the mid- and late-July, when two processes of heavy rain appeared in the regions of interest. There was still a channel of stable southerly at 90–110°E, which expanded eastward to cover a larger area corresponding to the heavy rain from 14 to 21 July. Due to the movement of the subtropical high towards the north and east in a new location dominating the Sea of Japan and the Yellow Sea on a stationary ridge between 33°N – 35°N, the easterly south of the high was heading all the way into the south of China (Fig.2b). It is then seen that the hard rain was caused by the subtropical monsoon of East Asia as well as by the Indian southwest monsoon and the South China Sea monsoon as presented above.

In the late decade of July 1994, the southern part of Japan, the Bay of Tongkin and the Bay of Bengal were all controlled by three lows, the most intense being over the second location and all joined by a well-defined zone of convergence. The zone was about 5 latitudes more to the north and longer in duration, as compared to the average year. Frequent influence from unusually active tropical systems also accounts for heavy rains in July in that part of China.

IV. TRANSPORT OF WATER VAPOR BY SUMMER MONSOON

It is indicated in the preceding analysis that the heavy rain in the south of China is caused by interactions between the northern and southern hemispheres and the easterly and westerly disturbances. The rain is closely linked to low-latitude ocean, which is a center of atmospheric heat, moisture and momentum and an important source for the formation and development of synoptic systems associated with the process. In addition to the Indian southwest monsoon and the West Pacific southeast monsoon, its moisture is also provided by a southwesterly airflow formed as a result of turned-away cross-equatorial current from the southern hemisphere. Warm and humid, these maritime flows transport abundant amount of water vapor to the south of China.

Studying the distribution of θ_{se} during the heavy rain in mid June (Figure omitted), the region of interest is found to be in an area of large θ_{se} south of concentrated contours of θ_{se}, which corresponds to a well-known stationary front in South China. The active summer monsoon plays an active part for the huge amount of water vapor in the rain process, making the cold air activity a minor factor. (It is easy to understand how little it means in northern July!) It is, therefore, natural that the contours of θ_{se} are mainly an indicator of the effects of water vapor and the frontal surface is just of potential equivalent temperature.

Studying the distribution of the 310 K θ_{se} surface on 13–17 June in the q field (Figure omitted), an extensive area of large specific humidity covers the low-latitude equatorial region, which includes the Arabian Sea, the Bay of Bengal, the South China Sea and the south of China. There is an east-west concentrated belt of specific humidity north of the region.

The specific humidity is studied from the Eularian point for the θ_{se} field and isentropic surface at 850 hPa. Nevertheless, how would the Indian southwest monsoon and East Asian monsoon transport water vapor? For a better description, the Lagrangian method is used to integrate the trajectory of the material line. The contour of specific humidity on the isentropic surface is the material line in an exact sense. The q line remains a material line with a high approximation on the θ_{se} surface even with inclusion of water vapor. Its evolution is a good indicator of the transport of large-scale water vapor.

1. *Evolution of the q system*

For an isentropic surface with θ_{se} =310 K, a number of well-defined q systems are selected in the integration of trajectory. The contour of q=14 g/kg is set as the initial line of state for the material line to be integrated. Fig.4a shows a large center of q locating from the Indochina to the southwestern part of China. After a 5-day integration of trajectory from 13 to 17 June, it shrinks north-south but prolongs east-west and transports water vapor to the east and then north to carry a center of high vapor to the southern part of China. Fig.4b shows a large center of q locating over the Indian Ocean, which first moves towards the Bay of Bengal and then heads to the Indochina Pen. with a 5-day integration of trajectory.

Fig.4c gives the variation in the trajectory integration of the q system on the 310 K θ_{se} surface from 15–19 July 1994. The center of large water vapor over the Arabian Sea moved to the Bay of Bengal as affected by the Indian southwest monsoon. Part of the water vapor there comes from the evaporation and transport over the Arabian Sea and the figure is just a reflection of the feature. Another center of large value, locating over the South China Sea (Fig.4d), shifted to the south of China and the other to the east.

It is then clear that the source areas of water vapor in low-latitude oceans, the Arabian Sea, the South China Sea and the Bay of Bengal transport centers of large q towards the Bay of Bengal, the Indochina Pen. and southern China, under the action of the Indian southwest monsoon and East Asian tropical monsoon. It is the on-going transferring processes that have maintained and strengthened the heavy rain in the south of China in 1994 and the four cases as cited above are only part of the real situation. Studying the fluxes of water vapor that have been vertically integrated over time average, we know that there are two channels of vapor transportation in all of the three processes: One is the transporting channel of Indian monsoon, which carries moisture to the South China Sea as well as southern China; the other is one that travels across the Equator (90–105°E) towards the northeast to southern China via the Indochina Pen and the South China Sea. An additional channel also exists in July, which is an easterly on the south of the subtropical high (Chen and Yang, 1994).

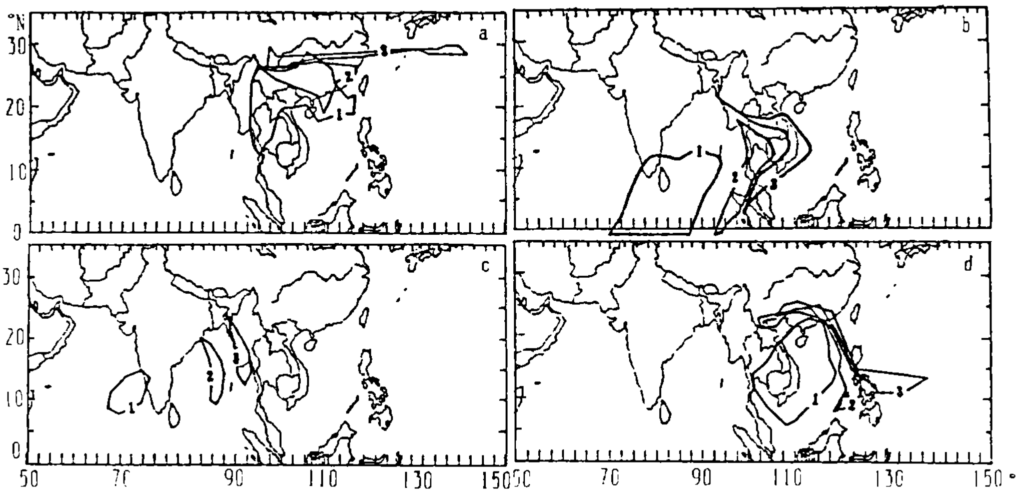

Fig.4. The evolution of material line of q=14 g/kg at θ_{se}=310 K. (The numerals 1, 2, 3 are the contours of Specific humidity at the initial time, Day 2.5 and 5 of integration.) a. 13–17 June; b. 15–19 July; c. 24–28 July.

2. *Trajectory of air particles*

In contrast to the treatment above that describes in a Lagragian way the transport of water vapor with the trajectory integration of q contours, more explicit illustration of the track along which it moves, integration is now conducted of the trajectory for the latitudinal points on the 310 K isentropic surface and the transporting effect of airflow on q is studied from the point of air particle trajectory.

Fig.5a gives the integration of the latitudinal points along 0–50°N. For latitudes from 0° to 10°N, the points generally move to east-northeast in areas west of 90°E. They are divided into two branches over the Bay of Bengal, one turning to northeastern India and the other heading towards the South China Sea and southern China via the Indochina Pen. For the latitudinal points east of 90°E, however, the cross-equatorial air current contributes more as compared to the Indian southwest monsoon. The figure has shown that the points move northeast to transport water vapor directly from the low latitudes to the South China Sea and then to southern China. Such transfer by the southwesterly on the northwest side of the subtropical high in June becomes much more vigorous because of its anomalously southward location.

The northward air particles along 20°N in Fig.5a meets the southward-moving ones along 30°N to form a strong convergence, favorable for updrafts in the development of heavy rains.

There is consistent westerly transport at mid-and lower-latitudes west of 90°E (Fig.5b) while the cross-equatorial tropical monsoon is still recognizable east of 90°E. At 120°E through 140°E, the latitudinal airflow on 30°N, 25°N, and 20°N travel southwestward when the subtropical high shifts northward. The airflow indicates the transport of the easterly south of the high, which carries water vapor to the south of China from the Pacific Ocean.

It is now seen that for the source of water vapor, the South China Sea is provided by the Bay of Bengal and the cross-equatorial current around 100°E and the Bay of Bengal is in turn supplied by the cross-equatorial Somali jet stream around 45°E, which carries moisture from low latitudes and the Arabian Sea. On the other hand, the source for the south of China is mainly the Bay of Bengal, the South China Sea, and partially the West Pacific in July.

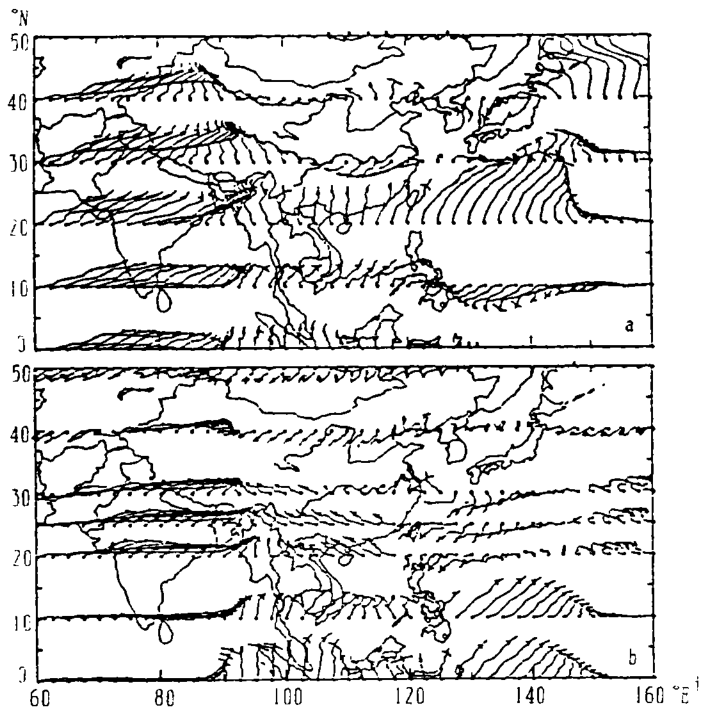

Fig.5. A 5-day integration of trajectory of latitudinal air particles.
(a) 13–17 June, (b) 15–19 June.

V. CONCLUDING REMARKS

In the first part of this work, the isobaric data in the lower troposphere are used to study the effects of the Indian southwest monsoon and East Asian monsoon on a heavy rain in South China. It is concluded that the heavy rain is linked with the anomalous variation in the summer monsoon (especially over East Asia). For the floods in 1994 in southern China, the anomalously stronger cross-equatorial airflow at 100°E is decisive for the increased East Asian tropical monsoon.

The second part of the work involves itself in the application of the Lagrangina method in integrating the trajectory on the isentropic surface, the study of relevant integral variation for determination of the source and evolution of water vapor by setting the contours of maxima of specific humidity as the initial state of the material line, and the more direct indication of the transport of water vapor by integrating the latitudinal air particles.

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