Sensitivity Experiments on Summer Monsoon Circulation Cell in East Asia

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ABSTRACT

The East-Asian summer monsoon meridional circulation (SMMC) cell is simulated together with two vigorous rainbands in terms of a primitive-equation model including in itself a variety of diabatic heating, frictional dissipation and moist processes under the condition of mountains available. Results are comparable to observations. Also, performed are experiments with the reduction of water content, and exclusion of the cumulus convective process and mountain effect. Contrast analyses indicate that the cell is strongly sensitive to the condition of the humidity field in the atmosphere, more intensely at 120° than at 100° E, and the presence (absence) of the cumulus convection has considerable effect on the intensification(weakening) of the cell, with the mountain ranges exhibiting more influence upon the cell at 100° than 120° E. This may suggest that a great difference lies in the cause of the cell for the two meridions.

I. INTRODUCTION

The existence of the SMMC cell has long been known to all. Its cause has been examined by many authors, e.g., Murakami et al.(1970), Kuo et al. (1982) and He et al.(1984), who basically emphasized the influence of the sea-land distribution and thermal and dynamical effect of the Qinghai-Tibetan Plateau as an immense topography. Yet He et al.(1984) put the cause of the South-Asian summer monsoon into such aspects as i) sea-land differential thermal effect; ii) thermal and dynamic effect of the Qinghai-Tibetan and Iranian Plateaus; iii) influence of the SH circulation upon the NH monsoon; iv) dynamic mechanism inherent in the atmosphere, e.g., instability of various space- and time-scale motions, the interaction between waves of different scales, and the energy-dissipative mechanism for planetary-scale motions. Obviously, these factors are bound to differ in their effect, when acting at different latitudes and circulation backgrounds of Asia.

Chen (1983) shows that Asian summer monsoon system can be divided into East-Asian and Indian subsystems, and Zhu et al.(1986) further propose that the East-Asian monsoon can, in turn, fall into the South-China-Sea and China's Mainland subsystems, the latter being of subtropical nature. This suggests that the separate study of all these subsystems are important to the exploration of the cause of Asian summer monsoon circulation. In addition, the sea-land distribution and the immense Plateau depend on the atmospheric circulation patterns for their effect upon the behavior of the general circulation, i.e., they have different effect on the monsoon circulation thermally and dynamically for diverse atmospheric circulation patterns.

Based on these considerations, it is appropriate to explore the cause of the Asian SMMC from these separate subsystems. Li (1986) indicates the results and analyses of numerical experiments on the Indian summer monsoon circulation cell. The present article, following the course shown by the author, presents results from a series of contrast experiments done under the conditions of various circulation patterns as initial fields, moist processes of varied water content, and presence and absence of mountain effect with a view to further examining the causes of the SMMC over East Asia (100° and 120° E).

II. BRIEF DESCRIPTION OF THE MODEL

1. *Basic Equations*

For investigating the effect of mountains chosen is the P–σ coordinate system, with $\sigma=(P-P_0)/(P_s-P_0-50)$, in which P_0 and P_s are the pressure at the upper boundary of the coordinate and at sea level, respectively. In order to decrease the complexity in calculation with the σ coordinate the P system is adopted for the upper troposphere (Fig. 1). The interface is at the level of $P=P_0$, where $\sigma=0$, and P_0 is assumed to be 400 hPa.

Let $\pi=P_s-P_0$ and we have a system of basic equations for the σ coordinate system,

$$\frac{\partial u}{\partial t}=PG_\lambda+fv+F_u-\frac{1}{\pi}\left[\nabla_\sigma\cdot(\pi u\vec{V})+\frac{\partial}{\partial\sigma}(\pi u\dot{\sigma})+u\frac{\partial\pi}{\partial t}\right] \tag{1}$$

$$\frac{\partial v}{\partial t}=PG_\varphi-fu+F_v-\frac{1}{\pi}\left[\nabla_\sigma\cdot(\pi v\vec{V})+\frac{\partial}{\partial\sigma}(\pi v\dot{\sigma})+v\frac{\partial\pi}{\partial t}\right] \tag{2}$$

$$\frac{\partial T}{\partial t}=\frac{RT}{C_pp}\omega+\frac{Q}{C_p}+F_T-\frac{1}{\pi}\left[\nabla_\sigma\cdot(\pi T\vec{V})+\frac{\partial}{\partial\sigma}(\pi T\dot{\sigma})+T\frac{\partial\pi}{\partial t}\right] \tag{3}$$

$$\frac{\partial}{\partial t}q=M+F_q-\frac{1}{\pi}\left[\nabla_\sigma\cdot(\pi q\vec{V})+\frac{\partial}{\partial\sigma}(\pi q\dot{\sigma})+q\frac{\partial\pi}{\partial t}\right] \tag{4}$$

$$\frac{\partial\pi}{\partial t}+\nabla_\sigma\cdot(\pi\vec{V})+\frac{\partial}{\partial\sigma}(\pi\dot{\sigma})=0 \tag{5}$$

$$\frac{\partial\Phi}{\partial\sigma}=-RT/(\sigma+p_s/\pi), \tag{6}$$

where $\dot{\sigma}=d\sigma/dt$, the vertical velocity for the given coordinate; F_u, F_v, F_T, F_q are the horizontal and vertical transport of u, v, T, q by turbulence, respectively; the PG term represents the horizontal pressure force for the coordinate, which the Corby scheme is used for calculation. Thus we have

$$PG=-\nabla_\sigma\left\{\pi RT+\frac{\partial}{\partial\sigma}\left[(\sigma\pi+P_0)(\Phi-\Phi_0)\right]\right\}. \tag{7}$$

where Q and M are the diabatic heating and source / sink of vapor, respectively, and the operator in the form

$$\nabla_\sigma(\quad)=\frac{1}{a\cos\varphi}\left[\frac{\partial}{\partial\lambda}(\quad)+\frac{\partial}{\partial\varphi}(\quad)\cos\varphi\right], \tag{8}$$

in which Φ is the geopotential height on the σ surface, the other notations being usual.

As stated earlier, the P coordinate is employed for the upper part of the model used and its basic equations are in the same form as those of the type and hence omitted here. The junction condition between the two coordinate systems is determined by expanding the vertical velocity $\omega = dP/dt$ of the P coordinate in the σ system. Hence, if $P = P_0$, then we get the boundary condition for the junction in the form

$$\omega(P_0) = \left(\frac{dp}{dt}\right)_{P=P_0} = \left(\frac{\partial}{\partial t}p + \vec{V}\cdot\nabla_\sigma P + \dot{\sigma}\frac{\partial p}{\partial \sigma}\right)_{\sigma=0} = \pi\dot{\sigma}. \quad (9)$$

To take into consideration the boundary layer effect, the 5th layer (Fig.1) is regarded as the frictional layer of the model, evaluated as 50 hPa. Therefore, if $\sigma_B = 1$ (as the lower boundary), then $\dot{\sigma}_B = 0$, and for $P = 0$ (as the upper), $\omega = 0$.

The model's horizontal difference has the form of a spheric grid–mesh of Type A, with the longitude–latitude scale 5° × 5°. The area covered by the model is 55°N – 25°S and 0°–180°E; the eastern and western boundaries satisfy the periodic boundary condition with fixed northern and southern limits; the time step length is 15 minutes; the integration is performed alternately in terms of the Eular backward scheme for 1h and central finite difference scheme for 2 hs, and once every 6h space smoothing of u, v, and P_s is done at the grid points next to the northern and southern boundaries, thus making steady the integration of initial values for the model.

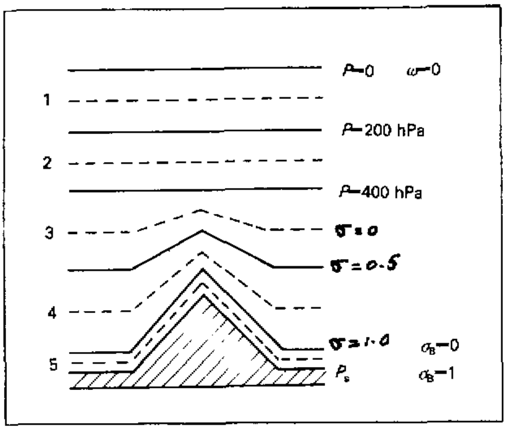

Fig.1. Vertical structure of the numerical model used in the experiments.

2. *Numerical Experiment Scheme and Initial Field*

To consider the influence of mountains and diabatic heating on the SMMC under the condition of different circulation patterns, contrast experiments are conducted with the initial fields of data of 0000 GMT 8 July and 1200, 22 August 1979. The circulation pattern of the former case is featured by the Indian monsoon transition from a break to active phase (designated as Process A hereinafter) and by the reactivation of Meiyu(plum rains) happening between 30° – 35°N over the Changjiang–Huaihe basin (East Asia).For the latter case it is marked by the Indian monsoon in a break phase (Process B) and by the Meiyu that has already ended, during which time a new rainband occurs at 25°N (South China).

Experiments below are labelled by A and B, respectively, to indicate the corresponding initial field condition. The initial field data are taken from FGGE IIIb grid data base including 5 height fields (100, 300, 500, 700 and 1000 hPa) and 4 humidity fields (RH), i.e., 300, 500, 700 and 850 hPa. Three sets of contrast experiments are designed for the two initial fields, separately. Each of the experiments is integrated over 72hs, except the DM set that run 120hs.

Let us go into detail of these experiments.

(1) *Numerical experiment* DM

Incorporated in the model is consideration of all diabatic heating processes with the mountain effect present (DM), in which the diabatic heating of the atmosphere Q, considered in three parts, is calculated separately. For Q we get

$$Q = Q_R + Q_L + Q_S, \tag{10}$$

where Q_R is the short– and long–wave radiation heating. In order to more realistically reflect the atmospheric transport of radiation is used the spectral–band calculation method (which is widely employed in the GCM) to compute Q_R in which the effect of the cloud thickness upon the radiation transfer is included; Q_L is the heating due to vapor condensation from large–scale rainfall and cumulus convective precipitation, the latter using Kuo's cumulus parameterization scheme in calculation; Q_S the vertical transport of sensible heat, which, for its transfer starting from the surface and sea level, has the following expression

$$H_s = \rho_s C_p C_D \left| V_s \right| (T_s - T_a). \tag{11}$$

Included in DM are surface water evaporation and other physical processes relative to diabatic ones. For the details and expressions refer to Li (1986).

(2) *Numerical experiments* DQ *and* DC

To examine the effect on the SMMC cell of the moist process during the atmospheric diabatic heating, and particularly the interaction between the atmospheric humidity and cumulus convection, and large–scale flow field, two types of numerical experiments are designed, one on reducing the water content (DQ) and the other on removing cumulus process effect (DC) in this model. Their results can be, separately, used to be compared with those of DM for contrast analyses, to help understand the importance of the moist process to the cell.

In DQ the humidity field (RH) of initial data is reduced in value to 1 / 5 of the original, which is then initialized before being fed into the model, where the operating physical processes are the same as in DM. To avoid the effect of excessive vapor due to the evaporation from the model underlying surface the numerical reduction of the model humidity field is repeated once every 6hs throughout integration.

DC is carried out on the basis of DM, with the removal of cumulus process effect and with the same initial field and processes as in DM. All the latent heating effect in DC is produced from the large–scale systematic precipitation.

(3) *Numerical experiment* DN

DN is an experiment made under conditions of diabatic processes and removal of mountain effect. To investigate the effect on the cell of the interaction between mountains and large–scale circulation under the circumstances of various circulation patterns, DN is conducted with Process B as the initial data, which are, after removing the influence of mountain, initialized and fed into the model. For the sake of contrast analyses all processes in DN are the same as in DM, except that the effect of mountains in the scope of the model is removed, but the sea–land distribution remains unchanged. The height for the land and sea level is taken as

$$h=\begin{cases} h & \text{if } h<100\ m; \\ 100\ m & \text{if } h\geqslant 100\ m. \end{cases}$$

III. ANALYSES OF THE RESULTS

1. *For* DM

Fig.2 depicts the SMMC on the *100* ° E (a) and *120* ° E (b) cross sections with Process A as the initial field (designated as ADM). It can be seen that on the 100 ° E panel a large–scale SMMC cell is operating with its ascending branch about 20 ° N and descending between 5 ° –10 ° S. The cell consists of two subcells with two strong updraft regions, one being over 20 ° –25 ° N and the other in the neighbourhood of the equator, each accompanied by intense rainfall (solid line in Fig.2c), and on the 120 ° E panel, the northernmost boundary of the cell reaches 35 ° –40 ° N, with vigorous ascending located north of 30 ° N, around 35 ° N and in 10 ° –15 ° N , the last being strongest. These are matched by intense rainbelts around 10 ° and 30 ° N, respectively (broken line in Fig.2c), the former corresponding to the rainband of the South–China–Sea monsoon trough and the latter to the Plum rain band.

Fig.3 illustrates the same as Fig.2 except for Process B(designated as BDM). In the 100 ° E panel the ascending leg remains south of the Plateau, with strong updraft around 25 ° and 5 ° N, and the descending south of the equator. These updraft regions are each matched by a vigorous rainfall, located at 25 ° and 0 ° –5 ° N, respectively (solid line in Fig.3c). At the 120 ° E cross section updraft is observed over 20 ° N and 5 ° –10 ° N, respectively. The rainfall curve (solid line in Fig.3d) shows two profound peaks in its meridional distribution. However, around 35 ° N the rising and rainfall are both weaker than in ADM.

In summary, the conditions of the SMMC cell for the Plateau and region east of it obtained with ADM and BDM are in fairly good agreement with observations. They show clearly two vigorous rainbands, characterizing the typical climate during the prevailing summer monsoon, which correspond respectively to the monsoon rainbands of the South–China–Sea and China's Mainland, as indicated by Zhu et al. (1986) and He et al. (1986). Besides, it can be seen that for the 120 ° E panel the northern leg rainband is around 30 ° N (20) in ADM (BDM). Since the feature of the circulation with Process A (B) marks the active (break) monsoon in India, the difference in the results of the experiments suggests that during its active (break) period the northern leg rainbelt is closer to the Changjiang–Huaihe basin (South China). This is what we have said about the anti–phase (in–phase) of the Indian monsoon with the rainfall in South China (Changjiang basin and region north of it).

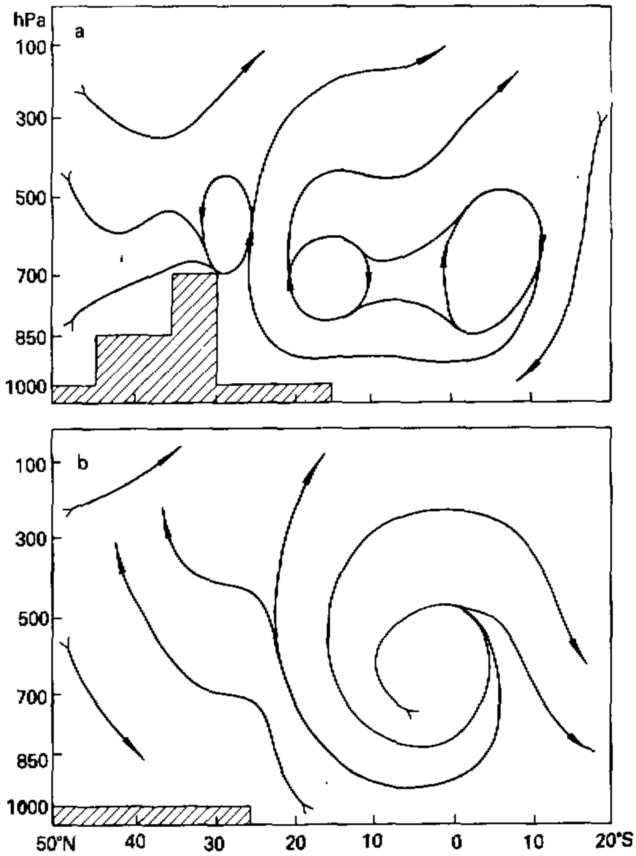

Fig.2a–b. Meridional circulation on the cross section of 100° E (a) and 120° E(b), obtained by the experiment ADM.

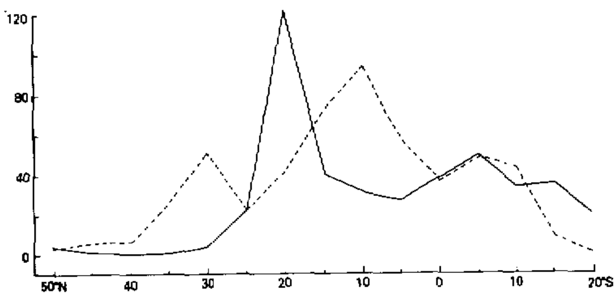

Fig.2c. Precipitation rate(10^{-1} mm d^{-1}) from ADM.The solid(broken)line denotes the area of 100° E(120° E).

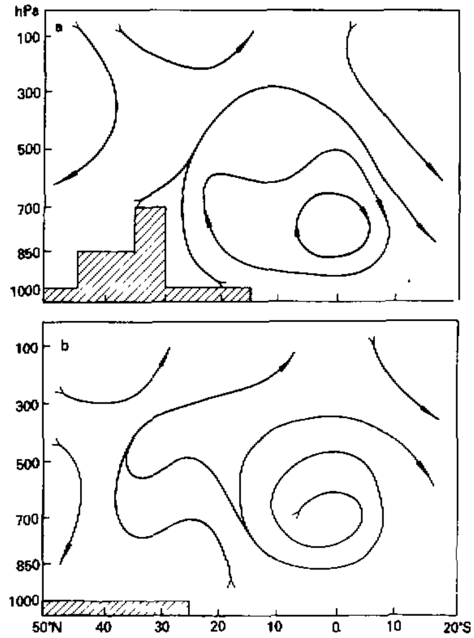

Fig.3a–b. Meridional circulation on the cross section of 100°E (a) and 120°E (b), obtained by BDM.

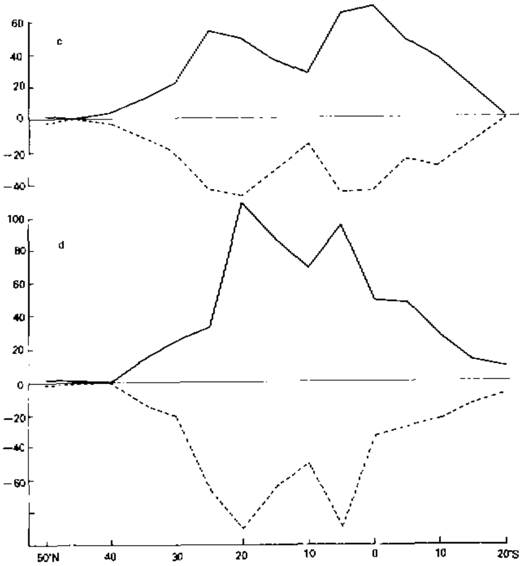

Fig.3c–d. Precipitation rate from BDM for 100°E (c) and 120°E (d) represented by solid line. The difference in total rainfall rate between the results of BDQ and BDM is denoted by broken line. Unit: 10^{-}[illegible] mm d^{-1}.

2. *For* DQ

Figure 4 delineates the cell obtained by DQ in the presence of Process A (designated as ADQ). The cell has been changed greatly in comparison with that by ADM. The 100 ° E panel (a) shows that the 20 ° –25 ° N strong updraft has been replaced by downdraft; the monsoon cell north of the equator has gone completely out of being, with a rising close to the equator (0 ° –5 ° N); the location of downdraft south of the Plateau and in the SH is somewhat similar to that of the wintertime situation. The 120 ° E panel (b) indicates no appearence of the cell, with the circulation's direction almost entirely opposite to that shown by ADM, in which north (south) of 5 ° N downdraft (updraft) takes the place of updraft (downdraft), and BDQ yields analogous results (figure not shown). It appears that the vertical circulation of the SMMC over the latitudes is strongly sensitive to the water content of the model atmosphere, more at 120 ° than at 100 ° E. Analyses of the numerical difference in the vertical motion reveal that places of stronger rising are sensitive to the decrease in water content more heavily, which suggests that the humidity field is of much importance to the vertical motion. To further bear this out, calculations are made to find out the difference in the rates of total and cumulus rainfall between BDQ and BDM, separately, as shown in Fig. 3c–d (broken line) and Fig.5. Apparently, the place of a maximum rainfall rate indicated by BDM has the maximal decrease in both rates after reduced water content, suggesting that the moist process is of vital importance to the formation of the SMMC.

To examine the effect of cumulus convection on the SMMC cell, an experiment is done with Process A as the initial field excluding from it the effect of the convection processes (designated as ADC). Fig.6 shows the difference in vertical velocity (W(ADC)–W(ADM)) in the second layer ($\sigma = 0.75$). The 100 ° E panel depicts that in the area north of 5 ° N the vertical motion is greatly weakened with a maximum decrease happening around 20 ° N, where the largest rainfall rate occurs in ADM; the rising south of 5 ° N has experienced no profound decrease, and, instead, shown some increase. The 120 ° E panel illustrates that the vertical motion for all latitudes north of the equator is weakened with a maximum decrease around 25 ° and 10 ° N, respectively, largely in agreement with the locations of the maximum rate in ADM; that south of the equator is more or less strengthened, with a maximum increase at 5 ° S. In ADC the increased vertical velocity actually implies the decreased downdraft in the neighbourhood of the equator. Therefore, the weakened northern updraft and southern downdraft, respectively, indicate the decreased SMMC. In short, in the updraft zone, the presence of convection and associated release of latent heat are essential to the maintenance of the SMMC and the more vigorous the rising, the more sensitive would it be in good agreement with the ADQ results. In the downdraft zone near the equator, both the convection and related release intensify downdraft, which, however, is not so much dependent on the former as in the updraft zone. This may well be due to the fact that cumulus convective activities of the descending zone are always weak, and it is understandable that the exclusion from the model of the convection together with the associated latent heat release has little effect upon the rising.

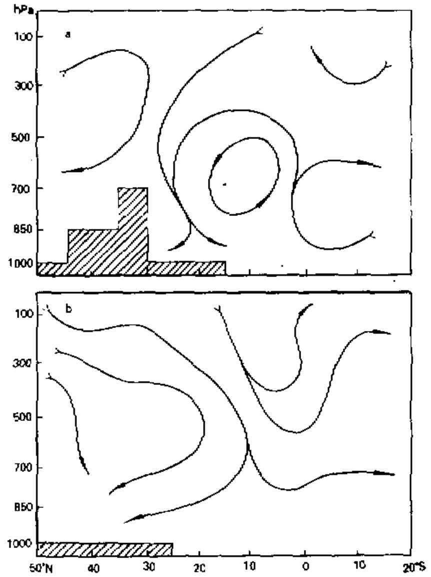

Fig.4. Monsoon circulation on the cross section of 100 ° E(a) and 120 ° E(b), acquired through ADQ.

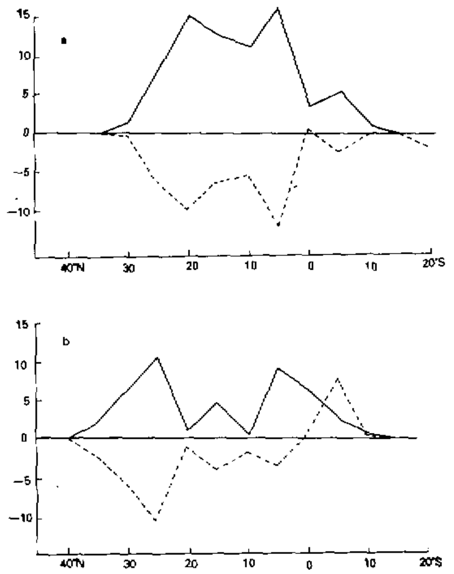

Fig.5. The cumulus rainfall rate (solid) obtained by BDQ and the rate difference between BDQ and BDM (broken line). (a)denotes the 100 ° E and (b) 120 ° E area.

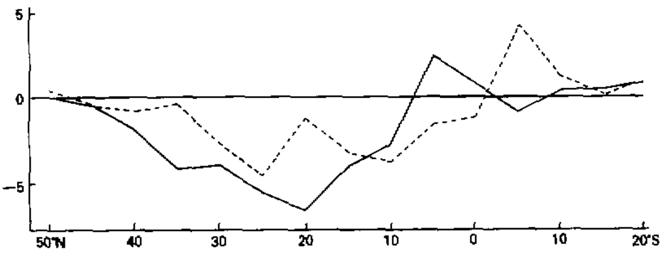

Fig.6. The difference in vertical velocity between ADC and ADM at the level $\sigma = 0.75$ with unit 10^{-4} m s^{-1}. The solid line denotes the area of 100 ° E and broken of 120 ° E.

3. *For* DN

Many studies show that the immense Plateau of Qinghai–Tibet plays an important role in the generation of the mean summer monsoon circulation, and in the advance of East–Asian monsoon circulation and the behavior of the monsoon system to the east.

Fig.7 illustrates the SMMC cell obtained with Process B as the initial field and with the removal of mountain effect (called BDN). Comparison of the results from BDN and BDM (Fig.3) indicates that on the 100 ° E panel the cell has considerably retreated toward the south, and updraft been replaced by downdraft on the south side of the Plateau. This happens because the Plateau as a great barrier, after being removed, no longer shows effect on the southward–moving air from the north, and more important, acts as a vast heat source for the troposphere in summer. Under such conditions, the NW flow to the north of the Plateau prevents the current to the south from its northward invasion, leading to a fact that downdraft occurs over the Plateau and its south–facing slope. The two currents converge and rise in 10 ° –15 ° N far away from the Plateau, thus moving to the south the northern boundary of the monsoon cell and the major updraft zone from 25 ° (south–facing slope) to 10 ° –15 ° N; on the 120 ° E panel (East–Asian coast) the cell obtained by BDN has experienced no profound change in the basic structure, except that with the mountain's effect removed the convergence of the two currents is intensified on the SE side of the Plateau (around 20 ° –25 ° N), resulting in the somewhat increased rising, which, on the whole, is weak.

Fig.8 delineates the latitudinal distribution of difference in the total and cumulus rainfall rates between BDN and BDM. It clearly shows that on the 100 ° E panel both rates are decreased in the north and increased in the south after the mountain's effect is removed, a fact that is in good agreement with the analysis indicating that the SMMC cell and thus vigorous updraft are moved toward the south; on the 120 ° E panel the general trend is that the total rainfall rate is reduced at all latitudes, with a maximum decrease around 15 ° N (in contrast with some increase of the cumulus rainfall rate about 20 ° and 10 ° N), and sharp decrease in the equatorial zone. On the whole, however, such variations are not large, which agrees quite well with the structure of the monsoon cell that remains almost unchanged, according to the result of BDN.

From the above, it can be seen that mountains have effect on the SMMC, with significant difference between the 100 ° and 120 ° E cross section. At the 100 ° E panel the presence of mountains causes the cell to be moved a considerable distance toward the north, while at the 120 ° E, mountains exerts no significant effect on its basic structure, except that, with the mountain's effect removed, the large-scale rainfall rate will be reduced, particularly in the South-China-Sea (around 15 ° N).

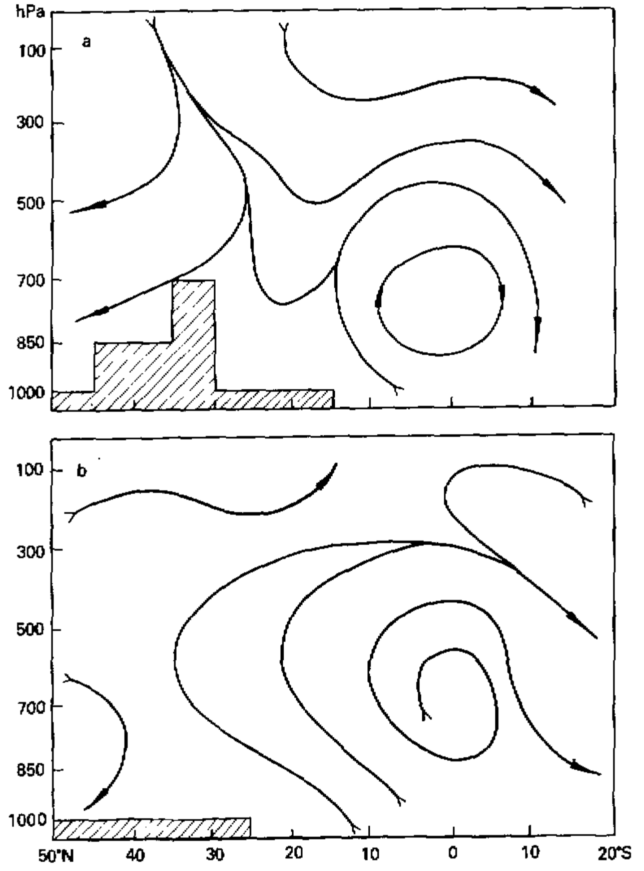

Fig.7. Monsoon circulation on the cross section of 100 ° E (a) and 120 ° E (b) obtained through BDN.

These results indicate that the Qinghai-Tibetan Plateau has far more considerable effect on the monsoon circulation meridionally than zonally. This may suggest that there exists a profound difference in the cause of the SMMC between 120 ° (East Asia) and 100 ° E (the Plateau).

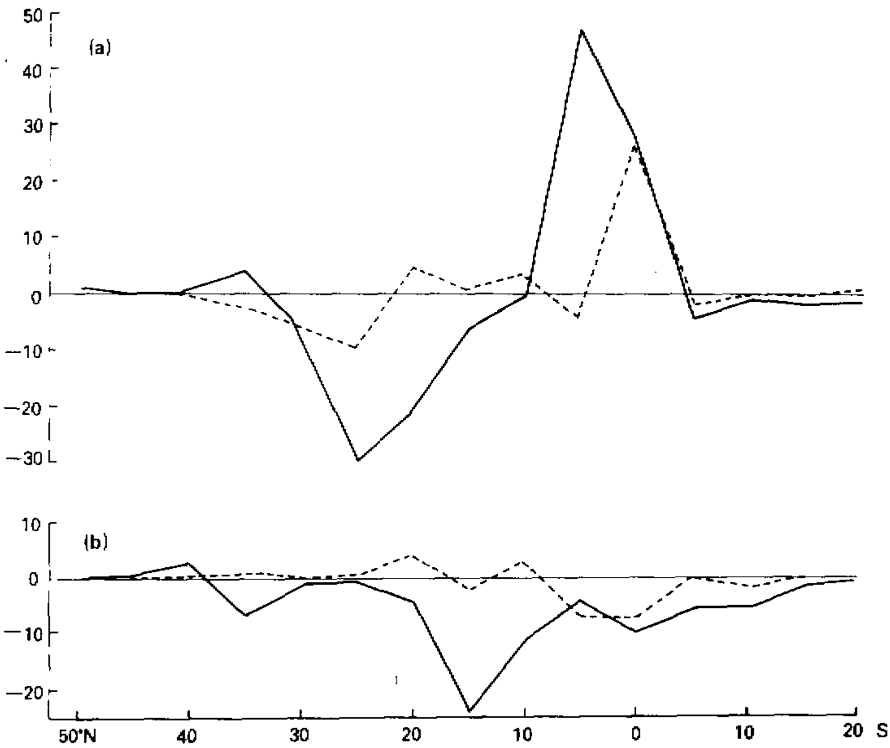

Fig.8. The difference in rainfall rate between the results of BDN and BDM. The solid (broken) line represents total precipitation rate (cumulus rainfall rate). (a) denotes the area 100 ° E and (b) 120 ° E.

IV. CONCLUSIONS

From the foregoing analyses we can arrive at some preliminary conclusions as follows:

1. With consideration of various physical processes (e.g., diabatic heating) and the presence of mountain's effect, the numerical integrations of the model can clearly reveal the condition of the SMMC cell and the existence of two intense rainbands in East Asia, in good concert with observations, and characterize the climate typical of the period of prevailing summer monsoon.

Comparison of the results acquired through a set of numerical experiments with Process A and B as the initial field, respectively, indicates that the presented model can show, to some degree, the anti–phase (in–phase) of the Indian monsoon with the precipitation over South China (the Changjiang basin and its northern regions).

2. The East–Asian SMMC is strongly sensitive to the water content of the atmosphere, more at 120 ° than at 100 ° E, when the atmospheric humidity field is reduced in intensity to 1 / 5, there is observed downdraft in place of updraft on the south side of the Plateau, resulting in a situation in which updraft occurs in the equatorial zone with downdraft on both sides, similar to the wintertime situation; the East–Asian SMMC cell (120 ° E) has broken

down, almost in striking contrast to the form obtained in terms of the actual humidity field, with great change occurring in the place of strong updraft. In addition, with different initial fields SMMC cells are sensitive to the humidity field to varying degree.

3. Cumulus convective processes and the associated latent heat release through condensation contribute much to the intensification of the SMMC; the processes alone make contribution to the intensification of rising in the updraft zone of the circulation, and more to the place of stronger rising while they help to amplify descending of the downdraft zone. The reversal happens after the effect of cumulus convection and related latent heat release is removed.

4. The effect of mountains on the SMMC varies considerably longitudinally; at the 100° E panel, with mountain's effect removed, the cell is significantly shifted southward, the intense rising zone advanced to around 10°–15° N, and at the 120° E panel no profound changes are observed in the structure of the cell only with a widespread decline of the rainfall, especially the large–scale precipitation rate, particularly over the South–China–Sea. The difference in the influence of mountains upon the cell may suggest that there exists significant difference in the cause of the cell over the Plateau (100° E) and East–Asian coastal region (120° E).

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