

## ADVANCES IN THE SOUTH CHINA FFS HEAVY RAIN RESEARCH

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### ABSTRACT

Heavy rain (HR) or even exceptional heavy rain (EHR) usually takes place during the first flood season in South China in every April—June. In spring, cold air coming from north often brings about a normal HR over a large area in South China. However, EHR is mainly caused by tropical weather systems, the warm moist SW current from the Bay of Bengal-southern/central parts of the South China Sea, as well as the warm moist SE current from the NW Pacific Ocean. Investigations show that the fields of flow and moisture in the lower troposphere play a more important role in HR rather than the potential height-temperature field. The ageostrophy and pulsation of SW jet stream in lower level have a distinct effect on the occurrence of HR and its non-uniform distribution in time-space. The sea/land breeze effect is obvious in South China. This is one of the important causes for very heavy rain to easily occur in South China and the different time of rain peak between coastal and interior regions.

### 1. INTRODUCTION

Heavy rain (HR) is one of the most significant weather patterns with damage or disasters to certain areas of China. South China is the region of the richest rainfall with maximal mean annual precipitation, the highest frequency and largest duration from April to September/October as compared with the others of the country<sup>(1)</sup>.

For South China the period from July to September is a typhoon flood season with high water caused by typhoons, ITCZ and other tropical systems while the time-span of April—June is also characterised by plentiful precipitation, generally called the first flood season (FFS) in contrast to the season immediately after it. For the latter rainy season, precipitation comes primarily from the westerly belt to the north of the subtropical high, usually with intensity of HR to exceptional HR (EHR). Fig. 1 shows long-term mean April—June rainfall distribution with 6 HR centers having maxima of over 900 mm, accounting for a half or more of the annual total of these regions.

During the past 10 years an extensive study has been done of the FFS HR over the area under consideration. In particular, a combined experiment was conducted in 1976—79 designed to make a detailed investigation of the FFS HR over such regions as central Guangdong, northern Guangxi and southwestern Fujian shown as enclosed regions in Fig. 1. This allows us to make a substantial advance in understanding the HR's mechanism.

## II. LOW-LEVEL FLOW FIELD AND MOISTURE FIELD

As depicted on the upper-level charts for April—June, generally 1 or 2 smooth contours alone pass across South China at lower latitudes with few closed pressure patterns. The low-level flow field and moisture field ( $\theta_{ss}$ ), however, experience significant changes, corresponding to weather evolution.

For large-scale flow fields in middle/high latitudes divergence is generally one order less than vorticity, but both have the same order for low-latitude meso-scale cases. The calculated values of  $\xi$  and  $D$  for a local HR in the region of Guangzhou are shown in Table 1, indicating that the values of divergence reflect the regime of the flow field more distinctly than those of positive vorticity in the lower levels in addition to the same order<sup>(3)</sup>. Obviously, in the vorticity equation

$$\frac{\partial \xi}{\partial t} = -\mathbf{V} \cdot \nabla \xi - fD - \beta v, \quad (1)$$

the divergence term made the greatest contribution to the 850 hPa vorticity variation of all and during the very heavy rain (VHR) process from 2000 LST, 27—0800 LST, 28 May, 1978 with rainfall of 148 mm at Fushan the divergence term was even one order higher than the vorticity advection term. Thus, we employ the divergence equation in full form

$$\frac{\partial D}{\partial t} = -A - \omega \frac{\partial D}{\partial p} - \nabla \omega \frac{\partial \mathbf{V}}{\partial p} - f\xi' - \beta u, \quad (2)$$

where

$$\begin{cases} -A = -\mathbf{V} \cdot \nabla D - D^2 - 2J[u, v], \\ -f\xi' = -(\nabla^2 \phi - f\xi), \end{cases} \quad (3)$$

where  $f\xi'$  is ageostrophic vorticity of  $10^{-3}\text{s}^{-2}$ , the highest-order in large-scale flow fields

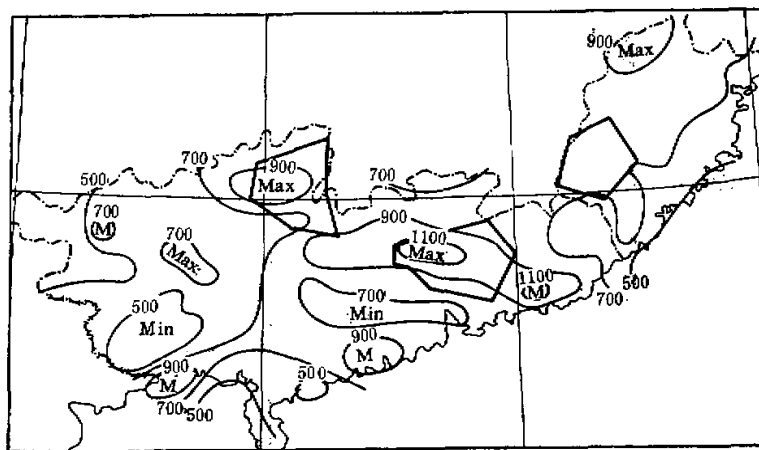


Fig. 1. Distribution of long-term mean April—June rainfall, 1959—79 in South China. Regions enclosed by heavy lines denote the major HR experimental ones.

**Table 1** Values of  $\zeta$  and  $D$  ( $\times 10^{-5} \text{s}^{-1}$ ) in the Region of Guangzhou for 27–28 May, 1979

	$\zeta$				$D$			
	Time				Time			
	0800*	2000*	0800	2000	0800*	2000*	0800	2000
100 hPa	-6.8	-4.9	-2.8	-4.6	3.0	-0.4	3.3	4.4
300 hPa	-3.3	-2.6	-2.6	-1.6	1.9	1.2	1.2	1.3
500 hPa	-2.6	0.0	-1.8	-2.1	-0.7	1.1	-0.1	-2.9
700 hPa	-3.1	0.7	-0.6	1.1	-3.0	-2.1	-1.7	1.9
850 hPa	2.2	2.8	0.0	0.4	-2.7	-1.9	-2.0	1.5
1000 hPa	0.8	1.0	0.1	-0.4	-2.1	-1.9	-1.3	-1.7

\* They denote the time of the 27th of May, 1979, the others for the 28th.

**Table 2** Calculated Values of the Various Terms in the Vorticity and Divergence Equations for 27–28 May 1979 (unit:  $10^{-9} \text{s}^{-1}$ )

	Time			
	0800*	2000*	0800	2000
$-\mathbf{V} \cdot \nabla \zeta$	-0.70	-0.07	0.03	-0.30
$-fD$	0.60	1.01	0.76	0.24
$-\beta v$	-0.16	-0.08	-0.07	-0.08
$A$	0.0	0.8	0.5	-0.2
$\zeta S'$	-0.90	-0.74	-0.10	-0.93

\* Same as in Table 1.

at mid- and higher latitudes, 1–2 orders greater than the other terms and  $\partial D / \partial t$  is of  $10^{-11} \text{s}^{-2}$ . Yet for the South China HR (SCHR) the terms other than term  $f\zeta'$  are greater. From scale analysis

$$O\left(\frac{\partial D}{\partial t}\right) = O(A), \quad (4)$$

it is apparent that term  $A$  includes the divergence advection and divergence terms. As indicated in Table 2,  $A$  was maximal at 850 hPa for 2000 LST, 27–0800 LST, 28 May, 1979, causing the greatest convergence growth, during which time precipitation reached its peak intensity.

Another result from the SCHR study is the discovery of dependence of the rain in the flow field of the planetary boundary layer (PBL)<sup>13-21</sup>. Fig. 2 depicts altitudinal distribution of various-level moisture flux divergence (the longitudinal component is dominant) during HR. It can be seen that convergence attained its maximum between 950–900 hPa in the PBL. Fig. 3 shows the 950 hPa divergence distribution at 0800, 27 May, 1978. The northern Guangxi and western Guangdong HR bands were each just in correspondence to the 950 hPa strong convergence regions.

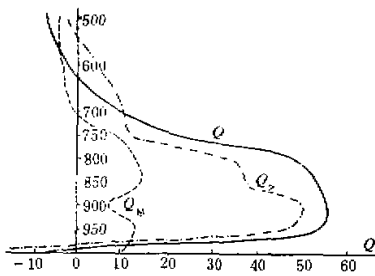


Fig. 2. The altitudinal profile of moisture flux divergence  $Q$  for the HR band, 6 June, 1978.  $Q = -\nabla \cdot \frac{1}{g} q V$  (Unit:  $10^{-7} \text{ g/cm}^2 \cdot \text{hPa} \cdot \text{sec}$ ).  $Q_z$  and  $Q_M$  are zonal and meridional components of  $Q$ , respectively.

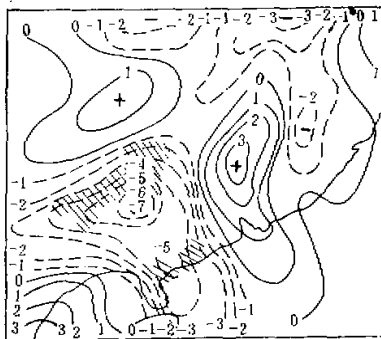
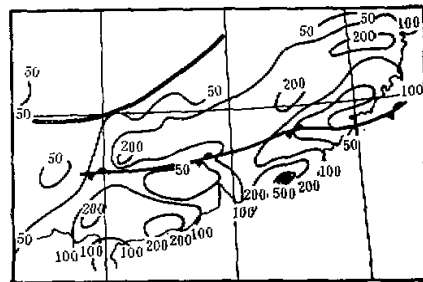
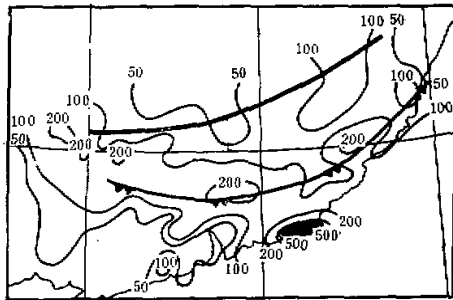


Fig. 3. 950 hPa divergence distribution at 0800 LST, 27 May, 1978. (unit:  $10^{-7} \text{ s}^{-1}$ ).

Fig. 4. Distribution of the total rainfall out of 3 SCHR events. Heavy line—Shear line at 850 hPa. From top to bottom: (a) The 5-day total of 1461 mm, 27 May—1 June, 1977; (b) The 3-day total of 677 mm, 5—8 June, 1978; (c) The 1-day total of 736 mm, 26—27 May, 1978.

The increase of temperature and humidity in the boundary layer below 850 hPa (The maximum can be 2.0—2.5°C every 12 hr) may create the maximal gradient zone of  $\theta_{se}$  in the surface layer, commonly called an energy frontal zone, where intense rainfall takes place more often.

### III. WARM SECTOR HEAVY RAIN

It is long believed that HR in China is mainly due to cold air and fronts. About 92.5% of the SCHRs was associated with southward-moving cold air activity, according to data of April—June, 1971—78. Generally, such events have larger dimensions, sometimes extending as long as 1000 km, but smaller rainfall intensity with the daily total under 100 mm and a sum of 200 mm or less out of a single event. Only weaker and moderate fronts, however, favour the occurrence of HR, whereas strong cold air or a swiftly-moving cold front produces no HR and, instead, makes the HR process that is going on will soon come to an end. A more interesting fact is that for most of the SCHR events hard rain of smaller extent can take place concurrently in the warm sector 200—300 km ahead of the front. Some EHRs of  $\geq 200$  mm daily rainfall or  $\geq 300$  mm sum from a single HR process tend to happen in a warm sector ahead or free of a front<sup>[6,7]</sup>. The distribution of the total amounts from 3 EHR events is shown in Fig. 4. Analysis of post-dense data from the 1977—79 HR Experiment indicates that 10 in 12 occurrences were partly or mainly precipitation from a warm sector HR ahead of the front, whose features can be summarized as follows:

1) The warm-sector HR (WSHR) has higher intensity, 3—4 times stronger than the frontal HR in general. And 8 EHR events for 1977—78 are all of this type.

2) The WSHR is strongly convective in nature with intense thunderstorm activities. The top of the radar echoes is the order of 14—16 km and most of the HRs are slow-moving or stationary.

3) The WSHR has a smaller scale, making up less than 1/3 to 1/4 of the area occupied by the entire HR event. Some EHRs have a distance scale of 20—30 km only.

4) The WSHR precipitation is relatively concentrative. Measurements show the 5-day total of 1461 mm for May 27—June 1, the diurnal total of 884 mm during 1400, 30—1400, 31 June and the 6-hr total of 634 mm for 0800—1400, June 31, 1977 and the 45-min maximum of 174.0 mm, as recorded at the Beishimen Reservoir, Lufeng, Guangdong.

Moreover, it is also worth noting that for April to early May when cold air remains stronger, precipitation is typically frontal and less intense for the most part. And in the second decade of May when trans-equatorial airflow will reach the eastern Indo-China Peninsula and the South-China coastal regions, a steady SW monsoon appears at 850 hPa over the Xisha Islands. At this time, the FFS precipitation comes to its prime with frequent HR and abrupt increase in the amount. As shown on satellite cloud pictures, the monsoon clusters or tropical ones (or arrays of clouds) from the Bay of Bengal—the Indo-China Peninsula and the southern/middle South China Sea develop in its northward movement or come into conjunction with frontal cloud belts, which is found to be the main cause of South-China VHR/EHR. For instance, a 700 hPa monsoon trough from Bengal moved eastward with a series of monsoon clusters ahead on June 25, 1977 and on the following day they merged with the cloud system of a low moving southeastward from Guizhou, producing an EHR event over northeastern Guangxi with maximal daily rain-

fall of 385 mm at Luzhai.

As a consequence, although cold air can give rise to large-scale normal HR in South China, VHR/EHR take place generally in the warm sector, where tropical warm moist air plays a particularly important role.

#### IV. LOW-LEVEL SOUTHWEST JET

Apart from fronts, shear lines and lows, the low-level southwest jet (SWJ) is the most significant system responsible for the FFS HR in South China. According to data of May–June, 1970–73<sup>[3]</sup>, there were 19 strong SWJ occasions ( $\geq 16 \text{ m s}^{-1}$ ), 16 of which produced VHR of  $\geq 100 \text{ mm}$  per day in Guangdong within 1–5 days, the other three occurring north of the Nanling mountains due to the northward march of the SWJ.

The SWJ exhibits two different processes in its development. One such process is that when the subtropical high is intensified or the westerly low-value system grows toward the south, thus approaching each other, the low-altitude SWJ is likely to be induced. Such SWJ, when coming to South China, tends to give rise to usual HR over a large area. A tropical SWJ will come into being along South-China coastal regions when SW monsoon or warm moist air is strengthened from the equator or tropics at very low latitudes. Typically it will produce VHR/EHR. Both jets can possibly exist simultaneously 300–400 km apart, with two rainbands. They can also join or merge into each other, thus intensifying the SWJ with greater duration to result in a persistent situation for VHR.

Take as an example the EHR occurring toward the end of May 1977<sup>[3]</sup>. For 28–30 May the Indian depression grew intensely with the 850 hPa closed contour below 1400 gpm. The 850 hPa height difference between Madras and New Delhi started to increase to +30, +40 and +60 on 28, 29 and 30 of the month, respectively from 0–+20 gpm on the preceding days. The 850 hPa wind speed increased gradually from  $\leq 4\text{--}6 \text{ m s}^{-1}$  on 26 to  $8\text{--}12 \text{ m s}^{-1}$  on 28–30 May and large-scale monsoon cluster genesis and development took place over the Bay of Bengal—the Indo-China Peninsula. Next, from May 25 an equatorial buffer zone near Indonesia around  $5^\circ\text{S}$  was reinforced, shifting northward across the equator with anticyclonegenesis within it. This belt reached  $5^\circ\text{N}$  at 2000, 27 and about  $10^\circ\text{N}$  at 0800 of the next day. Moved with it were the outer-brim cloud belt and the SW wind band north of the equatorial anticyclone, causing the 850 hPa SW wind to increase to  $8\text{--}10 \text{ m s}^{-1}$  from Saigon via Xisha to Manila. Finally, a surface hot low developed vigorously in West China to create surface pressure difference of 10.0–12.5 hPa between the Gulf of Beibu and the Philippines, leading to an onset of a monsoon surge. On 30 May, the 850 hPa wind was  $8\text{--}12 \text{ m s}^{-1}$ ,  $10\text{--}14$  and  $12\text{--}16$  or more in India, the northern Indo-China Peninsula and South China—the northern South China Sea, respectively (see Fig. 5). It is in the period of 28 May to 1 June that an extremely steady and strong tropical SWJ came into being in the northernmost South China Sea and along the jet axis there was a maximal wind center ( $\geq 18\text{--}20 \text{ m s}^{-1}$ ) moving eastward twice to  $115^\circ\text{E}$ , once from 2000, 29 to 0800, 30 May and again between 0800 and 2000, May 31. This is in good coincidence with two strongest HR occurring at Lufeng.

Being at lower latitudes and facing the Sea, South China is abundant in unstable moister air. Since SWJ transports large amounts of warm moist air inland to this area, geopotential unstable energy grows intensely, a favourable condition for HR genesis. Two maximal centers of  $-\Delta\theta_{e_0}$  (500–850 hPa) recorded at Station Yangjiang upstream of HR

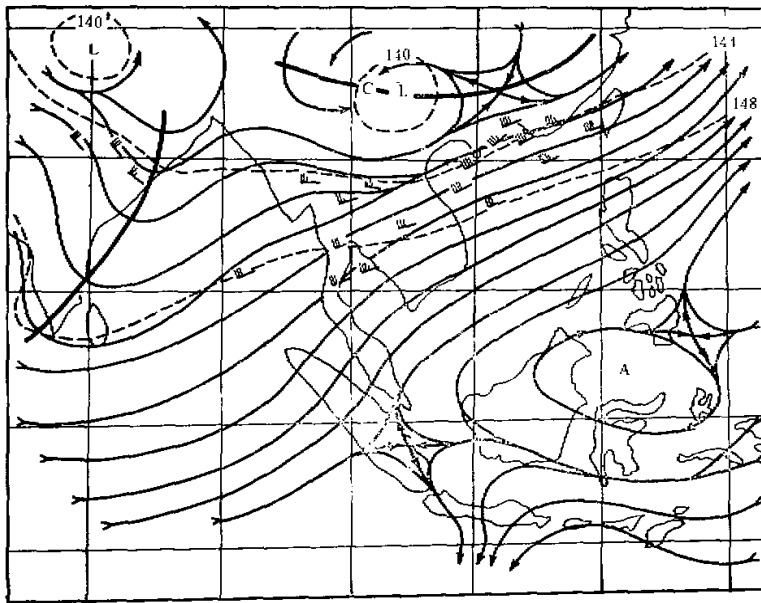
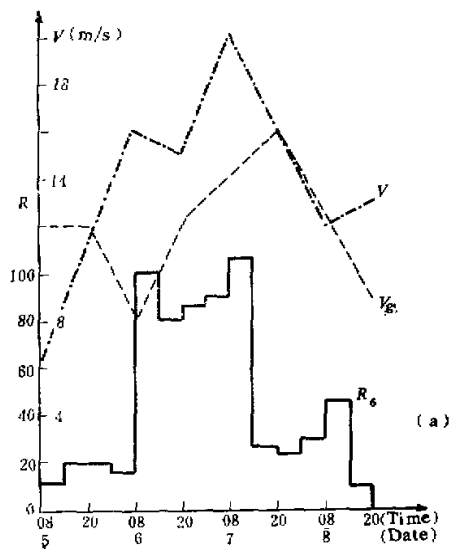


Fig. 5. The 850 hPa flow field at 0800, May 30, 1977

band at the end of May 1977 each corresponded to the eastward-moving jet centers in time. That is, the unstable energy produced by the increase of temperature and humidity at lower levels was carried downstream by the tropical SWJ, thus causing EHR over Lufeng.

A striking feature of the low-level SWJ is its nongeostrophy<sup>[13]</sup> (see Fig. 6). In the HR



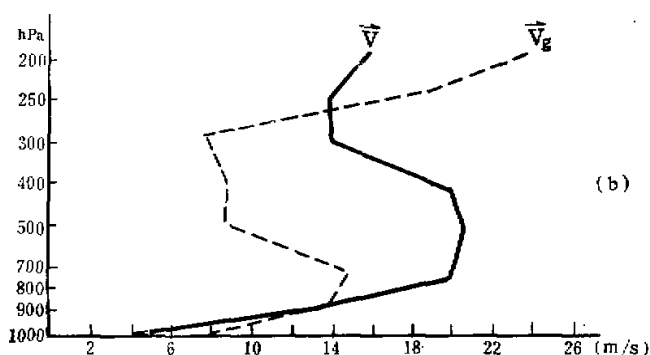


Fig. 6. Evolution of wind ( $V$ ) and geostrophic wind ( $V_g$ ) at Shantou, 5–8 June, 1978. (a) the wind profile for 0800, 7 June; (b) the 3000 m altitude wind evolution and 6 hr rainfall  $R_6$ , 5–8 June.

area the air layer between 900–500 hPa is strongly supergeostrophic and at times the real wind more than twice as much as geostrophic wind. The time-dependent development of the SWJ speed indicates that the time interval of HR successive occurrence is that of super-geostrophic wind showing the highest intensity.

Another important characteristic of the SWJ consists in its fluctuation. Wind records at low-altitude mountain sites show a larger amplitude of fluctuation of more than 10–12  $\text{m s}^{-1}$  in 1–2 hr, and a shorter period generally of 4–12 hr. It is found that the fluctuation peak value is closely related to intense rainfall downstream.

The low-level SWJ transports warm moist air and is under its control as well. For saturated air observed vertical wind shear can be approximately expressed as<sup>[11]</sup>

$$\mathbf{V}_{ST} = -\frac{\partial \mathbf{V}_{sg}}{\partial p} \cong \frac{R}{f\rho} \frac{\bar{T}}{\bar{\theta}_{se}} \mathbf{k} \times \nabla \bar{\theta}_{se}, \quad (5)$$

$$\xi_{ST} = \mathbf{k} \cdot \nabla \times \mathbf{V}_{ST} \cong -\frac{R\bar{T}}{f\rho\bar{\theta}_{se}} \nabla^2 \bar{\theta}_{se}, \quad (6)$$

where  $\mathbf{V}_{sg}$  is geostrophic wind in moist air,  $\mathbf{V}_{ST}$  is pseud equivalent potential temperature (PEPT) wind,  $\xi_{ST}$  its vorticity and  $\bar{\theta}_{se}$  mean PEPT in saturated air. It can be seen that whether the flow field is initially of even SW airflow or of still air, low-level SWJ is easy to be created to the right (to the south/southeast) of the warm moist center (where  $\bar{\theta}_{se}$  attains a maximum) once the layer becomes saturated while the high-level SWJ is likely to be formed to the left. Therefore, the low-level SWJ and the warm moist center are dependent upon each other in development, which facilitates the HR genesis and prediction.

South China is frequented by a convergence belt of low-level meso-medium scale SE–SW current, which was first discovered on 12–13 May, 1970, causing an EHR process in the coastal region of western Guangdong with 12 hr rainfall of 671 mm recorded in Shuangji, Yangjiang County<sup>[6]</sup>. This belt was reported more often for 1977–79 (Figs. 7–8<sup>[12]</sup>). It can appear both in the leading edge of low-level SWJ and in the SW jet stream as well



but with smaller dimension an frequent occurrence in the PBL. Nor is this all. It is often associated with a surface meso-scale energy frontal zone (where isopleths of  $\bar{\theta}_{se}$  are denser). This type of SE-SW current convergence is the important system responsible for VHR/EHR in the FFS over South China.

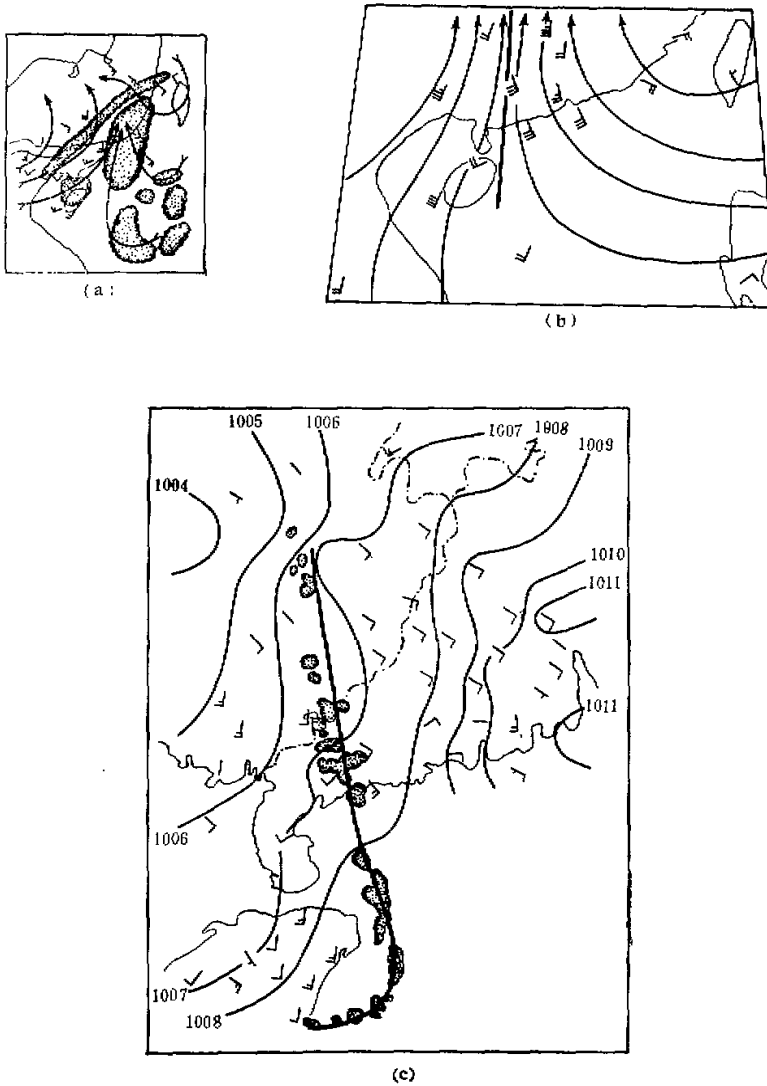


Fig. 7. Low-level flow fields for three HR events, May, 1977-79. (a) at 850 hPa, 0800, May 27, 1977; (b) at 1000 m altitude, 0800, May 27, 1978; (c) at the ground surface, 1100, May 12, 1979.

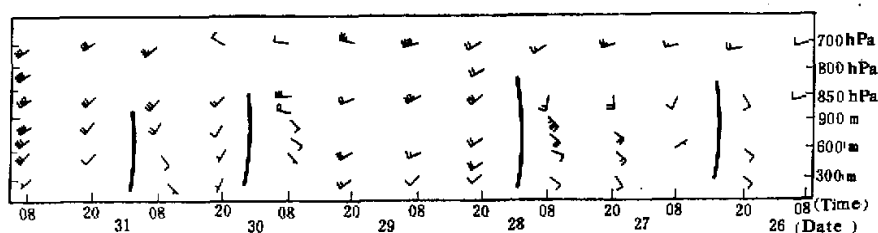


Fig. 8. The time-section of wind measurement, 26—31 May, 1977.

It must be noted that over the S-SW jet in the PBL gravity waves<sup>[13]</sup> can result whose phase velocity  $C_g$  is more or less equal to the displacement of the HR isochrones,

$$C_g = -\bar{v} \pm \sqrt{\frac{g}{\theta} \frac{\partial \theta}{\partial z} / (k^2 + f/2A)}, \quad (7)$$

where  $k$  is the wavenumber,  $A$  friction effect with the depth of the Ekman's layer  $D = \pi \sqrt{2A/f}$ . However, the PBL jet-type gravity wave has only the order of  $10 \text{ cm s}^{-1}$  for its vertical velocity, which acts as a trigger rather than as a direct producer for SCHR.

It also merits noting<sup>[14]</sup> that if the wind directions are evenly-distributed at 300, 600 and 900 m elevation and is parallel to the terrain slope (with a 6% angle) at the speed of  $8-10 \text{ m s}^{-1}$ , then the terrain-caused events account for 60% of the record of precipitation, and when wind directions in the layer between 300—900 m above the surface differ, the rain-fall reaches simply moderate intensity. This shows the significance of the PBL flow field for the HR geneses.

#### V. SEA/LAND BREEZE

The South-China coastline is long and tortuous with numerous smaller peninsulas and harbours, a place of high frequency of sea/land breeze, significantly affecting the diurnal range of rainfall and occurrence of EHR<sup>[15]</sup>. Land breeze blows from midnight to morning with the prime between 0300—0500 and sea breeze from forenoon to evening with the peak hours between 1400—1700. Their extent can reach 600—900 m height and the sea wind can be as far as 100 km from the shore in the plain regions of South China.

The sea/land breeze effect can bring about a local surface divergence field (Fig. 9). For land breeze a convergence belt comes along over the coastland of South China with 3 centers being at Qingzhou-Beihai, in the vicinity of Yangjiang and for Shantou-Shanwei. A T-shaped convergence zone appears from the interior to the Leizhou Peninsula and Hainan Island. The reverse is true for sea breeze.

The sea/land breeze effect can also further the genesis of mesoscale disturbances<sup>[16]</sup>. According to the statistics of May—June, 1977—79, such perturbances took place 44 times for 0300—0500 when land breeze was the strongest and only 8 were recorded during 0600—0900 when it was weakened. In contrast, for 1200—1700 when sea breeze was strengthened, 75 inland disturbances of meso-scale came to pass with 15 for 1800—2000 in the diminishing phase of sea breeze.



position of the Guangxi frontal HR in the vicinity of the observed one and the false rainband still in sight. All these illustrate that the PBL meso-scale convergence is intimately related to the WSHR in reality.

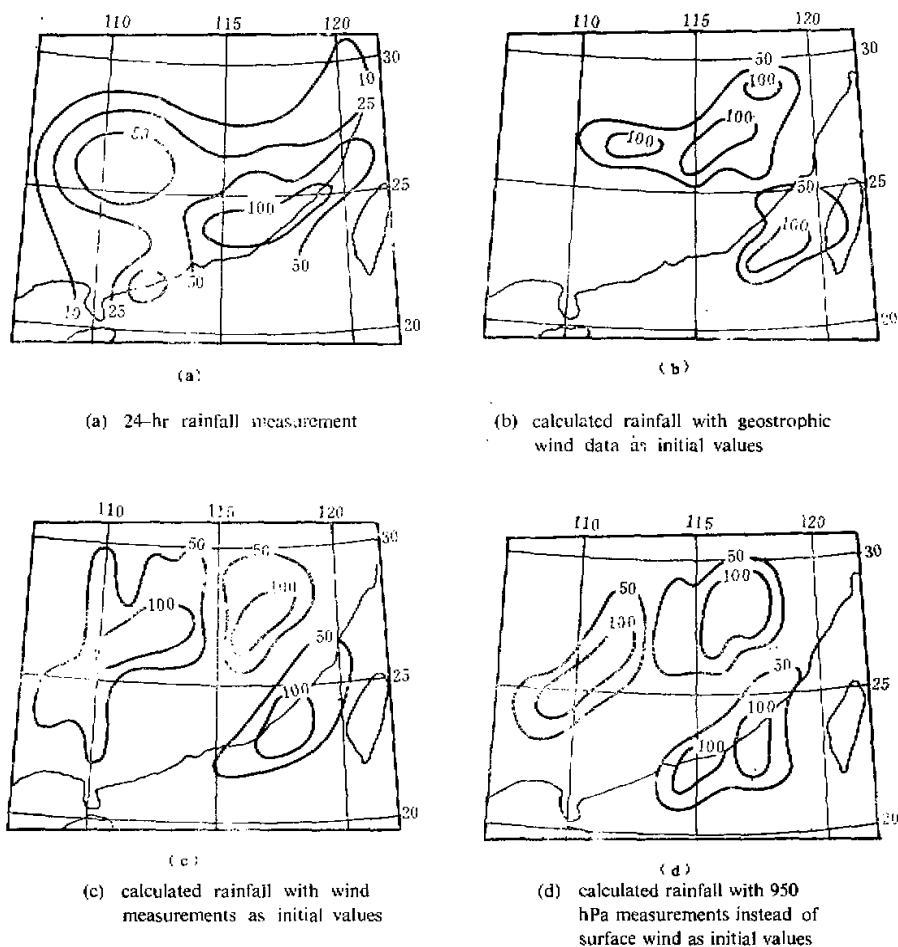


Fig. 10. The numerical experiment with a HR event lasting from 0800, 10—0800, 11 June, 1979.

## VII. SUMMARY

Based on the above, a schematic model is developed of EHR in the FFS over South China<sup>[14]</sup>. It is apparent from Fig. 11 that the westerly low-value system and SWJ may cause large-scale usual HR in South China while the major systems producing small-scale warm-sector EHR remain with PBL tropical SWJ, SE-SW flow convergence of meso-medium scale and the surface energy frontal zone.

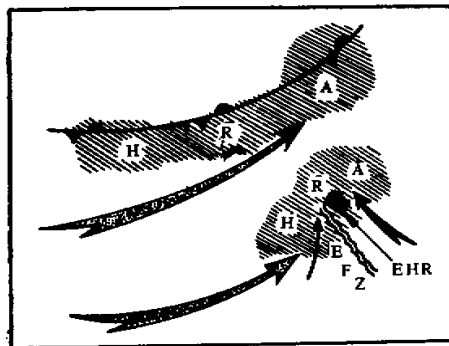


Fig. 11 A synoptic model of SCHR during the FFS.

HRA: Heavy rain area, EHR: Extremely heavy rain.  
EFZ; Energy frontal zone.

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