Evolution of Asian Summer Monsoon and the Slowly Varying Disturbances

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ABSTRACT

The evolution of Asian summer monsoon is analyzed by means of decomposition of the atmospheric circulation into basic current and slowly varying monsoon disturbances. It is seen that the major slowly varying disturbances are two vortical couples, one located in the Indian Ocean and Indian Peninsula, and another in the Northern Hemispheric western Pacific Ocean and the East Asia. This indicates that the Asian summer monsoon consists of two branches, the Indian monsoon and the East Asian monsoon. Moreover, the analysis shows that the evolutionary processes of these two vortical couples are rather independent each other, and they all can be qualitatively interpreted by the dynamical theory of wave packet. The different stages of summer monsoon can be very well characterized by the location and intensity of the two vortical couples. Besides, in particular years there exists also some quasistationary wave train and its characteristics should be further analyzed.

Key words: Asian summer monsoon, Slowly varying disturbances, Vortical couple

I. INTRODUCTION

Monsoon is the most significant component of seasonal variation in the atmospheric general circulation.

The January mean circulation at 850 hPa can be considered as the typical winter monsoon in the lower troposphere, which is characterized by the existence of the stable and strong easterly wind belt occupying low latitudes from Indian Ocean to the vast western Pacific Ocean in the Northern Hemisphere, although there are also some minor structures. The July mean circulation at 850 hPa can be considered as the typical summer monsoon, which is characterized by the prevailing strong southwesterly wind belt extended from the equatorial Indian Ocean to the subtropical regions of East Asia (Indo–China, East China and Japan) and the vast area over the western Pacific Ocean, but the tropical western Pacific is occupied by the strong easterly wind. The difference between July and January mean circulations at 850 hPa is very similar to but stronger than that of July. This means that in the monsoon region the summer circulation is almost opposite to the winter circulation. The difference between July and January circulations can be considered as the maximum monsoon component of the atmospheric general circulation. In this paper we will deal with the problem of evolution of the monsoon component in Asia.

II. DECOMPOSITION OF THE CIRCULATION INTO BASIC CURRENT AND SLOWLY VARYING MONSOON DISTURBANCE

In order to represent the monsoon and its evolutionary process clearly, it is better to decompose the fields such as wind at 850 hPa into two parts, the basic current and the disturbance.

First of all a field $\psi(x,y,p\,;t)$, scalar or vector, is decomposed into a steady part $\psi^*\ (x,y,p)$, and a transient evolutionary part $\psi^{**}\ (x,y,p;\ t)$ as follows,

$$\psi(x,y,p;\ t)=\psi^{*}\ (x,y,p)+\psi^{**}\ (x,y,p;\ t)\ . \tag{1}$$

Second, it is desirable to subtract the zonal part ψ_z^{**} from ψ^{**} in order to enhance the display of the local structure of disturbances:

$$\psi^{**}\ (x,y,p;\ t)=\psi_z^{**}\ (y,p;\ t)+\psi'(x,y,p;\ t)\ . \tag{2}$$

We will call ψ' the disturbance, and $\bar{\psi}(x,y,p;\ t)\equiv\psi_z^{*}\ (x,y,p)+\psi_z^{**}\ (y,p;\ t)$ the basic part:

$$\psi(x,y,p;\ t)\equiv\bar{\psi}(x,y,p;\ t)+\psi'(x,y,p;\ t)\ . \tag{3}$$

Because we are interested in the evolution of general structure of the Asian summer monsoon, we will also neglect the minor structure such as the synoptic scale and high frequency variabilities. Therefore, in the present analysis the temporal filtered observational field will be taken

$$\psi(f)=\int_{t_1=t-\Delta t}^{t_2=t+\Delta t} f(x,y,p;\ t')W(|t-t'|)dt'\ , \tag{4}$$

where $W(t')$ is the weighting function,

$$\int_{-\Delta t}^{\Delta t} W(t')dt'=1\ , \tag{5}$$

and $2\Delta t$ = 15days in the present study. Besides, we take

$$\psi^{*}\ (x,y,p)\equiv\frac{1}{\Delta t^{*}}\int_{\text{April}}^{\text{September}}\psi(x,y,p;t)dt\ , \tag{6}$$

where $\Delta t^{*}=0.5yr$.

III. SLOWLY VARYING DISTURBANCES CHARACTERIZING THE EVOLUTION OF ASIAN SUMMER MONSOON

The maps of $\mathbf{v}'$ at 850 hPa from the late April to late July can very clearly show the major characteristics of the evolutionary process of Asian summer monsoon. Especially, during the summer monsoon period there are two couples of major anticyclone and cyclone in the field $\mathbf{v}'$ at 850 hPa, one couple is located in the Indian monsoon region, and another in the East Asian monsoon region. Figs.1–3 show the 1992 case.

Fig.1 shows the situation just before summer monsoon season (1–15, May). The two couples of vortices in the field $\mathbf{v}'$ have been formed. One couple (couple I) is located over the equatorial Indian Ocean, a strong cyclonic disturbance is centered slightly north to the Equator and accompanied by the westerly wind along the Equator, but the clock–wise circulation with a center at 10°S is rather weak. Another couple (couple II) consists of a cyclone located in the region of East Asia and an anticyclone centered over the western Pacific Ocean (at 25°N, 130°N). This anticyclone extends to the South China Sea and the vicinity where a secondary center is formed. The intensity of couple II is moderate. However, due to the existence of couple II there is rather strong southwesterly wind belt with early monsoon precipitation in the coastal region.

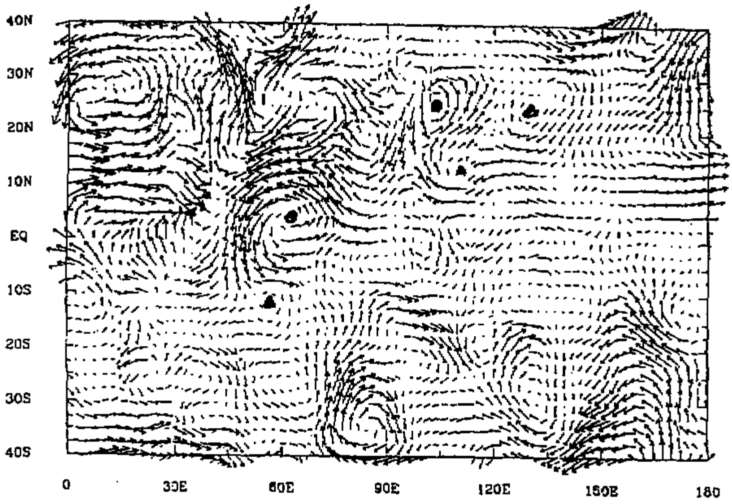

Fig. 1. Slowly varying (15 days weighted mean) disturbances for May 1–15, 1992. The vortical couples I and II are indicated by ● (cyclone) and ▲(anticyclone).

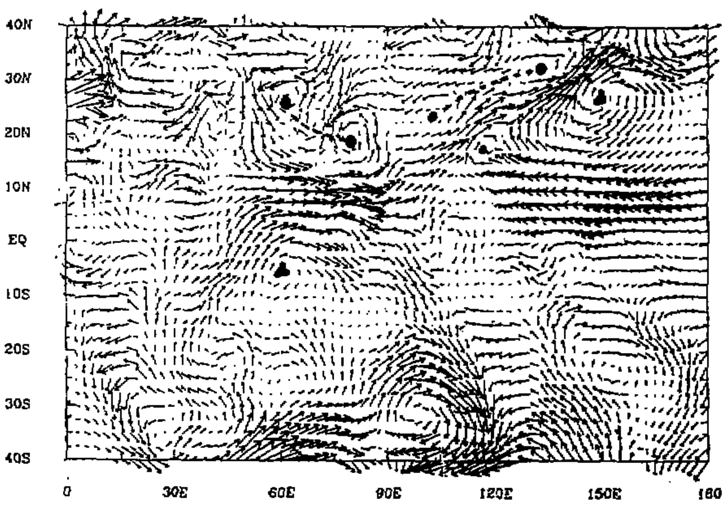

Fig. 2. The same as Fig. 1but for June 6–20, 1992.

Fig.2 shows the situation of the onset of summer monsoon (6–20, June). The major cyclone of vortical couple I moves to the north and located in Indian Peninsula, and the center of the clock–wise vortex moves slightly to the north and is very much intensified. As a consequence, there is very strong westerly jet over the South India and the tropical Indian Ocean in the Northern Hemisphere. Meanwhile, a newly formed anticyclone belonging to vortical couple II occupies vast subtropical western Pacific and results in a very strong easterly jet in the region of tropical western Pacific and a very strong southwesterly jet extended from the South China Sea to the South Japan. The cyclonic circulation of couple II is elongated and

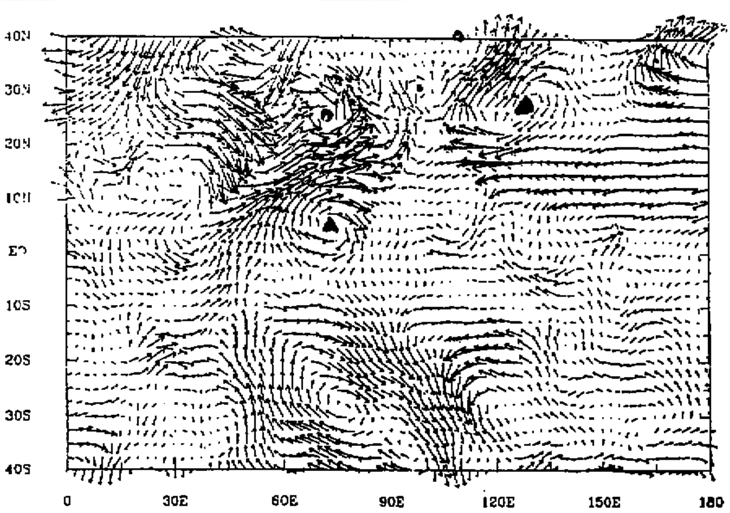

Fig. 3. The same as Fig. 1 but for July 16–30, 1992.

extended from Indochina to Japan. As a result, the summer monsoon rainy season comes into India and East Asia almost simultaneously.

Fig.3 shows the situation of typical summer monsoon case (the mature stage, 16–30 July). The vortical couple I is similar to Fig.2 but moves northwards slightly. It is very stably established. The vortical couple II moves northwards greatly, the anticyclonic ridge also extends to East China along 30°. As a consequence, the Mei–yu stops and the precipitation occurs in the North and Northeast China.

Comparing with the analyses made by Zeng et al. (1994) for 1992 case shows that the different stages and their major structures are consistently characterized by the vortical couples.

IV. PROPAGATION OF SLOWLY VARYING MONSOON DISTURBANCES

The evolutionary process of the two vortical couples clearly characterizes the structure and evolution of Asian summer monsoon.

First, the existence of two vortical couples indicates that the Asian summer monsoon consists of two branches, the Indian monsoon and the East Asian monsoon.

Second, each of the two branches, or each of the two vortical couples, has its evolutionary process. They are rather independent each other, although there is also some correlation.

Fig.4 shows the propagation of the two vortical couples. In Fig.4 the locations of cyclone and cyclonic centers for every 5 days interval are plotted.

It can be seen, that (a), the propagation of vortical couple I is rather simple, the major part of trajectory of both the cyclonic and anticyclonic vortices is directed northwards and with small eastward component, although the cyclone migrates eastward–westward after it reaches the North India. However, the trajectory of vortical couple II is complicated: there is a cyclone emitted successively from the source region and then propagated northeastwards; and the major anticyclone moves firstly westwards, then eastwards, then westwards again after finishing a spiral, and then rather rapidly moves northeastwards. And (b), the vortical couple I is rather established after it formed in early to middle May; but the vortical couple II is rather varying, each vortex undergoes a whole lifecycle, i.e. the processes of formation,

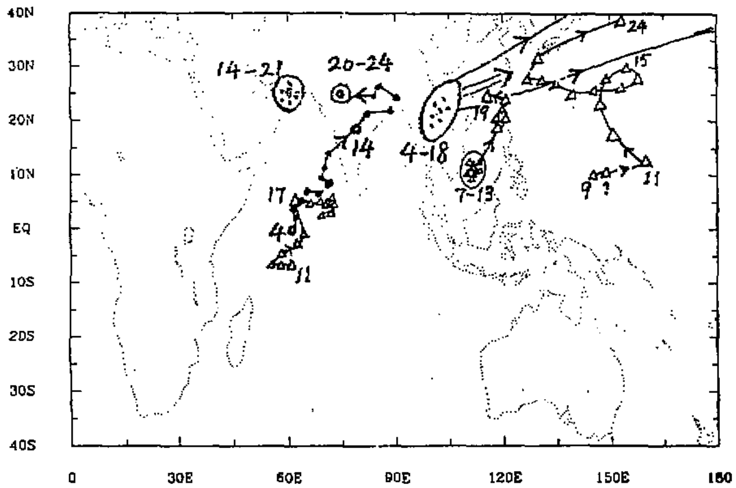

Fig. 4. Propagation of slowly varying (15 days weighted mean) disturbances for 1992. The number is the order every 5 day intervals: 1,2, ···, 24 stands for 1–15 April, 6–20 Apr., ··· , 26 Jul. –10 Aug. respectively. The anticyclonic and cyclonic centers are indicated by ▲and ●respectively.

intensification, propagation and decay or moving away. This character agrees with the facts that the East Asian summer monsoon possesses more variabilities.

The propagation of slowly varying disturbances can be qualitatively interpreted by the dynamic theory of wave packet in most cases. However, these disturbances must be forced by the heating because they are associated with heavy precipitation. They are also forced by the orography if located in the vicinity of high and complicated mountains such as Tibetan Plateau. In fact the dynamics of slowly varying disturbances can be described by the quasi–balanced model, and the most part of heatings comes from the release of latent heat due to the condensation of water vapor and can be approximately considered as proportional to the vertical velocity, and hence, reduces the Rossby deformation radius. Therefore, when a disturbance is located far from the high and complicated mountains, the theory shows that a wave packet

$$\psi'(x, y, \zeta, t) = \Psi(\varepsilon x, \varepsilon y, \varepsilon\zeta, \varepsilon t)e^{i\theta(x, y, \zeta, t)} \quad ,$$

with instantaneous and local amplitude Ψ and phase angle θ propagating with phase velocity $\mathbf{c}$ and group velocity $\mathbf{c}_g$ is as follows:

$$\begin{cases} c_x = \dfrac{m}{\sqrt{m^2+n^2}}(\bar{u} - \bar{\beta}_y / v^2) \ , \\ c_y = \dfrac{n}{\sqrt{m^2+n^2}}(\bar{v} - \bar{\beta}_x / v^2) \ , \end{cases}$$

$$\begin{cases} c_{gx} = \bar{u} - v^{-4}[2m(n\bar{\beta}_x - m\bar{\beta}_y) + v^2\bar{\beta}_y] \ , \\ c_{gy} = \bar{v} - v^{-4}[2n(n\bar{\beta}_x - m\bar{\beta}_y) + v^2\bar{\beta}_x] \ , \\ c_{g\zeta} = -2v^{-4}k[n\bar{\beta}_x - m\bar{\beta}_y] \ , \end{cases}$$

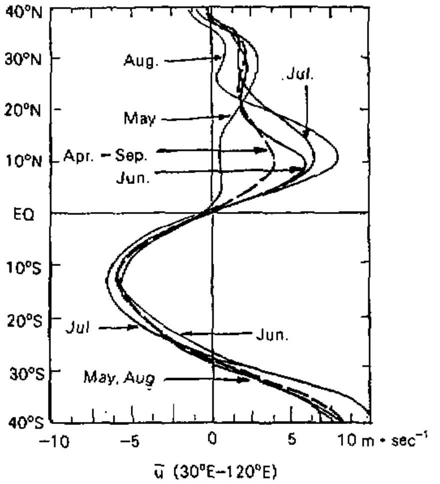

Fig. 5. Mean zonal wind averaged for 30°E–120°E, 1992.

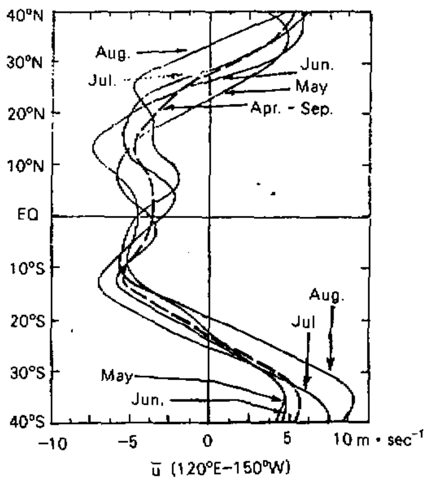

Fig. 6. The same as Fig. 5, but for 120°E–150°W.

and the centers (maxima and minima) of the disturbances propagate with some velocity between c and c_g (Lu, 1992; 1993). In these formulas all variables are nondimensional, $\bar{u}$, $\bar{v}$ are the components of basic flow, m, n, k are the instantaneous and local wavenumbers along x, y and ζ respectively, $\zeta = \ln p_s / p, p_s$ the surface pressure, and ε is a small parameter.

The basic current $(\bar{u}, \bar{v})$ plays an important role. These currents in the Indian monsoon region and East Asian monsoon region are different (Figs.5, 6). This is the primary cause leading to the different characteristics of the propagation of the two vortical couples. Secondary, the ray of vortical couple I is almost meridional orientated, according to the theory, both c_x and are small, the vortical couple I propagates almost northwards most of the time. However, the ray of vortical couple II tilts to the latitudinal cycle, and the anticyclone is superimposed first on an easterly basic current and then on a westerly basic current, therefore it moves first north–westwards or westwards and then eastwards. Besides, the spiral part is probably due to the temporal variation of the line with and can not be simply interpreted by the theory. On the other hand, the propagation of the transient cyclone can be well predicted by the theory but the local basic current is different.

It should be pointed out that the migration of the cyclone of vortical couple I and the stationary nature of the mother cyclone of vortical couple II located in Southwest China and Indo–China can be interpreted only if the orographic forcings are taken into account.

V. ANOTHER KIND OF SLOWLY VARYING DISTURBANCES IN THE MONSOON REGIONS

Our analysis of observational data for 1980–1989 shows that the general picture for every year is similar to that shown by Figs.1–4, although there are some interannual variabilities of the location, intensity and the orientation of the two vortical couples and so on, which characterize the interannual variabilities of Asian summer monsoon.

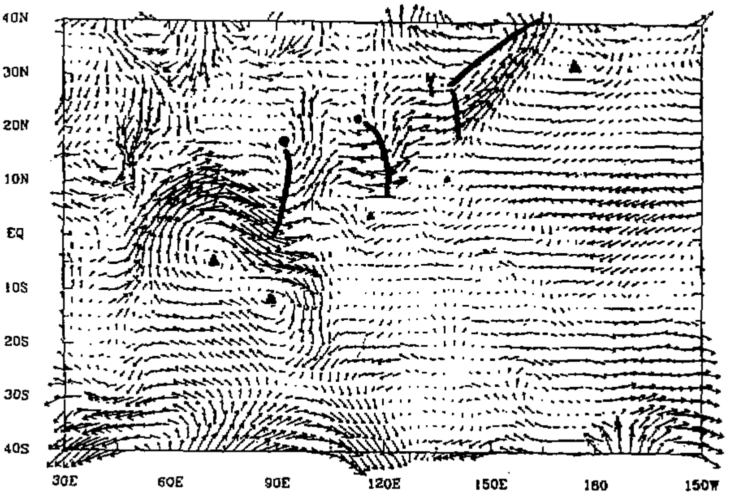

Fig.7. The same as Fig. 1, but for June 21–July 5, 1987.

It should be pointed out that there exists another kind of slowly varying disturbances in some particular years besides the vortical couples. Fig.7 is for the case of 1987. It is seen that along the southwesterly low level jet there is a well developed quasistationary wave train. Its dynamic properties and synoptic–climatic significance need to be analyzed, and the theory of forced wave packet or the theory of wave packet in forced mean flow (Zeng, 1985) might be applied.

Appendix

Governing equation for the baroclinic model is given by

$$\left(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x}+\bar{v}\frac{\partial}{\partial y}\right)\left[\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial \zeta^2}-H\right)\psi'\right]+\bar{\beta}_y\frac{\partial \psi'}{\partial x}-\bar{\beta}_x\frac{\partial \psi'}{\partial y}=F \ ,$$

where $\zeta \approx \ln p_s p, H \approx 1/4, \bar{\beta}_y \equiv \partial\bar{q}/\partial y, \bar{\beta}_x \equiv \partial\bar{q}/\partial x, \bar{q}$ is the potential vorticity of the basic current, and F is the source term (Zeng, 1985).

Wave packet approximation of the solution to the equation is

$$\psi' = \Psi(\varepsilon x, \varepsilon y, \varepsilon\zeta; \varepsilon t) \times e^{i\theta(x,y,\zeta\, t)} \ ,$$

where

$$\begin{aligned}
&\theta \approx k\zeta + \sqrt{m^2+n^2}\,(\xi - ct) \ , \\
&\xi \equiv (m^2+n^2)^{-1/2}(mx+ny) \ , \\
&c = (m^2+n^2)^{-1/2}[m(\bar{u}-\bar{\beta}_y v^{-2}) + n(\bar{v}+\bar{\beta}_x v^{-2})] \ , \\
&v^2 = m^2+n^2+k^2+H \ , \\
&m \equiv \frac{\partial\theta}{\partial x}, \quad n \equiv \frac{\partial\theta}{\partial y}, \quad k \equiv \frac{\partial\theta}{\partial\zeta}, \text{ and } \sigma \equiv -\frac{\partial\theta}{\partial t}, \\
&c \equiv (m^2+n^2)^{-1/2}\sigma \ .
\end{aligned}$$

ε small positive parameter.

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