Branches of the Summer Asian Lower–Level Jet Stream and Its Influence on the Rain Belt in China

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ABSTRACT

Based on the analysis of the Asian lower–level jet stream, this paper indicates that having shifted to the Bay of Bengal, this large–scale lower–level jet(LLJ) develops into two branches: the northern branch (NB) which is a strong southwest flow moving into the inland of China along the southeast side of the Qinghai–Xizang Plateau and then moving eastward to Japan along the north side of the subtropical high, and the southern branch (SB) which continues to be a west flow and travels into the West Pacific across the Indo–China Peninsula along the south side of the monsoon trough. Above the two branches are two synoptic–scale transient tubular monsoon circulation systems, the northern branch being a subtropical monsoon stream tube (SMST) and the southern branch a tropical monsoon stream tube (TMST). Their ascending branches, corresponding to a subtropical monsoon rain belt and a tropical monsoon rain belt respectively, bear considerable influence on the weather over China.

I. INTRODUCTION

It is well known that there exists a large–scale LLJ over East Asia during the summer time. Along with the Somali jet stream in East Africa, the LLJ in Asia becomes an important part of the lower–level circulation over this vast area in summer. For lack of observational data in the past, most studies were limited to the role that the southerly flow in the west of the subtropical high played in the establishment of the LLJ. It was believed that the strong wind on the axis of the jet was the result of its overlapping with the trough in the westerlies or the air flow in front of the low vortex. With the accumulation of data from the southern ocean surfaces as well as from the tropics, it is now possible to acquire a comprehensive understanding of the large–scale LLJ.

The summer monsoon occurring over China is closely related to the Indian monsoon. Having entered the Bay of Bengal, the strong west flow originating from the Arabian Sea and the Indian subcontinent penetrates deep into the inland of China and the South China Sea and then shifts north and south with the seasons.

Based on the information for the summers of 1979, 1983 and 1986 from the European and Washington Weather Centers, this paper intends to make further investigations of the evolution of the large–scale LLJ in East Asia and its relation to the Asian monsoon and influence on the weather and climate in China.

II. BRANCHES OF THE STRONG LOWER–LEVEL WEST FLOW

The Asian lower–level westerly jet stream is a large–scale LLJ active in the monsoon region. Its upstream is interlinked with the Somali jet stream, and after the Indian monsoon has extended eastward, its downstream, upon reaching the Bay of Bengal, develops into two branches: the NB in which the strong winds move along the southeast side of the Himalaya, crossing the Yunnan–Guizhou Plateau and usually joining the southeasterly flow west of the

West Pacific and then continue to move northeastward, pepetrating the inland of China and finally reaching the Sea of Japan across the East Sea, and the SB in which the strong winds cross the Indo–China Peninsula along the monsoon trough, entering the area of the South China Sea and then, after joining the transtropical flow over Southeast Asia, disappearing over the Philippines. Now let us have a look at the following two cases:

Case 1 shows the flow field at 850 hPa at 202000 June 1979.It is seen from Fig.1 that the subtropical high ridge was located near 25 ° N and its western ridge extended to the vicinity of the Bay of Tonkin, with a cyclone over the Arabian Sea and a strong west flow of more than 30 m / s on its south side. This strong west flow extended from the Arabian Sea to the Indo–China Peninsula and could be traced back to its upstream which was interlinked with two air flows coming from the Arabian Peninsula and the Somali jet respectively. After crossing the Indian subcontinent and entering the Bay of Bengal, the strong west flow broke into two branches. The strong winds in the NB entered the inland of China along the southeast side of the Himalaya, joined the southeast flow to the west of the West Pacific subtropical high along the east coast areas of China and then moved north–eastward to the area of the Sea of Japan. After joining the northerly flow coming from the inland over the Changjiang–Huaihe Valley, the NB became the Jiang–Huai shear. The strong west flow in the SB, after surging to the South China Sea along the south side of the monsoon trough, met with the transequatorial flow coming from the south and finally disappeared near the Philippines.

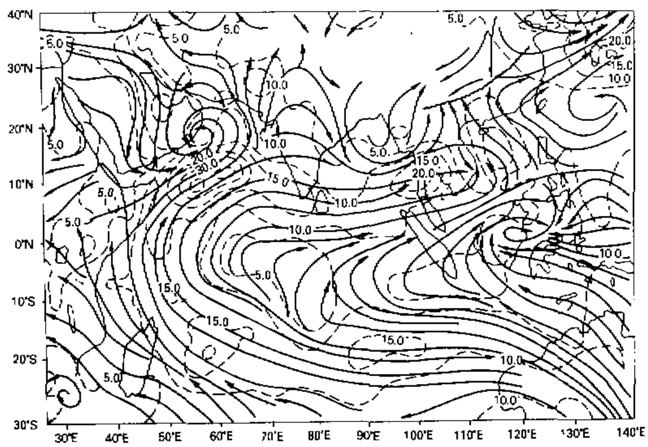

Fig. 1. Flow field at 850 hPa at 202000 June 1979.

Case 2 shows the branches of the LLJ on June 17, 1986. It is seen from the diagram(omitted) showing the flow field at 850 hPa on the same day that the West Pacific subtropical high ridge was located near 22 ° N. The western ridge had extended to the vicinity of the Taiwan straits. Over South China was observed a shear. A monsoon low–pressure circulation dominated the area from the Arabian Sea to the Indian subcontinent with a strong west flow on its south side. Fig.2 shows the zonal wind velocity at 850 hPa on the same day. It is seen that from the Arabian Sea down to the Indian subcontinent tip was an area of strong winds with speeds more than 20 m / s at the center. Upon reaching the Bay of Bengal, the flow gradually developed into two branches.

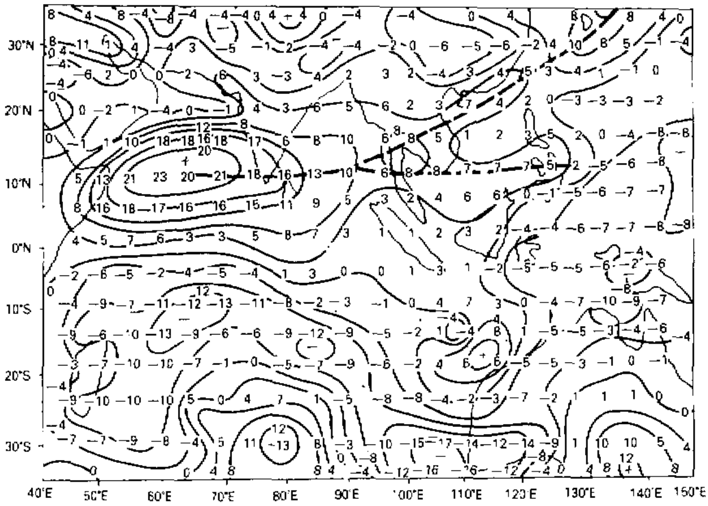

Fig. 2. Zonal wind velocity at 850 hPa at 172000 June 1986.

The strong flow in the NB entered the area of the South China Sea across the northern part of the Indo–China Peninsula and then arrived at Japan along the Taiwan Straits. It became weakened as it extended northeastward and then gradually intensified while moving over the Sea of Japan. Obviously, this could be attributed to the overlapping of air flows in front of the westerly low trough. The strong flow in the SB entered the area of the South China Sea after crossing the southern part of the Indo–China Peninsula and finally disappeared near the Philippines. As compared with the flow field diagram, the NB moved along the south side of the South China shear and the SB extended eastward along the monsoon trough.

It is shown from the above two cases that the South China shear and the Jiang–Huai shear are *both closely related to the strong large–scale lower–level northern branch in East* Asia. Analysis based on the data of the three years indicates that the branches of the East Asian LLJ emerge after the establishment of the Somali jet. The branches generally become weakened when turning to the east, the weakening process being faster in the SB than in the NB. The point where the strong west flow begins to branch is connected with the position at which the West Pacific subtropical high extends westward. The direction of the branching point varies with that of the westward extending point of the high. It is also found that the position (north or south) of the strong west flow after branching in connected with the position of the West Pacific subtropical high.

III. THE STRONG LOWER–LEVEL WIND REGION AND THE MONSOON STREAM TUBE

Based on data available, a diagram is constructed to show the meridional cross section at intervals of 5° longitude (50°N–35°S, 70–145°E) at 8 p.m. each day from May to July of 1979 and 1983. Analysis shows that in the monsoon area east of 70°E along the direction of the strong winds there was observed a monsoon vertical circulation cell, continuous in the east–west direction, which we have named the monsoon tube. However, it behaves differently in different climate regions, and in general, can be divided into three types: 1) The subtropical *monsoon stream tube (SMST) which occurs in the vicinity of the strong north flow in the East*

Asian monsoon region, with its ascending branch (AB) frequently above the shear north of the West Pacific subtropical high and its descending branch(DB) inside the subtropical high south of the shear. 2) The tropical monsoon stream tube (TMST) which is observed near the SB strong winds in the South East Asian monsoon, with its AB above the South China monsoon trough and DB often within the equatorial buffer zone south of the monsoon trough. 3) The Indian monsoon stream tube (IMST) which originates near the Indian strong wind region with its AB above the Indian monsoon trough and DB to the south of the trough. The following is a brief account of the real case occurring on June 27, 1979.

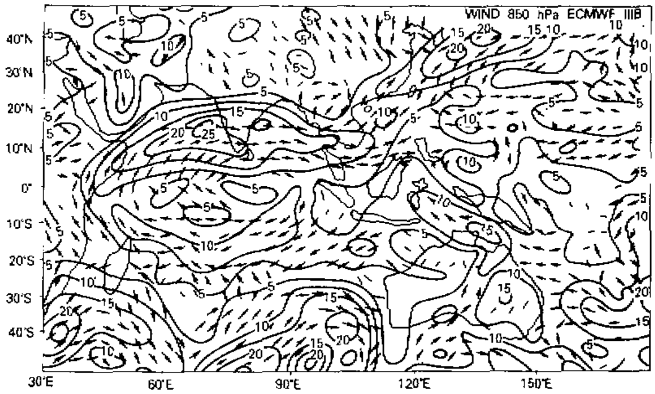

Fig. 3. Flow field at 850 hPa at 270800 June 1979.

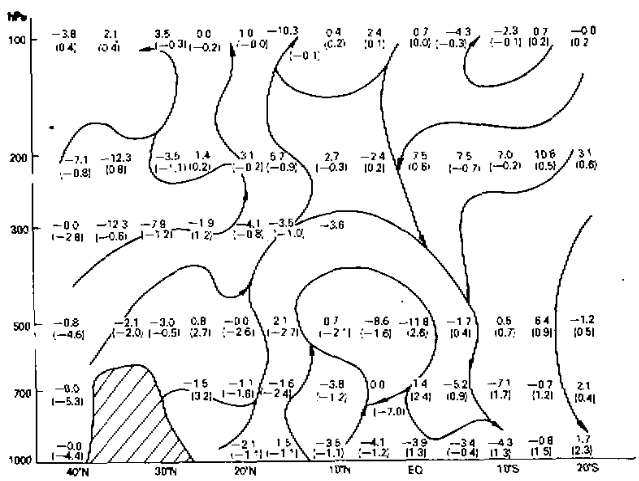

Fig.4a. Meridional cross section along 80 ° E at 272000 June 1979. The arrow line indicates the stream line. The numbers give the meridional wind components (m / s), "−" for the north wind and "+" for the south wind. The numbers in the brackets give the value of the vertical velocity · ω (10^{-3} hPa / s), "−" for the ascent and "+" for the descent.

Fig. 3 shows the flow field at 850 hPa at 270800 June 1979. Above the area of South Asia there was a strong wind belt, whose center was located south of the Indian subcontinent with speeds as high as 25 m / s. Upon entering the Bay of Bengal across the subcontinent, this strong wind belt developed into two branches. The NB penetrated deep into the inland of China through the Indo–China Peninsula. The SB entered the area of South China Sea after crossing the south tip of the Indo–China Peninsula, became weakened over the ocean surface of the eastern Philippines and finally shifted to the north upon joining the easterly flow along the south side of the subtropical high south of the Philippines.

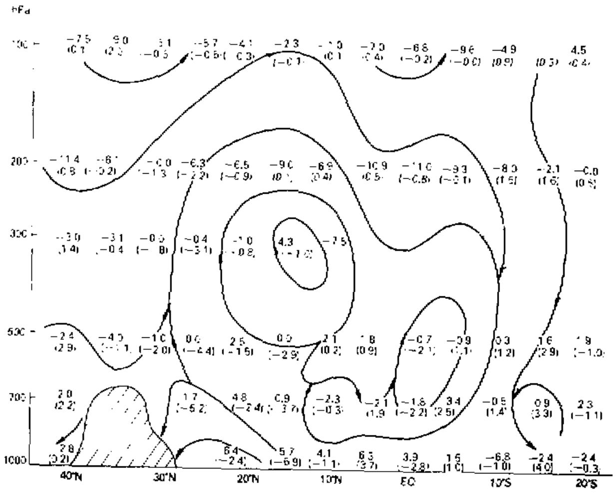

Fig.4b. Meridional cross section along 100 ° E at 272000 June 1979. (The caption is the same as in Fig. 4a.)

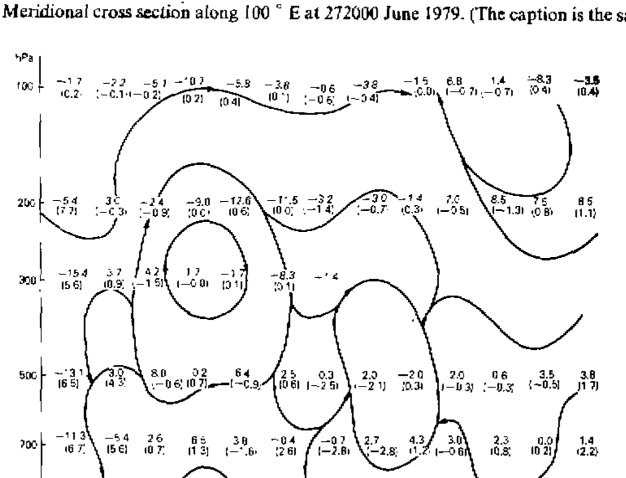

Fig. 4c. Meridional cross section along 120 ° E at 272000 June 1979. (The caption is the same as in Fig. 4a.)

Figs 4a–d show the meridional cross sections of the transverse monsoon stream tube along 80, 100, 120 and 140 ° E respectively at 272000 June 1979.

In Fig. 4a, a strong monsoon vertical circulation cell prevailed over the south of the Indian subcontinent with its AB above the Indian monsoon trough near Madras and DB in the vicinity of the equator. The center of the cell was found at the height of about 5 km and its horizontal scale spanned about 20 degrees of latitude. influencing the whole troposphere. The lower layer of the vertical circulation was, for the most part, dominated by the Indian strong west winds.

As shown in Fig.4b, the lower–level strong west flow over South Asia had broken into two branches. The AB of the monsoon vertical circulation cell in the vicinity of the NB strong west flow was observed above the shear at 850 hPa from 20 to 30 ° N and the DB in the vicinity of 10 ° N. The center of the vertical circulation was located at the height of about 8 km with its horizontal scale spanning about 15 degrees of latitude. Near the SB strong flow occurred a monsoon vertical circulation cell, with the AB above the monsoon trough and DB above the equatorial buffer zone near 5 ° S. The center was at the height of about 5 km, horizontal scale about 10 degrees of latitude, and the vertical height on the main below 12 km.

In Fig.4c, the AB of the monsoon vertical meridional cell above the NB strong winds was observed above the shear at 850 hPa near 30 ° N and the DB within the subtropical high ridge between 20–25 ° N. The monsoon vertical circulation cell behaved itself mainly in the lower and middle troposphere, with its center at the height of about 9 km and the horizontal scale about 15 degrees of latitude. The AB of the monsoon vertical circulation cell above the SB strong winds was observed above the monsoon trough near 10 ° N and the DB within the buffer zone near the equator. Its center was at the height of about 5 km, the horizontal scale about 10 degrees of latitude and the vertical height below 10 km.

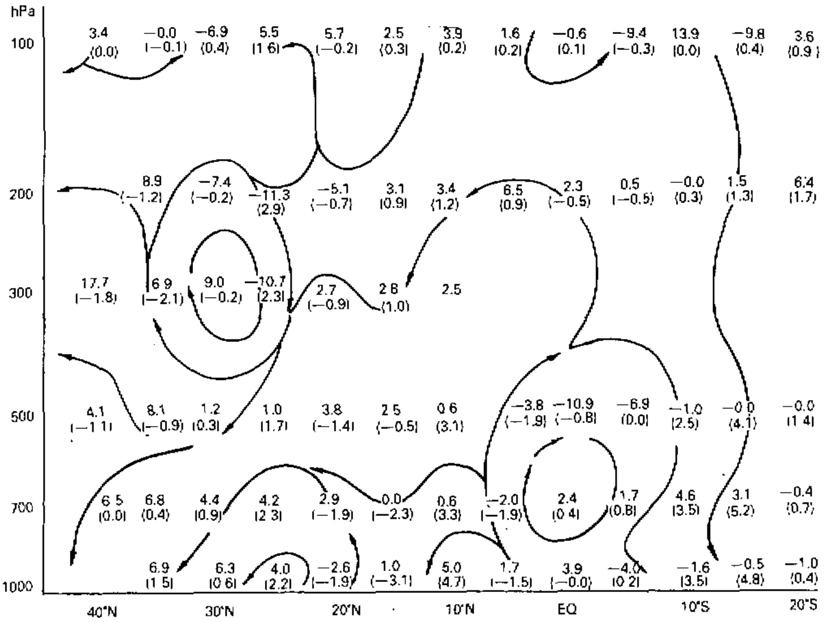

Fig. 4d. Meridional cross section along 140 ° E at 272000 June 1979. (The caption is the same as in Fig. 4a.)

In Fig. 4d, the AB of the monsoon vertical circulation above the NB strong winds was observed above the shear at 850 hPa between 30–35 ° N and the DB in the vicinity of the subtropical high ridge near 25 ° N. The center of the circulation was at the height of about 9 km, the horizontal scale about 10 degrees of latitude and the circulation cell mainly in the mid–troposphere. The SB strong winds had already abated and the monsoon vertical circulation cell was not observed any longer.

For purpose of understanding the relationship of the monsoon stream tube with the lower–level west flow, a comparison is made between the maximum rising and subsiding movements in the monsoon stream tube above the meridional cross section along 80, 100 and 120 ° E and the lower–level west wind velocity, as shown in Table 1.

Table 1. A Comparison between the Maximum Rising and Subsiding Movements in the Monsoon Stream Tube above the Meridional Cross Section along 80, 100, and 120 ° E and the Lower–Level West Wind Velocity

Latitude	80 °			100 °			120 °		
West Wind Velocity (W) m / s Vertical Velocity (ω) 10^{-3} hPa / s	W	ω_1	ω_2	W	ω_1	ω_2	W	ω_1	ω_2
IMST	21.7	−7.0	2.6						
SMST				13.8	−4.4	0.2	11.3	−1.5	1.3
TMST				6.8	−2.2	2.5	2.5	−2.1	1.2

Note: W is the maximum wind velocity at 700 hPa; ω_1 and ω_2 are the maximum vertical velocities of the AB and DB in the monsoon stream tube respectively.

If the intensity of the AB and DB in the monsoon stream tube can characterize the intensity of the tube, it is apparent from Table 1 that at 80 ° E the strengthening of the IMST varies with that of the west flow and at 100 ° E the weakening of the SMST varies with that of the west flow. At 120 ° E the west flow becomes more weakened and so do the SMST and TMST.

From the above–mentioned the following can be considered:

1. The IMST, SMST and TMST occur mainly in the south of the Asian continent and its adjacent waters. Their scope of influence becomes smaller and vertical movement reduces when moving over the ocean far from the continent.

2. The intensity of the monsoon stream tube is related to that of the west (southwest) flow in the lowest layer. In the area of India–the Bay of Bengal, the IMST increases with the wind velocity in the lowest layer and then the strong wind in the lowest layer decreases after branching, with the associated SMST and TMST becoming weakened.

3. The SMST and TMST are monsoon circulation systems of different nature. The former ascends above the shear north of the West Pacific subtropical high and descends within the high ridge, i.e., a subtropical monsoon system of great intensity with a high tube axis, while the latter ascends above the monsoon trough and descends where the equatorial buffer zone prevails, i.e., a tropical monsoon system, which is unstable and weak in intensity and has a low tube axis with the powerful IMST upstream. Although different in nature, the two tubes are related to each other, forming a typical monsoon circulation system over Asia.

IV. THE RELATIONSHIP OF THE STRONG LOWER–LEVEL WEST FLOW AND THE UPPER–LEVEL FAST FLOW WITH THE MONSOON STREAM TUBE

When summer comes, the westerlies begin to move northward. In the upper troposphere over the southern part of Asia there is observed a powerful tropical east flow, below which the prevailing southwest and southeast monsoons not only have a profound effect on the weather in this vast area but bear a close relation with the monsoon circulation system as well. Thus, it is necessary to have a detailed discussion here.

It is seen from daily weather charts that the easterlies in the upper troposhere mainly occur south of the Southeast Asian high. The daily zonal wind cross section along meridians indicates that within the broad easterlies there exist two powerful easterly jet centers, the northerly jet center (the northeasterly jet as shown in the daily weather chart) between 20–25 ° N and the southerly jet center between the equator and 5 ° N. Their positions correspond roughly to those of the NB and SB of the strong lower–level west flow respectively. The SMST is found to be in the vicinity of the upper–level NB easterly jet stream and the lower–level NB west flow, the TMST in the vicinity of the upper–level SB easterly jet stream and the lower–level SB strong west flow, and the IMST in the vicinity of the Indian upper–level easterly jet stream and the lower–level strong west flow.

Figs. 5a–c show the zonal wind vertical cross section along 80, 100 and 120 ° E respectively at 272000 June 1979.

At 80 ° E near 10 ° N in the upper troposphere there was observed a strong east flow center with its maximum speed of 35.4 m / s at the center. In the lower troposphere there was a strong west flow, its maximum wind velocity at the center being 21.7 m / s. It is found by calculation that at this time the AB of the powerful IMST was near 20 ° N, the DB near the equator and the axis near 5 ° N.

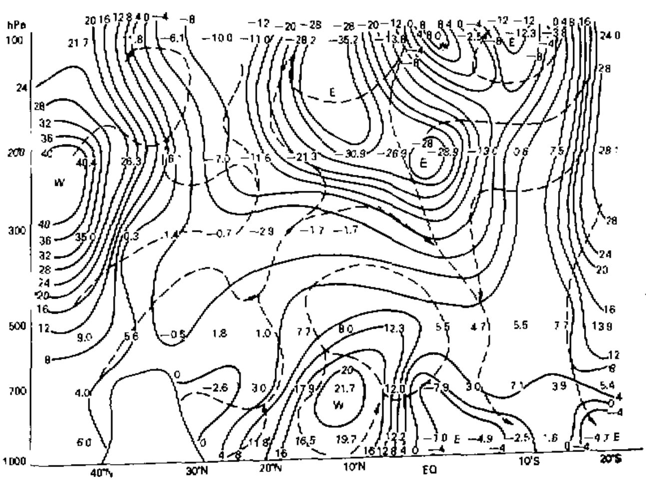

Fig. 5a. Zonal wind vertical cross section along 80 ° E at 272000 June 1979. The solid lines indicate the isotaches and the broken lines the stream lines of the monsoon stream tube. The numbers show the zonal wind velocity (m / s).

At 100 ° E in the upper troposphere there existed two powerful east flows. The NB was found near 15 ° N, its maximum wind velocity at the center being 25.9 m / s and the SB above the equator, its maximum wind velocity at the center being 19.1 m / s. In the lower troposphere there were observed two powerful west flows. The NB was near 10 ° N, its maximum wind velocity being 13.8 m / s and the SB near the equator, its maximum wind velocity 6.8 m / s. At this time, by calculation, the AB of the SMST was found near 20–25 ° N and the

SB near 10 ° N while the AB of the TMST above the monsoon trough and the DB near 5 ° S.

At 120 ° E in the upper troposphere, the NB strong east flow was located near 20 ° N, with its maximum wind velocity being 16.0 m / s at the eenter and the SB strong east flow near the equator, with its maximum wind velocity 12.1 m / s. In the lower troposphere, the NB strong west flow was near 25 ° N, with its maximum wind velocity at the center being 11.3 m / s and the SB strong west flow near the equator, its maximum wind velocity having weakened to 2.5 m / s. At this time, by calculation, the AB of the SMST was near 30 ° N and the DB within the subtropical high ridge near 20–25 ° N. And the AB of the TMST was near 10 ° N and the DB near the equator.

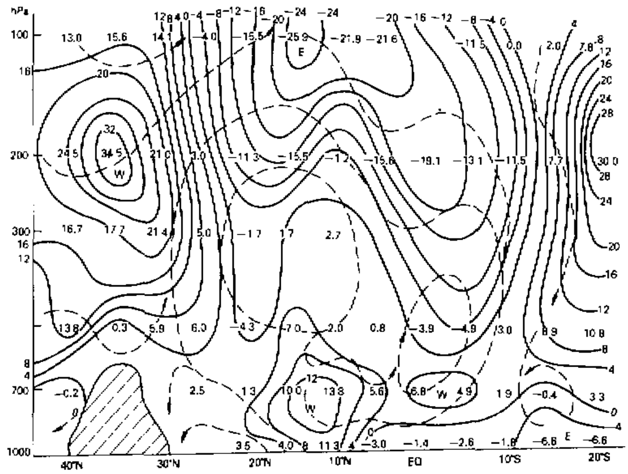

Fig. 5b. Zonal wind vertical cross section along 100 ° N at 272000 June 1979. (The caption is the same as in Fig. 5a.)

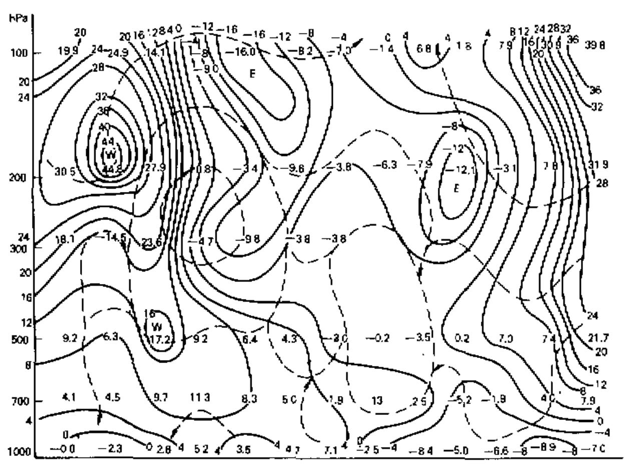

Fig.5c. Zonal wind vertical cross section along 120 ° N at 272000 June 1979. (The caption is the same as in Fig. 5a.)

The above case indicates that the position of the monsoon stream tubes is related not only to the position of the upper–level east and strong lower–level west flows but also to the intensity of the two flows. When the two flows are powerful, the monsoon stream tubes are powerful too and as a result have great horizontal and vertical scales, and vice versa. This is understandable if we have a look at the daily weather regime. The strong upper–level east flow in question is located south of the South Asian high and usually takes the form of northeasterly flow, thus having a southward component. The strong lower–level west flow is formed when the Indian monsoon extends eastward, often in the form of southwesterly winds, thus having a northward component. In the area they dominate, the monsoon vertical circulation will have great intensity when encountering proper rising and subsiding air currents. As a result, the evolution of the strong upper–level east flow and the lower–level west flow are expected to cause changes in the monsoon stream tubes.

V. THE INFLUENCE OF THE BRANCHES OF THE LLJ ON THE RAIN BELT IN CHINA

Many Chinese meteorologists have made investigations of the formation and evolution of the summer rain belt over China. However, studies in the past laid stress only on the rain belt north of the subtropical high. For lack of data, it was quite difficult to do research on the rain belt south of the subtropical high. Since satellite cloud charts and global data became available, it has been found that not only are the rain belts related to each other, but also they have a direct influence on the weather over China. Owing to their different nature and also for convenience of discussion, we name the rain belt north of the subtropical high the subtropical monsoon rain belt (SMRT) and that north of the high the tropical monsoon rain belt (TMRT). Now let us have a look at the evolution of the two rain belts in the summer of 1979. During the period from mid–May to mid–June, the main rain belt was observed in South China, i.e., the rainfall in the early stage of the South China rainy season. Around June 20, the SMRB shifted to the Changjiang River Valley and the Meiyu started over the Jiang–Huai area (Yin, 1987). Meanwhile, the TMRB came into being over the South China Sea. In mid–July, the SMRB was transferred to North China. The Meiyu came to an end over the Jiang–Huai area and the North China rainy season started. Now the TMRB had moved to China's south coasts with the result that the vast area of South China was under its influence. Upstream of the two rain belts was the Indian monsoon rain belt, which was influenced by the Indian monsoon. The following are two real cases:

Case 1.

It is seen from Fig.6 that over the Bay of Bengal was a cloud region, which broke into two cloud belts upon reaching the Indo–China Peninsula, the NB being the subtropical monsoon cloud belt (SMCB) and the SB the tropical monsoon cloud belt (TMCB). Inside the SMCB, cumulus clouds aligned in a SW–NE orientated cloud belt north of the SMCB was a filiform jet stream cloud belt caused by the subtropical west flow and on its south side was a twiggy cloud system. The TMCB was loosely distributed so that weak eddy cells could be seen in the belt. This might be connected with the disturbance of the easterlies. For convenience, a comparison is made of the strong lower–level and upper–level wind belts with the monsoon stream tubes 12 hours before, i.e., at 272000 (see Figs 4a–d and 5a–c). It is found that the position of the subtropical cloud belt was just north of the NB upper–level and lower–level strong winds, i.e., where the AB of the SMST was, and the position of the tropical cloud belt was just north of the SB upper–level and lower–level strong winds, i.e., where the AB of the TMST was.

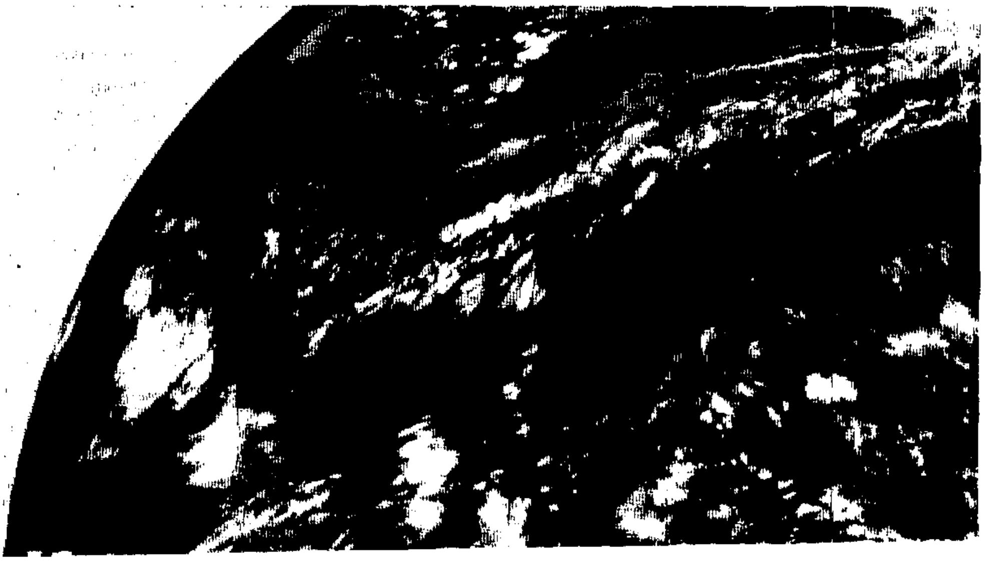

Fig. 6. Infrared cloud at 282000 June 1979

Case 2.

Fig. 7 Infrared clouds at 172000 June 1986

It is seen from Fig.7 that over the Bay of Bengal was a cloud region. After reaching the Indo–China Peninsula the cloud belt, with the branching of the strong lower–level west flow.

gradually broke into two belts. The subtropical cloud belt was SW–NE orientated along the NB west flow, mainly influencing the southeast coast areas of China. Upon reaching Japan, the cumulus clusters in the belt became quite distinctive, aligning in good order. When moving over the East Sea, the cloud belt became loose in structure mainly in stratiform clouds. South of the subtropical cloud belt was a scattered or cloudless area dominated by the subtropical high. Farther south was the tropical cloud belt, whose position was roughly where the SB strong winds prevailed. Influenced by the disturbance of the east flow, the cloud belt was not so distinctive as the subtropical cloud belt.

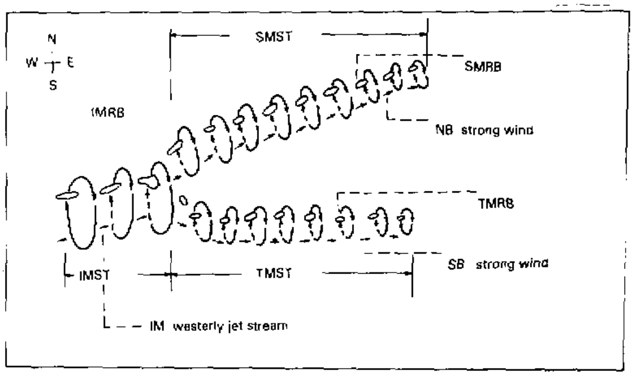

Fig.8. A possible, typical monsoon vertical circulation in the Asian monsoon region and its weather model.

Based on the analysis for the data of the three years, therefore, we can obtain a typical monsoon circulation model occurring in the Asian monsoon region as follows:

Over the Indian subcontinent is the powerful IMST, with the SMST and TMST observed downstream. Over the area of India–the Bay of Bengal in the lower layer is a large–scale westerly jet stream, whose downstream develops into two branches, the NB connected with the SMST and the SB with the TMST. A subtropical rain belt is found where the AB of the SMST lies, a tropical rain belt is found where the AB of the TMST lies and the Indian monsoon rain belt is found where the AB of the IMST lies, as shown in Fig. 8.

VI. SUMMARY AND DISCUSSION

1. The branching of the strong lower–level west flow occurs over the Bay of Bengal and the area to its east after the Indian monsoon extends eastward. Its branching point is related to the position of the western ridge of the subtropical high. The direction of the west flow branching point varies with that of the western ridge of the high. After branching, the NB enters the inland of China along the north side of the subtropical high and gets to Japan across the East Sea, and the SB enters the West Pacific after moving along the monsoon trough and crossing the Indo–China Peninsula.

2. Above the strong lower–level west flow are monsoon stream tubes. Over the area of India–the Bay of Bengal is the IMST, above the NB strong winds the SMST and above the SB strong winds the TMST. These three tubes are all transient monsoon circulation systems and, when influenced by the powerful easterly and westerly disturbances, can break, i.e., they become discontinuous in the east–west direction.

3. The SMST and TMST correspond quite well to the cloud–rain belts in the monsoon region, the former to the subtropical monsoon cloud–rain belt north of the subtropical high,

and the latter to the tropical monsoon cloud–rain belt south of the subtropical high. These two belts both bear a direct influence on the weather over China. The former can extend its influence over the Jiang–Huai Valley, forming the well–known Meiyu and the latter mainly influences the Indo–China Peninsula and the area of the South China Sea including South China.

4. Unlike the mean strong monsoon vertical circulation cell over East Asia in summer pointed out by Yeh Tucheng et al.(1979), the two stream tubes we reveal here occurring in the vicinity of the two jet streams may be two secondary monsoon vertical circulation systems of different nature included in the strong monsoon vertical circulation cell pointed out by Yeh et al.. It is found that the SMST is its northern boundary and the TMST its southern boundary.

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