STUDY OF PHYSICAL MECHANISM FOR ACTIVE AND BREAK PHASES OF SOUTH ASIAN MONSOON

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ABSTRACT

Using a low-order spectral model derived from the equatorial equilibrium model, possible physical mechanisms are interpreted by the theory of multiple equilibria states for the active and break phases of the South Asian Monsoon, with consideration of the effects of heating by cumulus heating and cooling by radiation. The result shows that the South Asian Monsoon is active when the cumulus convection intensifies (or the radiation cooling weakens): the monsoon breaks when the convection weakens (or the cooling intensifies). It is consistent with the hypothesis of cloud-radiation by Krishnamurti et al.

Key words: South Asian Monsoon, active and break phases, multiple equilibria states

Ⅰ. INTRODUCTION

Medium-term oscillation of the monsoon is what is more commonly known its active and break phases. By the active phase. it is referred to as drastic intensification of the monsoon and increase of rainfall; by the break phase, it means that the monsoon weakens as most of the rainfall associated with it reduces significantly or disappears. The phases act by a cycle of about 15 days.

Krishnamurti (1976) suggests that the medium-term monsoon oscillation is resulted from feedback of clouds and radiation: the monsoon becomes active (or comes to a break) when convective clouds increase (decrease) in intensity and the radiation cooling weakens (intensifies). To confirm it in a viewpoint of multiple equilibrium states, Gosswami (1983) uses a two-layer axisymmetric model to obtain an equilibrium state – active monsoon, with inclusion of convective heating and radiation cooling. Using a barotropic equatorial equilibrium model with consideration of forcing by topographic features and land-sea heating, Zhu and Zhao (1987) derive two equilibrium states for monsoon in winter and summer. They further show that the barotropic model gives two equilibrium states while the baroclinic model gives just one (Zhao and Zhu, 1989). It is just based on the achievements that the barotropic equatorial model is still used in our work. Due to the necessity to include effects of cumulus convection and radiation cooling, the study is conducted from the approach of multiple equilibrium states to address the issue of possible mechanism of active and break phases of the South Asian Monsoon.

Ⅱ. BASIC EQUATIONS

The set of equations describing the equatorial β-plane, semi-geostrophic, and axisymmetric motion of the atmosphere with convection heating and radiation cooling are

$$\begin{cases} \dfrac{\partial u}{\partial t} + v\dfrac{\partial u}{\partial y} - \beta y v = -\gamma u \\ -\beta y u = \dfrac{\partial \Phi}{\partial y} \\ C_0^2 \dfrac{\partial v}{\partial y} - v\dfrac{\partial \Phi_B}{\partial y} = -Q_1 - Q_2 + \varepsilon(\Phi_e - \Phi) \end{cases} \tag{1}$$

where Q_1 is the diabatic heating caused by solar radiation and land-sea difference, Q_2 the diabatic heating by cumulus convection, and Φ_e the potential height that corresponds to equilibrium solar radiation [similar to the equilibrium radiation temperature in baroclinic atmosphere (Zebiak, 1986)]. The rest of the symbols follow the denotation of Zhu et al. (1987).

It is well known that heating by cumulus convection is achieved by $Q_2 = \eta W_1$, where W_1 is vertical velocity at the top of planetary boundary layer, $W_1 = \int_0^{H_1}\left(\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y}\right)dz = -H_1\dfrac{\partial v}{\partial y}$, and η the coefficient of proportion that reflects the intensity of cumulus convection. The provision is identical to the scheme of Zebiak (1986). If the characteristics of lower troposphere are depicted by those at the top of the PBL, it might as well do the job to write Eq.(1) for the latter with the subscript "1" dropped. Then Eq.(1) becomes

$$\begin{cases} \dfrac{\partial u}{\partial t} + v\dfrac{\partial u}{\partial y} - \beta y v = -\gamma u \\ -\beta y u = \dfrac{\partial \Phi}{\partial y} \\ \left(1 - \eta/g\right) C_0^2 \dfrac{\partial v}{\partial y} - v\dfrac{\partial \Phi_B}{\partial y} = -Q_1 + \varepsilon(\Phi_e - \Phi) \end{cases} \tag{2}$$

Based on the conclusions drawn in Zhao et al. (1989), an equilibrium equatorial model is constructed from Eq.(2) as in

$$\begin{cases} \dfrac{\partial}{\partial t}\left(\dfrac{\partial u}{\partial y}\right) + \dfrac{\partial}{\partial y}\left(v\dfrac{\partial u}{\partial y}\right) - \beta y\dfrac{\partial v}{\partial y} - \beta v = -\gamma\dfrac{\partial u}{\partial y} \\ \beta u + \beta y\dfrac{\partial u}{\partial y} + \dfrac{\partial \Phi^2}{\partial y^2} = 0 \\ C_0^2\left(1 - \eta/g\right)\dfrac{\partial v}{\partial y} - v\dfrac{\partial \Phi_B}{\partial y} = -Q_1 + \varepsilon(\Phi_e - \Phi) \end{cases} \tag{3}$$

For the sake of convenience, we set

$$C_0^2 = C_0^2\left(1 - \eta/g\right)$$

Applying the scale analysis method and setting $y = L_0 y'$, $(u, v) = U_0(u', v')$, $t = \dfrac{L_0}{U_0}t'$, and $\Phi_e = U_0^2\Phi_e'$ (quantities with "$'$" are without any dimensions), a dimensionless equation is obtained by substitution of Eq.(3) with the superscript dropped.

$$\begin{cases} \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(v\frac{\partial u}{\partial y}\right)-\beta^* v-\beta^* y\frac{\partial v}{\partial y}=-\gamma^*\frac{\partial u}{\partial y} \\ \beta^* u+\beta^* y\frac{\partial u}{\partial y}+\frac{\partial \Phi^2}{\partial y^2}=0 \\ \eta^*\frac{\partial v}{\partial y}-v\frac{\partial \Phi^*{}_B}{\partial y}=-Q^*{}_1+\varepsilon^*(\Phi_e-\Phi) \end{cases} \tag{4}$$

in which

$$\beta^*=\beta L_0^2/U_0,\quad \gamma^*=\gamma L_0/U_0,\quad \varepsilon^*=\varepsilon U_0 L_0/C_0^2,$$

$$\Phi_B^*=\Phi_B/C_0^2,\quad Q_1^*=Q_1 L_0/C_0^2 U_0,\quad \eta^*=\left(1-\eta/g\right).$$

By the orthogonal function, $\Phi_B^*, u, v, \Phi, \Phi_B^*, \Phi_e, Q^*$ in Eq.(4) are expanded:

$$\begin{pmatrix} u \\ v \\ \Phi \\ \Phi_B^* \\ \Phi_e \\ Q_1^* \end{pmatrix}=\sum_{n=0}^{N}\begin{pmatrix} U_n \\ V_n \\ \Phi_n \\ h_n \\ \Phi_{en} \\ Q_n \end{pmatrix}D_n \tag{5}$$

Substituting Eq.(5) into the equation set Eq.(4) yields (with "*" dropped):

$$\sum_n b_{jn}\frac{\partial U_n}{\partial t}+\sum_n\sum_m a_{jnm}\cdot V_n U_m-\beta\sum_n c_{jn}V_n-\beta\sum_n a_j\delta_{jn}V_n$$
$$+\gamma\sum_n b_{jn}U_n=0$$

$$\beta\sum_n a_j\delta_{jn}U_n+\beta\sum_n c_{jn}\cdot U_n+\sum_n a_{jn}\cdot\Phi_n=0 \tag{6}$$

$$\sum_n\left(1-\eta/g\right)b_{jn}V_n+\sum_n a_j\delta_{jn}Q_n\sum_n\sum_m d_{jnm}U_n\cdot h_n$$
$$+\varepsilon\sum_n a_j\delta_{jn}(\Phi_n-\Phi_{en})=0$$

where

$$b_{jn} = \langle D_j, D_{ny} \rangle, \qquad b_{jnm} = \langle D_j, (D_n D_{my})_y \rangle,$$

$$c_{jn} = \langle D_j, yD_{ny} \rangle, \qquad a_j \delta_{jn} = \langle D_j, D_n \rangle,$$

$$a_{jn} = \langle D_j, D_{nyy} \rangle, \qquad d_{jnm} = \langle D_j, D_n D_{my} \rangle,$$

while $\langle A, B \rangle = \int_{-\infty}^{\infty} A \cdot B \cdot \mathrm{d}y$. For u, Φ, Φ_B^*, $n = 1, 2$; for v, Φ_e, Φ_1^*, $n = 0, 1$. As a result, the following truncated spectral model is obtained as in

$$\begin{cases} \dfrac{\partial U_1}{\partial t} = -1.588 V_0 U_2 - 0.363 V_1 U_1 + \beta V_0 - \gamma U_1 \\ \dfrac{\partial U_2}{\partial t} = 0.544 V_0 U_1 + 0.363 V_1 U_2 + 0.5 \beta V_1 - \gamma U_2 \\ \beta U_1 = 1.5 \Phi_1 \\ \beta U_2 = 2.5 \Phi_2 \\ \left(1 - \eta / g\right) V_0 = 2\varepsilon(\Phi_1 - \Phi_{e1}) - 2Q_1 - 1.633 V_0 h_2 \\ \left(1 - \eta / g\right) V_1 = 2\varepsilon \Phi_{e0} - 2Q_0 + 0.544 V_0 h_1 + 1.633 V_1 h_2 \end{cases} \tag{7}$$

where the truncated spectral model is identical to Zhu et al. (1987) when $\eta = 0, \Phi_{eo} = \Phi_{e1} = 0$.

The model in Eq.(7) is the simplest system of medium-term oscillation of lower-tropospheric monsoon in South Asia, which is characterized by

(1) U_1 and U_2, and V_1 and V_2 depict the general structure of airflow in lower layers of the troposphere. Especially, the cross-equatorial current V_1 reflects the changes in intensity of the monsoon;

(2) Q_0 expresses the meridional heating by solar radiation over the equatorial zone, which causes the monsoon to oscillate among others while Q_1, the land-sea difference across the Northern and Southern Hemispheres, is the principal reason behind the formation of monsoon;

(3) By a combined denotation, h_1 and h_2 indicate areas north of the equator as mountain ridge and those south of it as mountain valley.

(4) By a combined denotation, Φ_{e0} and ϕ_{e1} are the potential altitude in radiative equilibrium temperature, which is the maximum at 20°N; and

(5) η is the heating effects of cumulus convection.

It is then apparent that Eq.(7) contains basic physical factors of monsoon formation in South Asia and physical factors of medium-term oscillation, which is the right system for discussion of active and break phases of the monsoon.

III. MULTIPLE EQUILIBRIA STATES OF SOUTH ASIAN MONSOON

Deriving from Eq.(7) and setting $\frac{\partial U_1}{\partial t}=\frac{\partial U_2}{\partial t}=0$, the equilibrium equation set is as follows:

$$\begin{cases} 1.588V_0U_2+0.363V_1U_1-\beta V_0+rU_1=0 \\ 0.544V_0U_1+0.363V_1U_2+0.5\beta V_1-rU_2=0 \\ \beta U_1=1.5\Phi_1 \\ \beta U_2=2.5\Phi_2 \\ \left(1-\eta/g\right)V_0=2\varepsilon(\Phi_1-\Phi_{e1})-2Q_1-1.633V_0h_2 \\ \left(1-\eta/g\right)V_1=2\varepsilon\Phi_{e0}-2Q_0+0.544V_0h_1+1.633V_1h_2 \end{cases} \tag{8}$$

From the 3rd and 5th expressions in Eq.(8), we have

$$V_0=f_1U_1+G_1 \tag{9}$$

where

$$f_1=\frac{4}{3}\varepsilon\beta\Big/\left(1-\eta/g+1.633h_2\right)$$

$$G_1=(-2Q_1-2\varepsilon\Phi_{e1})\Big/\left(1-\eta/g+1.633h_2\right)$$

From the 6th expression of Eq.(8) and Eq.(9), we have

$$U_1=f_2V_1+G_2 \tag{10}$$

where

$$f_2=\left(1-\eta/g-1.633h_2\right)\Big/0.544f_1h_1$$

$$G_2=(2Q_0-2\varepsilon\Phi_{e0}-0.544G_1h_1)/0.544f_1h_1$$

and from the 1st and 2nd expressions in Eq.(8) we have

$$aV_1^3+bV_1^2+cV_1+d=0 \tag{11}$$

where

$$a=0.864f_1^2f_2^3-0.132f_2$$

$$b=0.864G_2(f_1f_2)^2-0.132G_2+1.728f_1f_2^2\cdot(f_1G_2+G_1)+0.363\beta f_1f_2$$

$$c=0.864(f_1G_2+G_1)^2\cdot f_2+1.728f_1f_2G_2\cdot(f_1G_2+G_1)+0.363\beta(f_1G_2+G_1)+0.794\beta$$
$$-\gamma\beta f_1f_2+\gamma^2f_2$$

$$d=0.864G_2\cdot(f_1G_2+G_1)^2-\gamma\beta(f_1G_2+G_1)+\gamma^2G_2$$

Let $V' = V_1' + \frac{b}{3a}$, then Eq.(11) changes into

$$V^3 + pV + q = 0 \tag{12}$$

in which $p = -b^2/3a^2 + c/a$, $q = \frac{2}{27}b^3/a^3 - \frac{1}{3}\frac{bc}{a^2} + \frac{d}{a}$. Inferring from the theory of Algebra, Eq.(12) is interpreted as a crescent-shaped catastrophe equation.

Ⅳ. STABILITY OF MULTIPLE EQUILIBRIA STATES

The equilibrium state $\overline{V}_1$ is derived from Eq.(11) and $\overline{U}_1, \overline{V}_0, \overline{U}_2$ and $\overline{\Phi}_1, \overline{\Phi}_2$ are respectively obtained from Eqs.(9) – (10). Each group of selected parameters corresponds to a group of equilibrium state. Setting

$$\begin{cases} U_1 = \overline{U}_1 + U_1', & U_2 = \overline{U}_2 + U_2', & V_0 = \overline{V}_0 + V_0', \\ V_1 = \overline{V}_1 + V_1', & \Phi_1 = \overline{\Phi}_1 + \Phi_1', & \Phi_2 = \overline{\Phi}_2 + \Phi_2', \end{cases} \tag{13}$$

Substituting Eq.(13) into Eq.(8) gives perturbations that meet the equation set that follows (with " ' " omitted):

$$\begin{cases} \frac{\partial U_1}{\partial t} = -1.588\overline{V}_0 U_2 - 1.588\overline{U}_2 V_0 - 0.363\overline{V}_1 U_1 - 0.363\overline{U}_1 V_1 + \beta V_0 - \gamma U_1 \\ \frac{\partial U_2}{\partial t} = 0.544\overline{V}_0 U_1 + 0.544\overline{U}_1 V_0 + 0.363\overline{V}_1 U_2 + 0.363\overline{U}_2 V_1 + 0.5\beta V_1 - \gamma U_2 \\ V_0 = f_1 U_1 \\ U_1 = f_2 V_1 \end{cases} \tag{14}$$

Reorganizing Eq.(14), we have

$$\begin{cases} \frac{\partial U_2}{\partial t} = A_1 U_1 + B_1 U_2 \\ \frac{\partial U_1}{\partial t} = A_2 U_1 + B_2 U_2 \end{cases} \tag{15}$$

where

$$\begin{cases} A_1 = \beta f_1 - \gamma - 1.588 f_1 \overline{U}_2 - 0.363\overline{V}_1 - 0.363\overline{U}_1/f_2 \\ B_1 = -1.588\overline{V}_0 \\ A_2 = 0.544\overline{V}_0 + 0.363\overline{U}_2/f_2 + 0.5\beta/f_2 + 0.544 f_1 \overline{U}_1 \\ B_2 = 0.363\overline{V}_1 - \gamma \end{cases}$$

The stability of Eq.(15) is determined by the characteristic root. The characteristic determinant of Eq.(15) is then written as

$$\Delta = \begin{vmatrix} \lambda - A_1 & B_1 \\ A_2 & \lambda - B_2 \end{vmatrix}$$

when $\Delta = 0$, the maximum real part of the root of λ is less than zero and the equilibrium state is stable; it will be unstable otherwise. As is shown in computation, the equilibrium line in

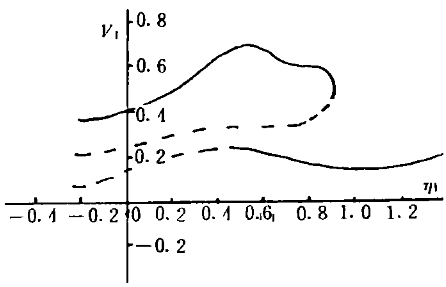

Fig.1. Variation of meridional wind V_1 with heating parameter η_1. The solid line is the stable equilibrium state and the dashed line is the unstable one

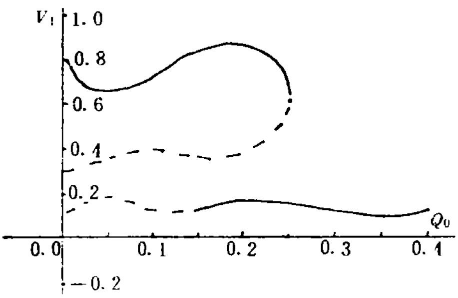

Fig.2. Variation of meridional wind V_1 with solar radiation heating Q_0.

the middle is unstable while the other two are stable.

V. NUMERICAL ANALYSIS OF PHYSICS OF MEDIUM-TERM OSCILLATION OF SOUTH ASIAN MONSOON

To study the physics of the medium-term oscillation of the South Asian Monsoon, variations of the meridional wind speed V_1 (the intensity of the cross-equatorial airflow) with the solar radiation Q_0, longwave radiation cooling ε and heating parameter of cumulus convection η.

1. *Influence of heating by cumulus convection on medium-term monsoon oscillation*

Based on Zhu et al.(1987), the change of the meridional wind speed V_1 with η is obtained by assuming that

$$h_1 = 0.25,\ h_2 = \frac{h_1}{3},\ \varepsilon = 0.3,\ \gamma = 0.2,\ \Phi_{e0} = 0.2,$$

$$\Phi_{e1} = 0.5,\ Q_0 = 0.04, \text{ and } Q_1 = -1.0,$$

with $\eta_1 = 1 - \eta/g$.

It is obvious from Fig.1 that V_1 jumps from 0.2 to 0.7 when $\eta_1 < 0.4$ ($\eta > 6$); V_1 falls from 0.5 to 0.15 when $\eta_1 < 0.9$ ($\eta < 1.0$). It is concluded that when there is more convective heating ($\eta > 6$), the cross-equatorial airflow intensifies rapidly, signaling the active phase of the monsoon; when there is less convective heating ($\eta < 1.0$), the airflow weakens sharply and the monsoon breaks.

2. *Influence of solar radiation on medium-term monsoon oscillation*

Assuming that $h_1 = 0.15, h_2 = 0.05, \varepsilon = 0.3, \gamma = 0.2, \eta = -1.5, \Phi_{e0} = 0.2, \Phi_{e1} = 0.5$, the variation of the meridional airflow V_1 with the solar radiation heating Q_0 is obtained (Fig.2.)

It is seen in Fig.2 that V_1 jumps from 0.17 to 0.9 when $Q_0 < 0.15$; V_1 falls from 0.6 to 0.17 when $Q_0 > 0.25$; only when Q_0 ranges between 0.15 and 0.25 will V_1 be in a dual-stables state of equilibrium. It is known from the numerical study that that when there is increasing solar radiation heating ($Q_0 > 0.25$), the cross-equatorial airflow weakens rapidly, signaling the break phase of the monsoon; when there is decreasing solar radiation heating ($Q_0 < 0.15$), the airflow intensifies sharply and the monsoon becomes active.

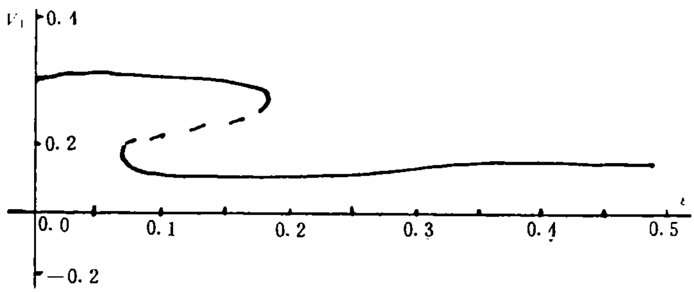

Fig.3. Variation of meridional wind V_1 with the cooling coefficient ε in longwave radiation.

3. *Influence of longwave radiation cooling on medium-term monsoon oscillation*

The meridional airflow V_1 with the coefficient of radiation cooling is determined by taking h_1=0.15, h_2=0.05, r=0.2, Φ_{e0} =0.5 and Φ_{e1}=0.2, Q_0=0.4 and Q_0=-1.5 (See Fig.3). It is seen that V_1 jumps from 0.15 to 0.3 when radiation cooling weakens ($\varepsilon<0.07$): V_1 falls from 0.3 to 0.15 when $\varepsilon>0.17$. It is obvious that the cross-equatorial airflow intensifies (weakens) as the atmospheric longwave radiation cooling weakens (intensifies). It is suggested that radiation cooling acts as a physical factor in the medium-term oscillation of the South Asian Monsoon, though causing much smaller amplitude than the factors discussed earlier in the text would do. It seems justifiable that it is less important than the two.

As shown in the numerical study, as the heating by cumulus convection is strong in South Asia, the monsoon is in active equilibrium state, there is much activity of cumulus convection over the monsoon region there and increasing solar radiation heating, so that the monsoon changes from the active state of equilibrium to the break state of equilibrium and the cross-equatorial airflow weakens. On the other hand, the weakened transportation of water vapor and decreased convection activity enhance the shift towards and maintenance of the break state of equilibrium, when the meridional heating by solar radiation turns weaker again, making the equilibrium state an active one, and increasing the cross-equatorial airflow and water vapor transfer, enhancing the cumulus activity over South Asia, eventually speeding up the process of the state shift and maintaining the active, equilibrium state. It is consistent with the hypothesis put forward by Krishnamurti et al. on the mechanism responsible for the medium-term monsoon oscillation.

VI. CONCLUSIONS

a. Two of the main factors that influence the medium-term monsoon oscillation in South Asia are solar radiation heating and cumulus convection heating; as a minor factor, the longwave radiation cooling exerts its effects the oscillation of the monsoon.

b. When solar radiation decreases, the cumulus convection increases, shifting the South Asia Monsoon; when the solar radiation increases, the convection heating decreases and the monsoon shifts from the active phase to the break one.

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