A Primary Study of Interaction Between Monsoon and Sea Surface Temperature in the Neighborhood Sea Area in South Asia*

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ABSTRACT

Using a coupled ocean-atmosphere model simplified, and the low spectrum method and the equilibria theory, we discussed the interaction of South Asian winter and summer monsoons with sea surface temperature (SST) seasonal variation in the neighbor sea area. The results indicate that, when the winter monsoon is strong, the winter SST is low, and the SST will also be low next summer; and vice versa. When the summer monsoon is strong, the summer SST is high; and vice versa. It is inconspicuous for SST in winter that summer monsoon is strong or weak. Ocean-atmosphere interaction reinforces winter monsoon and weakens summer monsoon.

Key words: South Asian monsoon, sea surface temperature (SST), coupled ocean-atmosphere, low-order-spectrum method, multi-equilibria

1. Introduction

South Asian monsoon is an important weather and climate phenomenon, and it is also an important constituent of the global atmospheric circulation, thus people pay more attention to it (Hahn and Manabe, 1975; Zhu and Zhao, 1987; Zhu et al., 1991; Zhou and Yang, 1994; Wu and Huang, 2001; Li et al., 1999). For example, Zhu and Zhao (1987) studied the effects of terrain on South Asian monsoon by the equatorial atmospheric balance model, indicating that terrain effect is very important for asymmetry of time length for winter and summer monsoons. Dynamic effect of terrain on atmosphere circulation catastrophe in June and October in Asia plays an important role, and makes asymmetry evidently for the two stable equilibria of winter and summer monsoons. It is well known that in South Asian monsoon area, there is the wide ocean from 20°N, thus air-sea coupled model is suitable for discussing South Asian monsoon interacted with ocean. From the point of view of the ocean-atmosphere interaction, in South Asia, winter and summer monsoons affect ocean current and sea surface temperature (SST) of neighborhood sea area, and ocean (especially oceanic thermocline) also affects monsoon by redistributing heat flux and SST (i.e., SST gradients change). Therefore it is significant to research South Asian ocean-atmosphere interaction by dynamical method for understanding deeply the strongness or weakness of winter and summer monsoons as well as the mechanism of their transition.

Nonlinear SST equation and equatorial balance model are adopted in this paper, and ocean-atmosphere interaction is put into the SST equation, thus a coupled air-sea model is established. Then we simplify it to a truncated-spectrum model convenient for analyzing and discussing by low-order spectral method. According to the theory and method of multi-equilibria and stability, we discuss respectively the effect of summer and winter monsoons on the SST seasonal variation in neighborhood field, and the effect of ocean-atmosphere interaction and of the SST meridional gradient on South Asian monsoon.

2. Basic equations

2.1 Atmospheric equations

Equatorial balance model describing South Asian monsoon including effects of terrain and heating is written as (Zhu and Zhao, 1987)

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where $v_S$ is the oceanic flow in y direction, $v_S \frac{\partial T_S}{\partial y}$ is the term for SST advection, thus Eq.(4) is a nonlinear equation. It is the same as that in paper by Pedlosky (1975) if $H_S$ is not considered.

According to a great deal of observation data, Ekman (1975) obtained the following empirical relationship between oceanic flow and surface wind

$$v_S = (0.0127/\sqrt{\sin \theta}) v_a,$$

where $v_S$ and $v_a$ are respectively oceanic flow and wind speed, and $\theta$ is latitude. In equatorial areas, $\theta = 5^\circ$ can be taken to be representative in general ($\sin \theta = 0.0875$) and put into Eq.(5). Let $v_a$ be written as $v$, then

$$v_S = \hat{a} v,$$  

where $\hat{a}$ is an empirical constant ($\hat{a} \approx 0.04$).

Substituting Eq.(6) into Eq.(4) yields

$$\frac{\partial T_S}{\partial t} + \hat{a} v \frac{\partial T_S}{\partial y} = H_S + \lambda(a_0 \phi - T_S) - \alpha_s T_S.$$  

(7)

Taking $H_S = \overline{H}_S + H'_S$, $\phi = \phi + \phi'$, $T_S = \overline{T}_S + T'_S$, where $\overline{T}_S$ represents the annual mean temperature, $T'_S$ the SST anomalies (in winter $T'_S < 0$, while in summer $T'_S > 0$), Eq.(7) can be linearized and simplified as

$$\frac{\partial T_S}{\partial t} + \hat{a} v \frac{\partial T_S}{\partial y} + \hat{a} v \frac{\partial \overline{T}_S}{\partial y} = H_S + \lambda(a_0 \phi - T_S) - \alpha_s T_S.$$  

(8)

Here superscripts $^\prime$ are omitted.

2.3 Coupled ocean-atmosphere equations

A set of coupled ocean-atmosphere equations describing South Asian monsoon can be obtained by Eqs.(1) and (8) as follows

$$\frac{\partial T_S}{\partial t} + \hat{a} v \frac{\partial T_S}{\partial y} + \hat{a} v \frac{\partial \overline{T}_S}{\partial y} = H_S + \lambda(a_0 \phi - T_S) - \alpha_s T_S,$$

$$\frac{\partial u}{\partial t} + \hat{a} v \frac{\partial u}{\partial y} + \hat{a} v \frac{\partial \overline{T}_S}{\partial y} - \beta y \frac{\partial v}{\partial y} = H_S + \lambda(a_0 \phi - T_S) - \alpha_s T_S,$$

$$\beta u + \beta y \frac{\partial u}{\partial y} + \frac{\partial^2 \phi}{\partial y^2} = 0.$$


where $D_n$ represents cylinder function, while taking $n=1$, 2 for $T_S$, $H_S$, $u$, $\phi$, and $n=0$, 1 for $Q, V$.

Several new variables in Eq. (11) are as follows: $T_1$ and $T_2$ are main structures of SST anomalies, and $T_1>0$ refers to summer, $T_1<0$ refers to winter. $H_1$ and $H_2$ are thermal forcing from sea, in particular here $H_1$ refers to the deviation of solar radiation (in whole year), and $H_2<0$ for winter, $H_2>0$ for summer. $u_1$, $u_2$ and $v_0$, $v_1$ describe main structures of air current in the lower troposphere, $v_0$ refers to the cross-equatorial flow in South Asia, $v_0<0$ for winter monsoon, and $v_0>0$ for summer monsoon. $Q_0$ and $Q_1$ are the atmospheric thermal forcing, here $Q_1$ refers to the difference of heating between sea and land. In winter and summer, signs of $Q_1$ are just opposite.

Putting Eq. (11) into Eq. (10) results in the following truncated-spectrum system by using the orthogonal relations of basic functions (here, marks “$\bar{\lambda}$” are omitted from all parameters except $\bar{\lambda}$ and $\bar{a}$):

\[
\begin{align*}
\frac{\partial T_1}{\partial t} &= -a_3 v_1 + \bar{\lambda} \phi_1 - \lambda_1 T_1 - \frac{2\bar{\alpha}}{\sqrt{6}} v_0 T_2 + H_1, \\
\frac{\partial T_2}{\partial t} &= -\lambda_1 T_2 + \bar{\lambda} \phi_2 + \frac{2\bar{\alpha}}{3\sqrt{6}} v_0 T_1 - \frac{\bar{\alpha}}{9\sqrt{6}} v_1 T_2 + H_2, \\
\frac{\partial u_1}{\partial t} &= -\frac{35}{9\sqrt{6}} v_0 u_2 - \frac{8}{9\sqrt{6}} u_1 v_1 + \beta v_0 - \gamma u_1, \\
\frac{\partial u_2}{\partial t} &= \frac{4}{3\sqrt{6}} v_0 u_1 + \frac{8}{9\sqrt{6}} u_2 v_1 + \frac{1}{2} \beta v_1 - \gamma u_2, \\
\beta u_1 &= \frac{3}{2} \phi_1, \\
\beta u_2 &= \frac{5}{2} \phi_2, \\
v_0 &= -2Q_1 + 2(\varepsilon - a_1) \phi_1 + 2a_2 T_1, \\
v_1 &= - 2Q_0.
\end{align*}
\]

In Eq. (12) the first 4 equations are evolution equations, and the last 4 are the balance equations. Equation (12) is a complex nonlinear system. To discuss the proposition with it, the following simplification is needed to make further. Supposing that the influence of the sensible heat flux is small to the atmosphere, but is important to the oceanic current, thus when considering oceanic current process, we use $v_0 = -2Q_1 + 2(\varepsilon - a_1) \phi_1 + 2a_2 T_1$ for the first two equations in Eq. (12), and we use $v_0 = -2Q_1 + 2\varepsilon \phi_1$. 

In summary, the atmospheric oceanic dynamical process of vertically averaged monsoon is a complex system of coupled nonlinear differential equations, and its solutions are difficult to get without computer. Therefore, we take a simple and natural model, which is just based on a couple of basic assumptions. With this model, we can observe that the essential dynamical features of South Asian monsoon are well represented by the simple dynamical system.
for the third, fourth and seventh equations. Thereupon, Eq.(12) can be rewritten as

\[
\begin{align*}
\frac{\partial T_1}{\partial t} &= -a_3 v_1 - \alpha_s T_1 + H_1 + \frac{4a_1 \dot{a}}{\sqrt{6}} T_2 - \frac{4\dot{a}}{\sqrt{6}} (\varepsilon - a_1) \phi T_2 - \frac{4\dot{a}}{\sqrt{6}} a_2 T_1 T_2, \\
\frac{\partial T_2}{\partial t} &= -\alpha_s T_2 + H_2 - \frac{\dot{a}}{\sqrt{6}} v_1 T_2 - \frac{4\dot{a}}{3\sqrt{6}} Q_1 T_1 + \frac{4\dot{a}}{3\sqrt{6}} (\varepsilon - a_1) \phi T_1 + \frac{4\dot{a}}{3\sqrt{6}} a_2 T_1^2, \\
\frac{\partial u_1}{\partial t} &= -\frac{35}{9\sqrt{6}} v_0 u_2 - \frac{8}{9\sqrt{6}} u_1 v_1 + \beta v_0 - \gamma u_1, \\
\frac{\partial u_2}{\partial t} &= \frac{4}{3\sqrt{6}} v_0 u_1 + \frac{8}{9\sqrt{6}} u_2 v_1 + \frac{1}{2} \beta v_1 - \gamma u_2, \\
\beta u_1 &= \frac{3}{2} \phi_1, \\
\beta u_2 &= \frac{5}{2} \phi_2, \\
v_0 &= -2Q_1 + 2\varepsilon \phi_1, \\
v_1 &= 2Q_0.
\end{align*}
\]

(13)

Equation (13) is the ocean-atmosphere coupled model (dynamic system) which is used to analyze and discuss in the following.

4. Equilibria in the coupled ocean-atmosphere model and their stabilities

4.1 Equilibria in model (13)

4.1.1 South Asian monsoon equilibria

In Eq.(13), we let the time derivative \( \frac{\partial}{\partial t} = 0 \) in the first four equations, and obtain

\[
\begin{align*}
-a_3 v_1 + \alpha_s T_1 + H_1 + \frac{4a_1 \dot{a}}{\sqrt{6}} T_2 - \frac{4\dot{a}}{\sqrt{6}} (\varepsilon - a_1) \phi T_2 - \frac{4\dot{a}}{\sqrt{6}} a_2 T_1 T_2 &= 0, \\
-\alpha_s T_2 + H_2 - \frac{\dot{a}}{\sqrt{6}} v_1 T_2 - \frac{4\dot{a}}{3\sqrt{6}} Q_1 T_1 + \frac{4\dot{a}}{3\sqrt{6}} (\varepsilon - a_1) \phi T_1 + \frac{4\dot{a}}{3\sqrt{6}} a_2 T_1^2 &= 0, \\
-\frac{35}{9\sqrt{6}} v_0 u_2 - \frac{8}{9\sqrt{6}} u_1 v_1 + \beta v_0 - \gamma u_1 &= 0, \\
\frac{4}{3\sqrt{6}} v_0 u_1 + \frac{8}{9\sqrt{6}} u_2 v_1 + \frac{1}{2} \beta v_1 - \gamma u_2 &= 0, \\
\beta u_1 &= \frac{3}{2} \phi_1, \\
\beta u_2 &= \frac{5}{2} \phi_2, \\
v_0 &= -2Q_1 + 2\varepsilon \phi_1, \\
v_1 &= 2Q_0.
\end{align*}
\]

In the system of Eq.(14), the last six equations signify the equilibria of monsoon. Its solution process is as follows. From Eq.(14), we can get

\[
\begin{align*}
\phi_1 &= \frac{v_0 + 2Q_1}{2\varepsilon}, \\
u_1 &= \frac{3}{2\beta} \phi_1 = \frac{3}{4\beta \varepsilon} (v_0 + 2Q_1), \\
u_2 &= \frac{1}{\gamma - \frac{16}{9\sqrt{6}} Q_0} \left[ \beta Q_0 + \frac{1}{\sqrt{6} \beta \varepsilon} v_0^2 + \frac{2Q_1}{\sqrt{6} \beta \varepsilon} v_0 \right].
\end{align*}
\]

(15)

Put Eq.(15) into the third equation in Eq.(14), then

\[
Av_0^3 + Bv_0^2 + Cv_0 + D = 0.
\]

(16)

This is a cubic equation of \( v_0 \) about the South Asian monsoon; and its coefficients are taken as

\[
\begin{align*}
A &= \frac{35}{54} \frac{1}{(\gamma - \frac{16}{9\sqrt{6}} Q_0)\beta \varepsilon}, \\
B &= \frac{35}{27} \frac{Q_1}{(\gamma - \frac{16}{9\sqrt{6}} Q_0)\beta \varepsilon}, \\
C &= \frac{35}{9\sqrt{6}} \frac{\beta Q_0}{\gamma - \frac{16}{9\sqrt{6}} Q_0} + \frac{4Q_0}{3\sqrt{6} \beta \varepsilon} + \beta + \frac{3\gamma}{4\beta \varepsilon}, \\
D &= \frac{8Q_0 Q_1}{3\sqrt{6} \beta \varepsilon} + \frac{3\gamma Q_1}{2\beta \varepsilon}.
\end{align*}
\]

(17)

Working out a balanced solution of \( v_0 \) from Eq.(16), and \( \phi_1, u_1, u_2 \) from Eq.(15), then with the sixth equation in Eq.(14) we obtained \( \phi_2, \) finally obtained the equilibria of the South Asian monsoon.

4.1.2 SST equilibria

Eliminating \( v_1 \) and \( T_2 \) from the system of Eq.(14), the cubic equation about SST anomalies \( T_1 \) is obtained:

\[
a T_1^3 + b T_1^2 + c T_1 + d = 0.
\]

(18)

Here coefficients \( a, b, c, \) and \( d \) have the following
form:
\[ a = \frac{8\dot{a}^2 a_2^2}{9}, \]
\[ b = -\left( \frac{4\dot{a}a_2}{3\sqrt{6}} \right) \left( \frac{4Q_1 a}{\sqrt{6}} - \frac{8\dot{a}\beta (\varepsilon - a_1)}{3\sqrt{6}} u_1 + \frac{4\dot{a}a_2}{\sqrt{6}} \right) \]
\[ + \left( \frac{8\dot{a}}{9\sqrt{6}} (\varepsilon - a_1) u_1 - \frac{4\dot{a}Q_0}{3\sqrt{6}} \right), \]
\[ c = -\left( \frac{4Q_1 a}{\sqrt{6}} - \frac{8\dot{a}\beta (\varepsilon - a_1)}{3\sqrt{6}} u_1 \right) \cdot \left( \frac{8\dot{a}}{9\sqrt{6}} (\varepsilon - a_1) u_1 - \frac{4\dot{a}Q_0}{3\sqrt{6}} \right); \]
\[ d = -\left( \frac{4Q_1 a}{\sqrt{6}} - \frac{8\dot{a}\beta (\varepsilon - a_1)}{3\sqrt{6}} u_1 \right) \cdot H_2 - (2a_3 Q_0)
\[ -H_1)(\alpha S + \frac{2\dot{a}a_0}{9\sqrt{6}}). \]

On the other hand, we can derive the relationship
\[ T_2 = \frac{2a_3 Q_0 + \alpha S T_1 - H_1}{\frac{4Q_1 a}{\sqrt{6}} - \frac{4\dot{a}a_2}{3\sqrt{6}} T_1 - \frac{4\dot{a}(\varepsilon - a_1)}{3\sqrt{6}} u_1}. \]

The balanced solution \( T_1 \) is obtained from Eq.(18), and then \( T_2 \) can also be obtained from the above \( T_2 \) expression.

4.2 Stability of multi-equilibria

Linear stable method was used to discuss the stability of multi-equilibria. Therefore, eliminating \( \phi_1, \phi_2, v_1, \) and \( v_0 \) from Eq.(13), then we obtain:
\[
\begin{align*}
\frac{\partial T_1}{\partial t} &= (H_1 - 2a_3 Q_0) - \alpha S T_1 + \frac{4Q_1 a}{\sqrt{6}} T_2 \\
&= \frac{4\dot{a}\beta (\varepsilon - a_1) u_1 T_2}{3\sqrt{6}} - \frac{4\dot{a}a_2}{3\sqrt{6}} T_2, \\
\frac{\partial T_2}{\partial t} &= H_2 - \frac{4\dot{a}}{3\sqrt{6}} Q_1 T_1 - (\alpha S + \frac{2Q_0 a_0}{9\sqrt{6}}) T_2 \\
&= -\frac{8\dot{a}\beta (\varepsilon - a_1) u_1 T_1}{9\sqrt{6}} + \frac{4\dot{a}a_2}{3\sqrt{6}} T_2, \\
\frac{\partial u_1}{\partial t} &= -\left( \frac{16Q_0}{9\sqrt{6}} + \gamma - \frac{4\dot{a}^2 \beta}{9\sqrt{6}} \right) u_1 + \frac{70}{9\sqrt{6}} Q_1 u_2 - \frac{140\beta \epsilon}{27\sqrt{6}} u_1 u_2 - 2Q_1 u_2, \\
\frac{\partial u_2}{\partial t} &= \frac{8\dot{a} a_1}{3\sqrt{6}} u_1 + \left( \frac{16}{9\sqrt{6}} Q_0 - \gamma \right) u_2 + \frac{16\beta \epsilon}{9\sqrt{6}} u_2 + \beta Q_0.
\end{align*}
\]  

(19)

Suppose that a variable \( x \) can be written as the summation of its value in equilibria (\( \bar{x} \)) and its disturbed value (\( x' \)), then we have
\[
\begin{align*}
u_1 &= \bar{u}_1 + u'_1, \\
v_2 &= \bar{u}_2 + u'_2, \\
T_1 &= \bar{T}_1 + T'_1, \\
T_2 &= \bar{T}_2 + T'_2.
\end{align*}
\]

(20)

Inserting Eq.(20) into Eq.(19), we obtain the linearized equation as follows:
\[
\begin{align*}
\frac{\partial T'_1}{\partial t} &= A_{11} T'_1 + A_{12} T'_2 + A_{13} u'_1 + A_{14} u'_2, \\
\frac{\partial T'_2}{\partial t} &= A_{21} T'_1 + A_{22} T'_2 + A_{23} u'_1 + A_{24} u'_2, \\
\frac{\partial u'_1}{\partial t} &= A_{31} T'_1 + A_{32} T'_2 + A_{33} u'_1 + A_{34} u'_2, \\
\frac{\partial u'_2}{\partial t} &= A_{41} T'_1 + A_{42} T'_2 + A_{43} u'_1 + A_{44} u'_2.
\end{align*}
\]

(21)

Here
\[
\begin{align*}
A_{11} &= -\alpha S - \frac{4\dot{a}}{3\sqrt{6}} \bar{T}_2, \\
A_{12} &= \frac{4\dot{a} a_2}{3\sqrt{6}} (\varepsilon - a_1) \bar{u}_1 - \frac{4\dot{a}}{3\sqrt{6}} \bar{T}_1, \\
A_{13} &= -\frac{4\dot{a}}{3\sqrt{6}} (\varepsilon - a_1) \bar{T}_2, \\
A_{14} &= 0; \\
A_{21} &= -\frac{4\dot{a}}{3\sqrt{6}} Q_1 - \frac{8\dot{a}\beta (\varepsilon - a_1) \bar{u}_1}{9\sqrt{6}} + \frac{8\dot{a}}{3\sqrt{6}} \bar{T}_1, \\
A_{22} &= -\alpha S - \frac{2Q_0 a_0}{9\sqrt{6}}, \\
A_{23} &= -\frac{8\dot{a}\beta (\varepsilon - a_1) \bar{T}_1}{9\sqrt{6}}, \quad A_{24} = 0; \\
A_{31} &= 0, \quad A_{32} = 0, \\
A_{33} &= -\left( \frac{16Q_0}{9\sqrt{6}} + \gamma - \frac{4\dot{a}^2 \beta}{9\sqrt{6}} \right) - \frac{140\beta \epsilon}{27\sqrt{6}} \bar{u}_2, \\
A_{34} &= \frac{70}{9\sqrt{6}} Q_1 - \frac{140\beta \epsilon}{27\sqrt{6}} \bar{u}_1; \\
A_{41} &= 0, \quad A_{42} = 0, \\
A_{43} &= \frac{8\dot{a}}{3\sqrt{6}} + \frac{32\beta \epsilon}{9\sqrt{6}} \bar{u}_1, \quad \text{and} \\
A_{44} &= \frac{16}{9\sqrt{6}} Q_0 - \gamma.
\end{align*}
\]

Thereupon, in order to examine the linear stability of the equilibria in the dynamic system of Eq.(13), in general one should judge that the disturbed quantity of the equilibria develops or weakens along with the time, and this is determined by the characteristic values of coefficient matrix \( A \) in the system of Eq.(21):
\[
A = \begin{bmatrix}
A_{11} & A_{12} & A_{13} & 0 \\
A_{21} & A_{22} & A_{23} & 0 \\
0 & 0 & A_{33} & A_{34} \\
0 & 0 & A_{43} & A_{44}
\end{bmatrix}.
\]  

(22)
After extracting the four characteristic values in matrix $A$ completely, we make the following judgment. If the real parts of characteristic values are all smaller than zero, then the equilibria are linear stable, and if at least one real part is bigger than zero, then it is unstable, actually, this kind of equilibrium will not be observed in physics.

5. Influence of South Asian monsoon on seasonal variation of SST

Zhou et al. (1994) indicated that the SST seasonal variation is mainly influenced by the solar radiation seasonal variation, the oceanic current nature and dominant wind system seasonal variation. For discussing above, we take South Asian monsoon $v_0$ as a parameter, and the solar radiation heating $H_2$ as an adjusting parameter. $T_1$ can be worked out from Eq.(18), and we analyze SST equilibria and judge its stability. For calculating coefficients $a, b, c, d$ from Eq.(18), we take the values of parameters related with atmosphere and South Asian monsoon same as those in the paper by Zhu and Zhao (1987), and the values related with sea as follows: SST anomalies scale $T_0=10^\circ\text{C}$, $H_1=0.15$, $a_3=-0.06$, $a_S=0.2$, $a_2=0.5$, and $\lambda=-0.5$.

5.1 Influence of South Asian winter monsoon ($v_0<0$) on seasonal variation of SST

Comparing Curve I with Curve II from Fig.1, we can see that the South Asian winter monsoon gets stronger (absolute value is bigger), the winter SST gets lower (absolute value of negative anomalies is bigger), moreover the summer SST gets lower (anomalies are also smaller) too. But when the South Asian winter monsoon gets weaker, the winter SST gets higher, and the summer SST is also higher. Zhu and Zhao (1987) point out that the winter process is the main factor affecting SST condition in the summer half year, and plays an important role in summer SST change. Positive and negative anomalies of SST which formed in the winter, all can be preserved in the entire summer usually. This observation fact is similar to dynamics analysis results in this article.

Figure 1 also shows that when winter monsoon becomes stronger, the solar radiation heating needed for jumping from negative SST anomalies (fourth quadrant) upward to positive anomalies (first quadrant), is bigger. Meanwhile the $H_2$ is also bigger needed for jumping from positive SST anomalies (second quadrant) downward to negative anomalies (third quadrant).

5.2 Influence of South Asian summer monsoon ($v_0>0$) on SST seasonal variation

Comparing two curves in Fig.2, we can see that when summer monsoon is stronger (bigger), summer SST is then higher, and when summer monsoon is weaker, summer SST is then lower. But it is not obvious that the South Asian summer monsoon affects the winter SST. It also shows then when the summer monsoon is stronger, the solar radiation heating, needed by SST anomalies for jumping from positive value to negative, is smaller (absolute value of $H_2$ is bigger). But the solar radiation heating, which SST needs for jumping from negative to positive anomalies, is also bigger.

Fig.1. Relations among SST anomalies ($T_1$), the solar radiation heating ($H_2$), and the South Asian winter monsoon ($v_0$). ($\varepsilon=0.3$, $\gamma=0.2$, $Q_0=-0.04$, $H_1=0.15$, $a_3=-0.06$, $a_S=0.2$, $a_2=0.5$, and $\lambda=-0.5$. Curve I: $v_0=-0.2$, Curve II: $v_0=-0.4$, it denotes winter monsoon if $v_0<0$, the solid line stands for the linear stable equilibrium, and the dashed line stands for the unstable equilibrium.)
Fig. 2. Relations among SST anomalies ($T_1$), the solar radiation heating ($H_2$) and the South Asian winter monsoon ($v_0$). (Curve I: $v_0=0.2$, Curve II: $v_0=0.4$. Other explanations are same as in Fig.1.)

6. Influences of the action of coupled ocean-atmosphere and the SST gradient on South Asian monsoon

6.1 Influence of coupled ocean-atmosphere action on South Asian monsoon

we aim at the cases with and without the ocean-atmosphere interaction. The heating difference $Q_1$ between sea and land is taken as an adjusting parameter. Other parameters are taken as in Section 5 if no otherwise explanation. We calculate the coefficients of Eq.(16) and work out $v_0$, then analyze the South Asian monsoon equilibrium and its stability. The results are shown in Fig.3.

It is seen from the comparison of curves I and II:

(1) The ocean-atmosphere interaction causes the intensity of both South Asian summer monsoon ($v_0>0$) and winter monsoon ($v_0<0$) to strengthen, moreover when ocean-atmosphere exchange becomes intense, South Asian winter and summer monsoons become stronger. (The curves drawn by other values of ocean-atmosphere exchange coefficient are omitted in Fig.3.) The results that the coupled ocean-atmosphere term makes the winter and summer monsoons all strengthen indicate that thermal energy effect between ocean and atmosphere and the sensible heat exchange have the important influence on the monsoon intensity.

(2) Transform from the summer monsoon to the winter monsoon shows that (state curves jump downward from second quadrant to third quadrant), when there is no ocean-atmosphere exchange, the small sea-land thermal difference ($|Q_1| \approx 0.18$) can realize this kind of transformation, and when exchange does exist, this kind of transformation occurs in the point ($|Q_1| \approx 0.3$) at which the thermal difference value is bigger.

(3) From the states that the winter monsoon transforms to the summer monsoon (state curves jump from fourth quadrant upward to first quadrant), we can see when no ocean-atmosphere exchange exists, it occurs at the bigger value point ($|Q_1| \approx 0.21$), and when ocean-atmosphere exchange exists, it at the smaller value point ($|Q_1| \approx 0.12$).
It can be summarized from the above views of (2) and (3) that under the effect of ocean-atmosphere coupling, in terms of the absolute value $Q_1$, the land-sea thermal difference which makes the South Asian winter monsoon transform to summer monsoon is smaller than that in the summer monsoon to winter monsoon. These indicate that the ocean-atmosphere interaction causes the summer monsoon duration to exceed in the winter monsoon duration.

### 6.2 Influence of average SST meridional gradient on South Asian monsoon

In the above discussions, we took $\partial T_s/\partial y=0$ in Fig.3, but in fact, average SST meridional gradient $\partial T_s/\partial y \neq 0$, and it has the influence on the South Asian monsoon. Generally, annual mean SST in low latitudes reduces from south to north, $\partial T_s/\partial y <0$, thus $\lambda = a_3<0$. Curve I in Fig.4 corresponds to $a_3=-0.03$; Curve II corresponds to $a_3=-0.06$, namely the SST gradient is big. By comparing curves I and II, we can see that SST meridional gradient becomes greater, the winter monsoon becomes stronger (absolute value of $\nu_0$ becomes big), but the summer monsoon becomes weaker.

Meanwhile, the SST meridional gradient ($a_3$) also influences the magnitude of sea-land heating difference $(Q_1)$ needed for the winter and summer monsoon transformation. Considering the case of monsoon from summer to winter transformation: when $a_3=0$ (curve I in Fig.3), it transform at $|Q_1| \approx 0.2$; when $a_3=-0.03$, transforms at $|Q_1| \approx 0.17$, and when $a_3=-0.06$, transforms at $|Q_1| \approx 0.15$. That is $a_3$ (absolute value) becomes bigger and $|Q_1|$ becomes smaller. However, for the progress of winter monsoon transforming to summer monsoon, if the SST meridional gradient becomes bigger, the sea-land heating difference needed for transformation becomes also bigger. Obviously, the big SST meridional gradient tends to make summer monsoon change to winter monsoon, but make the winter monsoon change to the summer monsoon difficulty. The total effects are advantageous to the winter monsoon sustaining and strengthening. This is different from the above view that ocean-atmosphere interaction is advantageous to the summer monsoon long-term maintenance.

### 7. Conclusions

We discussed the interactions between South Asian monsoon and SST in the neighbor sea by using a simplified coupled ocean-atmosphere system and the theory of multi-equilibria and their stabilities, and the main conclusions can be drawn as follows:

1. When the winter monsoon becomes stronger, the concurrent winter sea-surface temperature becomes lower, and the sea-surface temperature in the next summer will be lower too, and vice versa. When the summer monsoon becomes stronger, the concurrent sea-surface summer temperature becomes higher, and vice versa. The effect of summer monsoon intensity on winter sea-surface temperature is not evident.

2. The air-sea interaction enables the winter and summer monsoons to strengthen, and it makes summer monsoon tend to sustain.

3. Sea-surface temperature meridional gradient strengthens winter monsoon, but weakens summer monsoon, and it makes winter monsoon tend to sustain. Sea-surface temperature meridional gradient and air-sea interaction affect the asymmetry of two equilibrium states of winter and summer monsoons in different way.
The discussions of the above three conclusions are as follows:

(1) There are a great many differences between South and East Asian monsoons (Chen et al., 1991). In South Asia, sea and land are distributed mainly in south-north direction. When winter monsoon comes, the off-shore flow is generated, it makes cool sea water up welling, and as monsoon becomes stronger, the flow off shore becomes stronger, seawater upturn more, and sea temperature becomes lower. Summer sea temperature is deeply affected by winter monsoon, and it shows by analyzing a lot of observation data (Gravgleva et al., 1982) that winter sea temperature characteristics can keep until the next summer to autumn. In this way, winter monsoon affects winter sea temperature firstly, and then it affects summer sea temperature by winter sea temperature. When winter monsoon comes in South Asia, sea current flows to coast, and warm seawater stacks at seacoast. As summer monsoon becomes stronger, warm seawater stacks more and more, and sea temperature becomes higher. But, why is the summer monsoon not obvious to the winter SST influence? This question waits for further studies.

(2) The results obtained by the simple model have verified certain observation facts from the interaction between South Asian monsoon and SST in neighbor sea, and the reasonable discussion is presented. The results are close to some observation findings of South China Sea monsoon (Wang and Ding, 1997; Yan, 1997), for example, the process of winter monsoon - South China Sea SST - summer monsoon ocean-atmosphere interaction. Indeed, South Asian monsoon is an extremely complex macro-scale circulation, which cannot be summarized by the model in this paper. Therefore, the results conform to the fact in any degree, we must use the quite perfect coupled ocean-atmosphere model as well as the more observed data to confirm and to compare. These questions need to be studied further.

REFERENCES


