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EAST ASIAN SUMMER MONSOON—A CASE STUDY

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East Asian summer monsoon for 1992 is analyzed. It is shown that the East Asian summer monsoon can be tracked back to the "southeast monsoon" (southeastly wind at surface and southwestly wind at 850hPa) created during spring and connected with the large seasonal variation of atmospheric general circulation over the tropical and subtropical western Pacific Ocean. During early and middle summer after the onset of Indian summer monsoon, the East Asian summer monsoon is modified and combined with the Indian summer monsoon as a whole southwestly wind system, but the influence of tropical and subtropical flow from western Pacific Ocean and South China Sea is also very clear. According to the similarity of patterns the division of seasons of atmospheric circulation also shows that the summer pattern comes into India and East Asia almost simultaneously. The Indian monsoon region and East Asian monsoon region are indeed characterized by large seasonality (normalized seasonal variation). The other regions with large seasonality are tropical western Pacific Ocean and Australian monsoon region (both are directly connected with East Asian monsoon region), as well as those separated regions which are coincided with the seasonal migration of subtropical high over Pacific Ocean in both Northern and Southern Hemispheres. The monsoon rainfall belt is along the so-called shear line which is an elongated narrow zone with large wind shear and possesses character of quasistationary front (Mei-yu front). Superimposed on the shear line there are mesoscale disturbances causing heavy precipitation.

Key Words: East Asian Summer Monsoon; Southwest Monsoon; Tropical & Sub-tropical Flow; Mesoscale Disturbances; Mei-yu Stage; Climate Dynamics

Introduction

Monsoon is a climatological concept which expresses the most significant seasonal variation of climate regime in the tropical-subtropical zone of planetary scale, although it is still difficult to give a precise definition. Once the monsoon is a tropical-subtropical phenomenon of planetary scale associated with the seasonal variation, it is not difficult to imagine that the monsoon is closely related or strongly influenced by the interaction of air flows in the two, Northern and Southern, Hemispheres, and by the continent-air-ocean interaction, because the first cause of seasonal cycle is due to the periodical annual variation of solar declination between Northern and Southern Regressions, and that there is large seasonal variation of thermal contrast between the continent and ocean. However, the problem on the nature, especially the cause of monsoon, is still a big argument in the present time due to its complexity and the lack of adequate observational data and methods for their analyses.

Indian monsoon, i.e. the monsoon over Indian Peninsula and the Indian Ocean, is the typical one, and is the first branch of the monsoon which has been investigated by means of modern meteorology. The origin of Indian summer monsoon, the propagation of cross equatorial current, the geometrical constraints of East Africa and Tibetan Plateau, the onset of summer monsoon and its relation to the starting of rainfall and to the seasonal transition of planetary scale atmospheric general circulation and so on have been well studied due to the good observation data, especially after MONEX.

It is well known that East Asian summer monsoon is that branch of monsoon which is far extended into the north even more than 45°N. However, due to its complexity of nature and the lack of adequate observational data over the vast region of western Pacific Ocean, this branch has not been well understood by the world community of meteorologists. Even in the present some meteorologists still think that the East Asian summer monsoon is only a direct extension of the Indian summer monsoon, i.e., the extension of south-west wind coming from the Indian Ocean and passing Indian Peninsula, although many Chinese, Japanese and other scientists, starting from Chu's classical work[1], have indicated, that the Mei-yu (summer monsoon rainfall in Yangtze River Valley) and Baiu (in Japan) are due to the confluence of south-west flow (tropical air mass), south-east flow (tropical-subtropical air mass) and north-west and north-east flow (cold air mass), and that the strongest winter monsoon, in contrary to the summer monsoon, can propagate from the East Asian continent into the region south to Philippines and even penetrate into Southern Hemisphere (Li, 1935)[2]. This means that at least one channel of air mass exchange between Northern and Southern Hemispheres is located over the equatorial western Pacific Ocean.

Indeed, in the last 30 years, after improvement of observation by the satellite in the vast region of western Pacific Ocean, especially the period of TOGA Program, and some intensive investigations, it is revealed that large part of air flow considered as summer monsoon and reaching the East Asian continent can be tracked back to the region covered South China Sea and the vicinity of Philippines and to the western Pacific Ocean, although some other part comes from Indian Ocean. There exists a negative correlation between the two branches of summer monsoon, the Indian monsoon and East Asian monsoon. The structure of East Asian monsoon is more complicated and variable due to the strong interaction of the three flows mentioned above, and that there may be more transport of heat and other elements in that region and, consequently, may have significantly mutual influence with the variability of global general circulation. For example, some preliminary studies have shown that there is interaction of winter-summer monsoons and the ENSO. It is expected that the study on the East Asian monsoon, its relationship to the Indian monsoon, other branches of monsoon, and the global general circulation will be intensified.

In this paper, the authors give a case study (year 1992) in order to demonstrate clearly some basic pictures and characteristics of East Asian monsoon, sch as the seasonality (measure of seasonal variation), division of seasons, typical patterns of summer monsoon circulation and the associated rainfall belts during different stages of their evolution, the vertical structure of summer monsoon, and the role of weather and mesoscale systems in the maintenance of large and planetary scale monsoon flow.

The Seasonality

Monsoon climate is characterized by a large amplitude (variability) of seasonal cycle of wind, rainfall, and, may be, other meteorological elements. We first define the seasonality of a function or vector $F(\theta, \lambda, p, t)$ varying with time t and defined at the geographic point (θ, λ) and on a given p isopressure surface as follows:-

Let F_w and F_s are the typical fields of F for winter time and summer time respectively. For example, F_w and F_s are taken as January and July monthly means respectively. Obviously, $\Delta = |F_w - F_s|$ is the "amplitude" of seasonal cycle if F_w *and* F_s are indeed two extreme regimes of F. Let $\overline{F}$ be the annual mean of F, or simplify taken as $(F_w + F_s)/2$, the seasonality δ of F for a given area S can be defined as the normalized variability.

$$\delta \equiv \frac{\|\Delta\|}{\|\overline{F}\|}, \qquad \ldots (1)$$

where $\|\bullet\|$ is the norm, for example,

$$\|F\|^2 = \frac{1}{S}\int\int_S |F|^2 a^2 \sin\theta d\theta d\lambda, \qquad \ldots (2)$$

a is the radius of the Earth, and S denote the area and its measure both. S can also denote a point (θ, λ), if $\overline{F}(\theta, \lambda, p)$ is different from zero.

Figs 1-3 represent the January mean wind $\mathbf{v}_w$, July mean $\mathbf{v}_s$, and $\mathbf{v}_s - \mathbf{v}_w$ at 850hPa for 1992 respectively. Fig. 4 is the seasonality δ of wind at 850hPa for 1992 and is calculated for every grid point in the latitudinal zone 40°S-40°N. Note that in Fig. 4 we take $\bar{\mathbf{v}} \equiv (\mathbf{v}_s + \mathbf{v}_w)/2$, and that the annual mean wind field is similar to it, hence the associated δ pattern (not shown here) is also similar to Fig. 4. It can be seen that in all maps of $\mathbf{v}_w$, $\mathbf{v}_s$ *and* $\mathbf{v}_s - \mathbf{v}_w$ the meridional

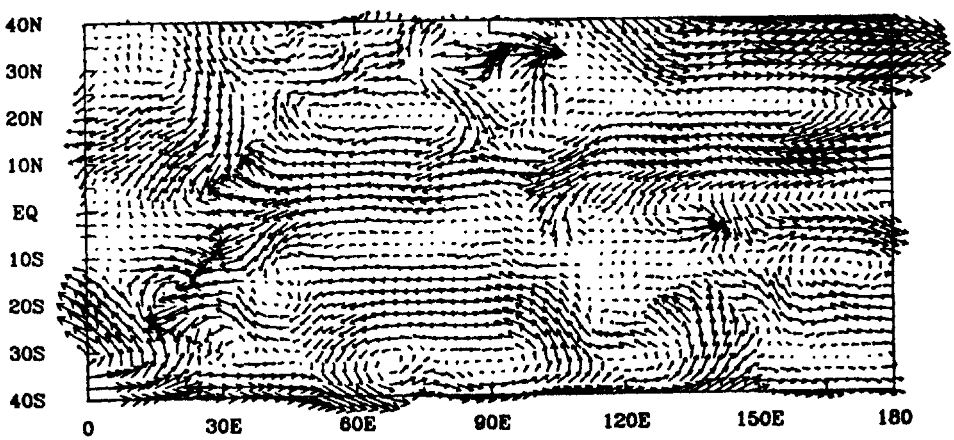

Fig 1 January mean wind $\mathbf{v}_w$ at 850hPa for 1992.

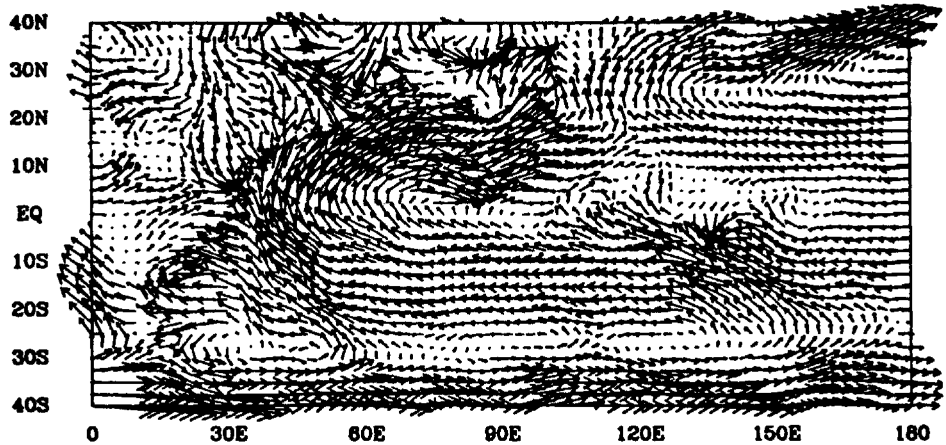

Fig 2 July mean wind $\mathbf{v}_s$ at 850hPa for 1992

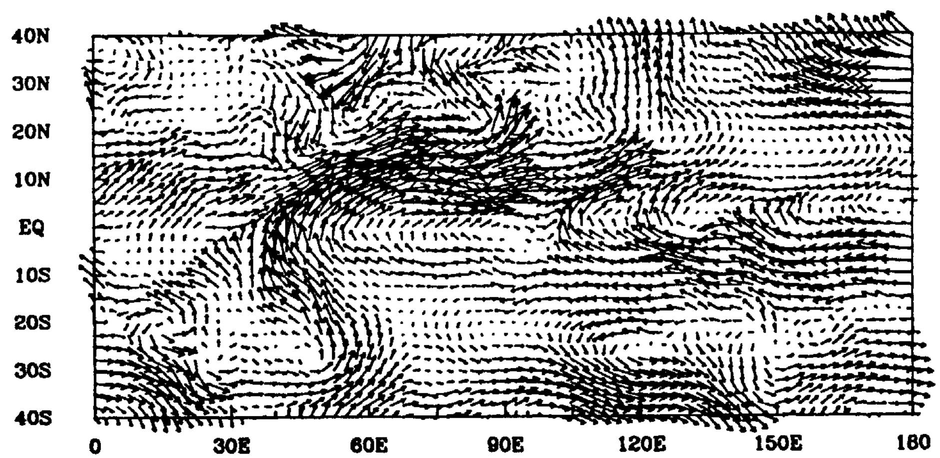

Fig 3 The difference of July from January means winds $\mathbf{v}_s - \mathbf{v}_w$ for 1992.

component is significant in the Indian monsoon region and East Asian monsoon region where the Δ and δ are also pronounced, and that the East Asian monsoon region is connected (extended) to a region with equally large or even larger Δ and δ which is located from 125°E to 165°W and from 15°S to 10°N (not uniform) and is correspondent to the Australian monsoon region and ITCZ with pronounced seasonal cycle in the Pacific Ocean. In other place of tropical zone both Δ and δ are small or not competitive even in the African monsoon and South American monsoon regions. However, in association with the seasonal migration of subtropical high over Pacific Oçean in both the Northern and Southern Hemispheres where Δ and δ are also pronounced, although they are not considered as monsoon regions in the literature.

It is clear in Figs 1-3, there are two channels of cross-equatorial flow, one (Channel 1) located in the Indian Ocean and associated with Indian monsoon, the other (Channel 2) located in the equatorial region near South China Sea and Philippines and connected with East Asian monsoon. Channel 1 is very intensive during summer, while Channel 2 is clear both in summer and winter, especially during winter. Due to the large difference $\mathbf{v}_s - \mathbf{v}_w$ in Channel 2 there δ is also large (not uniform).

One might also consider the three dimensional structure of seasonality of atmospheric general circulation by computing $\Delta(\theta, \lambda, p)$ and $\delta(\theta, \lambda, p)$.

Seasonal Transition of Atmospheric General Circulation

The seasonal transition and division of seasons of atmospheric general circulation can be determined by the following method (Zeng and Zhang, 1991)[3].

Denoting $\overline{F} \equiv (F_s + F_w)/2$, we calculated the depature $F'(\theta, \lambda, p, t) \equiv F(\theta, \lambda, p, t) - \overline{F}(\theta, \lambda, p)$, $F'_w \equiv F_w - F$, and $F'_s \equiv F_s - \overline{F}$. Obviously, $F'_s = F'_w$. The simi-

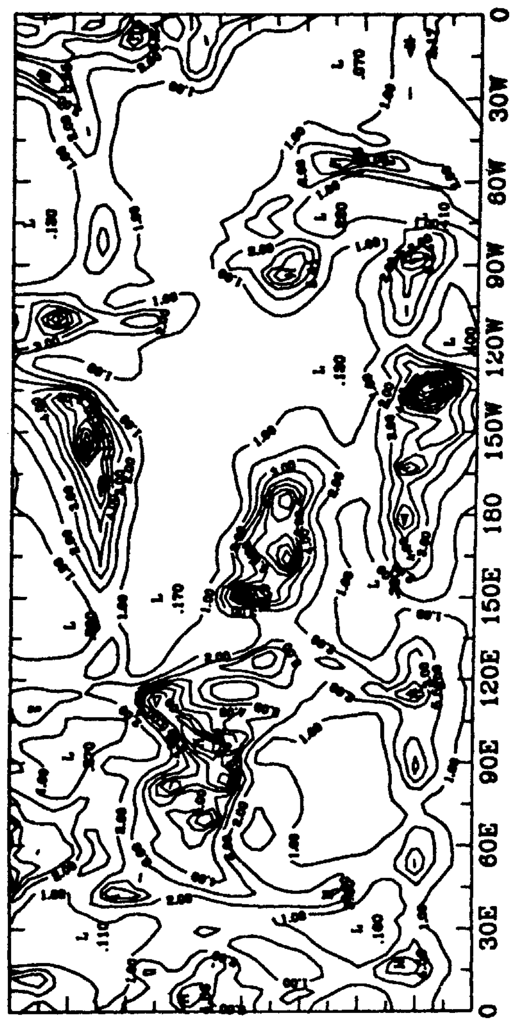

Fig 4 The seasonality δ (see (1)) of wind at 850hPa for 1992.

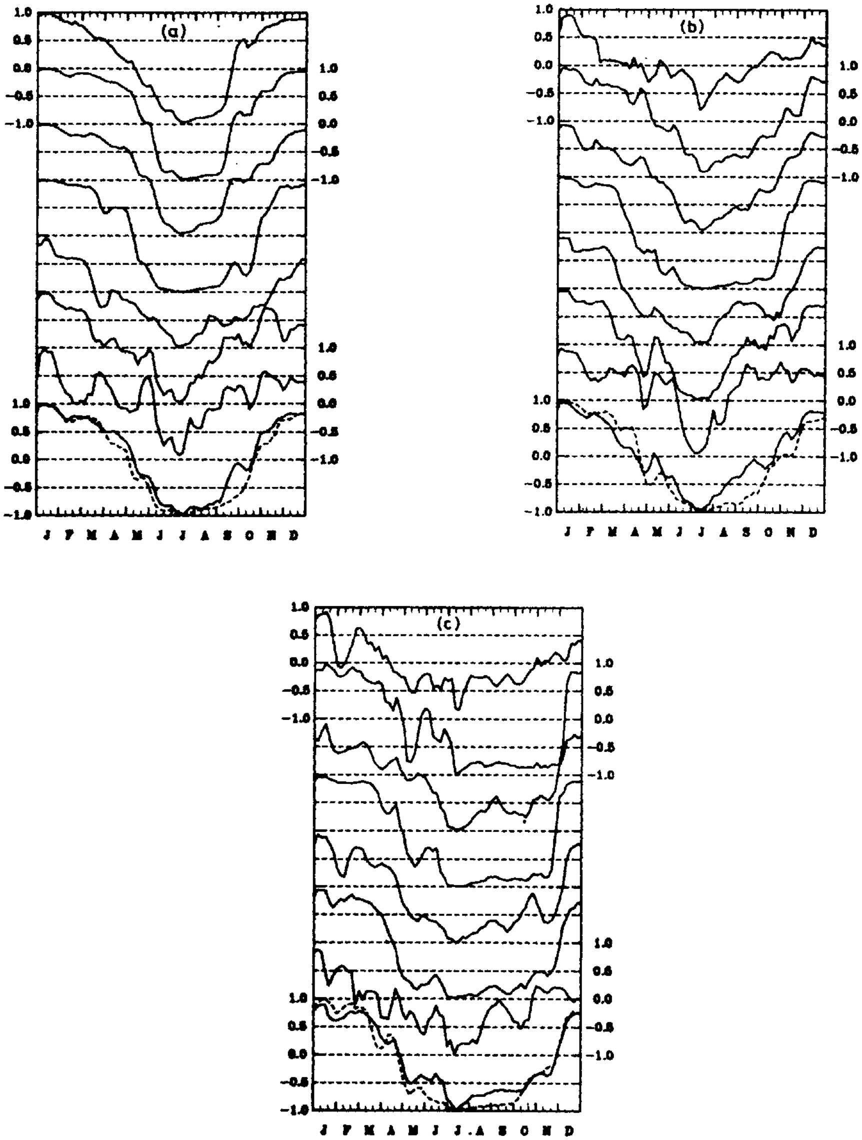

Fig 5 The curves of $R(t)$ which defines the division of seasons for different areas. (*a*) 60°E-100°E, (*b*) 100°E-140°E, (*c*) 140°E-160°E. From above to below: 40°N-20°N, 30°N-10°N, 20°N-0°N, 10°N-10°S, 0°-20°S, 10°S-30°S, 20°S-40°S, and 40°N-40°S respectively. The solid line for wind at 850 hPa, and the dashed for wind at 300hPa.

larity of F'_w and $F'(\theta, \lambda, p, t)$ for a given area S is defined as the normalized inner production

$$R(t; p) = (F', F'_w)/[\|F'\| \cdot \|F'_w\|], \qquad \ldots (3)$$

where the inner production (F', F'_w) is given by

$$(F', F'_w) = \frac{1}{S}\iint_S F' \cdot F'_w a^2 \sin\theta d\theta d\lambda \qquad \ldots (4a)$$

if F is a scalar function, or by

$$(F', F'_w) = \frac{1}{S}\iint_S \mathbf{F}' \cdot \mathbf{F}'_w a^2 \sin\theta d\theta d\lambda, \qquad \ldots (4b)$$

if F represents a vector, for example, the wind **v**.

It is clear, that typical winter regime is identical to $R=1$, and typical summer regime is $R=-1$. We can divide seasons as follows: $0.5 < R \leqslant 1$ – winter, $-1 \leqslant R < -0.5$ – summer, $-0.5 < R < 0.5$ – transitional seasons (spring or autumn). Note, precisely speaking, the regime $-0.5 < R < 0.5$ is correspondent to autumn only if F_w is taken as the typical field for the following winter. Besides, the ratio T_{sp}/T_w is a measure of the abruptness of transition from winter to summer, where T_{sp} and T_w are the duration times of spring and winter respectively. ively.

Taking F as the 15 day running mean of wind **v** for 1992,. Fig. 5 shows the $R(t, p)$ at different levels p(mostly $p=850$hPa, and some for $p=300$hPa) and for different areas S from 60°E to 160°E and from 40°S to 40°N with interval 40° along the latitudinal cycle (except for 140°E-160°E) and 20° along the meridian. It can be seen, that according to our definition of seasons of atmospheric general circulation, in the wind field at 850hPa we have (1) Spring comes ($R(t)=0.5$) earlier on about March 15 (from February 10 to April 10 in different subsector) in the sector (100°E-140°E, 40°S-40°N) where the East Asian monsoon region is located, on about March 25 in the sector (140°E-160°E, 40°S-40°N) but with earliest date, February 1, in the subsector (100°E-140°E, 20°S-0°S), and on about April 10 in the sector (60°E-100°E) where the Indian monsoon region is located with latest day, May 5 to 10 in the subsectors (60°E-100°E, 0°N-20°N) and (60°E-100°E, 10°N-30°N); (2) Summer comes ($R(t)=-0.5$) earliest from April 20 to May 10 in the subsector (140°-160°E, 0°S – 30°S), propagates north-westly into the subsectors (100°-140°E, 20°S-10°N) and (60°E-100°E, 10°S-10°N) on about May 15, and then northwards into 30°N, China and India, simultaneously on about June 10 and into North China, Japan and northeast area about July 10; (3) in the Northern Hemisphere autumn comes ($R(t)=-0.5$ after the summer) in the sector (60°E-100°E) earlier on about September 10, in the sector (100°E-140°E) on about September 25 (from September 20 in the north to October 25 along Equator) with exception for the subsector (100°E-140°E, 20°N-40°N) where the summer lasts for a very short time in 1992 and ended on July 25, and in the sector (140°E-160°E) much later than October 25 (from October 25 to December 5) except for the subsector (140°E-160°E, 20°N-40°N) where the summer is ended also early. Besides, the seasonal transitions are not synchronic in the vertical, for example, summer comes much earlier at 300hPa than at 850hPa, but is ended on the same time or even later. Note, at 300hPa summer comes as early as on May 1 in the sector (140°-160°E, 40°S-40°N).

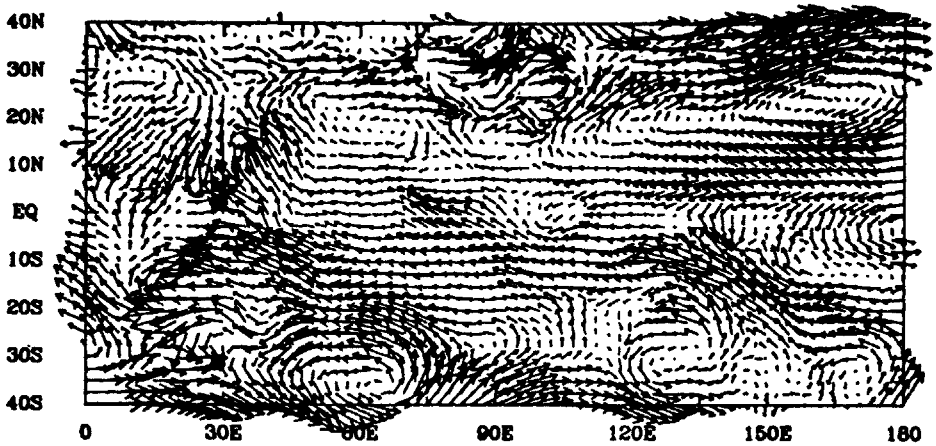

Fig 6*a* The mean wind field at 850hPa for April 16-30, 1992.

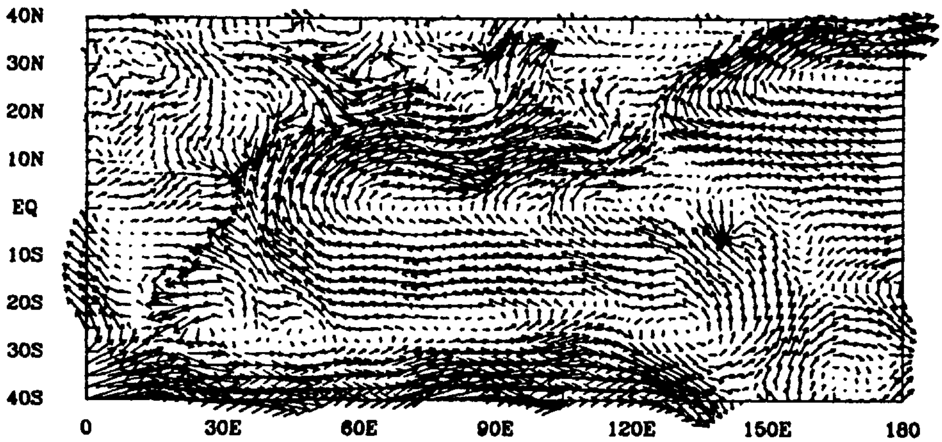

Fig 6*b* The same as Fig. 6*a* but for June 16-30.

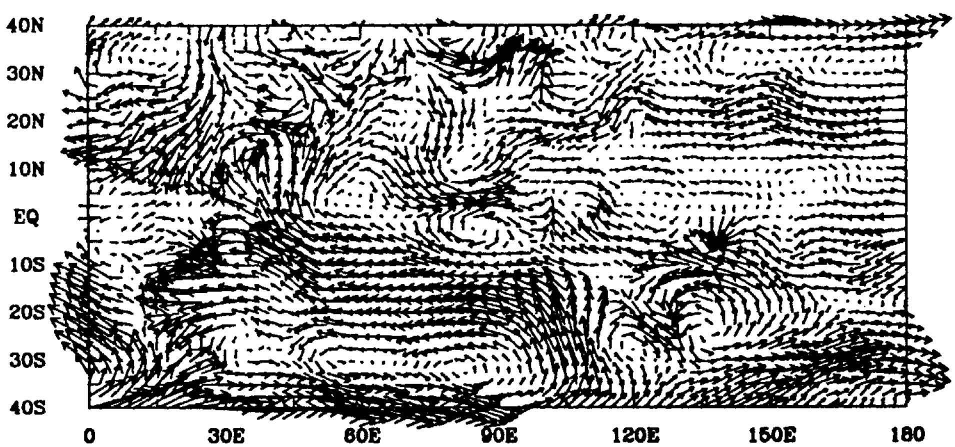

Fig 6*c* The same as in Fig. 6*a* but for September 16-30.

According to the results described in these two sections, it can be imagined that East Asian summer monsoon is more closely related to the seasonal variation of atmospheric generation circulation on the western Pacific Ocean, although connected and strengthened by the Indian summer monsoon.

Note, that the onset and the northern boundary of summer monsoon were determined by other criteria, for example by surface θ_{sw} (Tu and Hwang, 1944)[4] or by the so-called monsoon index (Tao *et al.*, 1987, 1988)[5,6] and that the division of seasons of general circulation and the abrupt seasonal transition were determined by the jet location and other characteristics[7-9]. Our new results are agreed with the previous ones to a large extent. May be due to the EI Nino or other interannual variations in 1992 spring comes too early and lasts for too long time, the transition from winter to spring over East Asia is not abrupt, although from $R=0$ to $R=-0.5$ is more or less abruptly. However the transition from summer to winter in 140°E-160°E region is very abrupt.

Different Stages of East Asian Monsoon

According to the division of seasons by our new method we can also divide the East Asian monsoon into several stages which are agreed to some extent with the definition of common sense. Obviously, the typical summer monsoon regime and typical winter monsoon regime are identical to $R=-1$ and $R=1$ and represented by the July mean and January mean respectively. The typical spring and autumn are identical to the first event with $R=0$ and last event with $R=0$ and given by April 16-30 and September 16-30 respectively for 1992 as can be seen in Fig. 6. As here we are mostly interested in the summer monsoon we will discuss summer season and the adjacent seasons in some detail.

(*a*) *Southeast Monsoon Stage*

During the whole spring and early summer, lasted from late March to the beginning of Mei-Yu season in the Middle June, there are southeasterly wind (so-called southeast monsoon in Chinese literature) at the surface and southwesterly wind at 850hPa in the southeast part of China and the adjacent area over ocean. This is the west wing of big anticyclonic gyre of wind system over the vast region of western Pacific Ocean. The strong winter monsoon over South China Sea completely ceases. The precipitation region occupies south China and extended to the western Pacific Ocean. The other rainfall belt is associated with ITCZ and its extension, located in Thailand, Malaysia, Philippines, Indonesia and their vicinity. The character of the precipitation is of quasi-stationary front type in the former region but of convective type in the later. Fig **6a** and Fig. **7a** are the typical patterns of 850hPa wind and precipitation. These figures are obtained by averaging for April 16-30, 1992 and associated with $R=0$. It can be seen that the southwest wind at 850hPa over southeast China is closely connected with easterly wind over tropical western Pacific Ocean, but clearly separated from the cross equatorial flow over Indian Ocean. The late just begins in the later April and is limited in a localized area along the Equator.

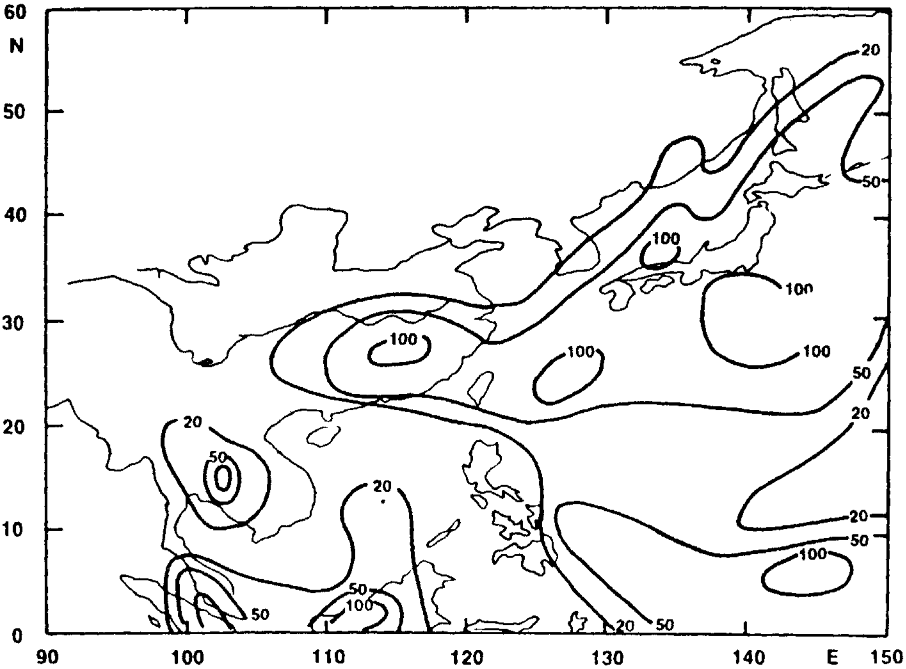

Fig 7*a* The accumulated precipitation for April 16-30, 1992. The unit is mm.

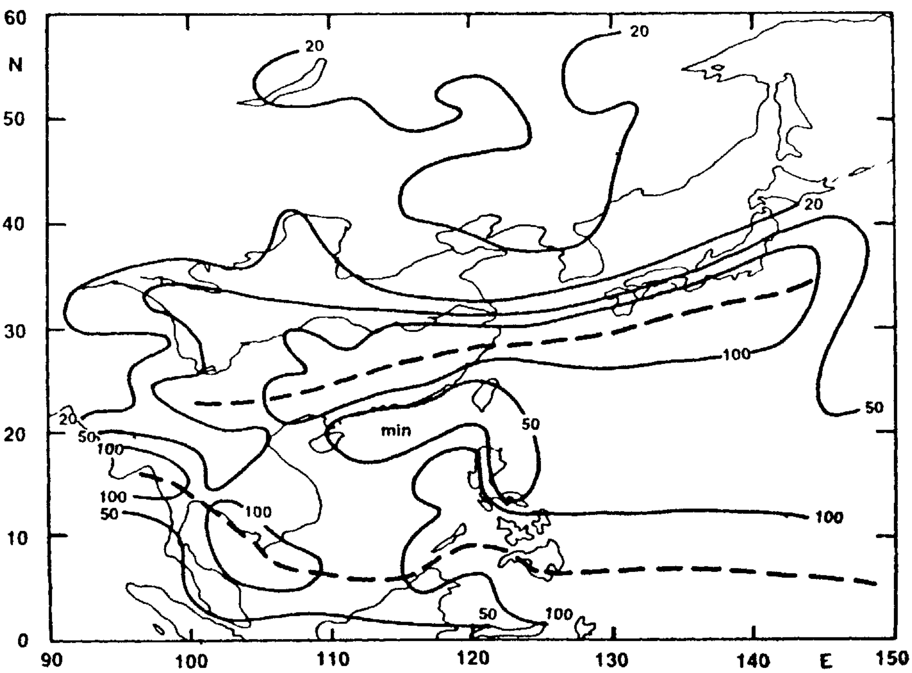

Fig 7*b* The same as Fig. 7*a* but for June 16-30. The belt with maximum precipitation is indicated by heavy dashed line.

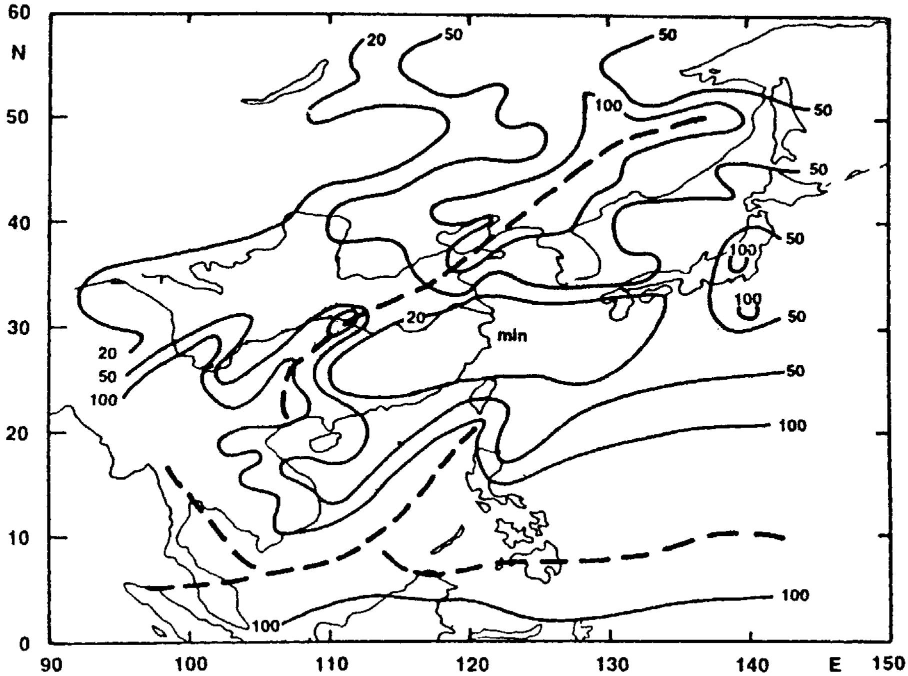

Fig 7*c* the same as Fig 7*b* but for July 16-30.

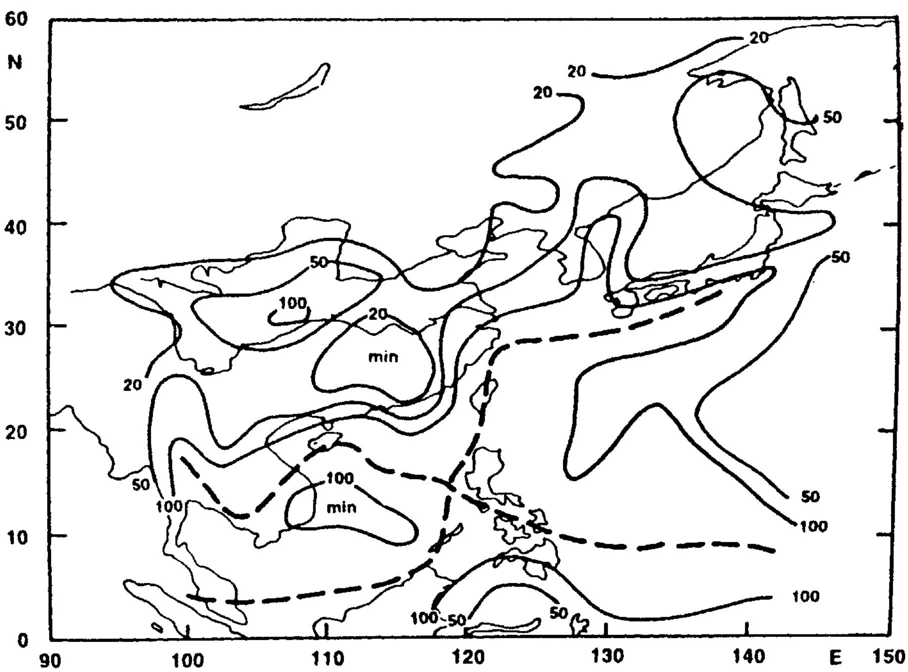

Fig 7*d* The same as Fig. 7*b* but for September 16-30.

(*b*) *Mei-yu Stage*

The southwestly wind at 850hPa over south China (hereafter referred as wind system A) is gradually intensified, extended northeastward, southward and southwestward and occupies very large region. During June 1-15, Indian monsoon (wind system I) comes into South India and is extended into Bay of Bengal. At the same time the cross equatorial southly wind frequently appears over South China Sea and the vicinity, and the ITCZ moves to the Northern Hemisphere. All these strengthen wind system A and make it connected with wind system I, and result in a intensive southwestly wind belt extended to Somalian jet Associated with wind system A there is southeasterly or southwesterly wind at the surface. Starting from Middle June and lasted for about 25 day or so, the quasistationary front migrates along Yangtze River to Hai River (30°N approximately) and extends to Japan in normal year but slightly south to them in 1992 (may be due to the influence of El Nino), and results in a bulk precipitation (Mei-Yu) there, Fig. 6*b* and Fig. 7*b* are the typical patterns obtained for June 16-30. Figs 8-10 show one example of synoptic analysis during Mei-yu period.

(*c*) *Hot Summer Stage*

After Mei-yu period the subtropical high over western pacific Ocean moves northward, its ridge is extended into East China along 30°N, and the ITCZ moves into 10°-20°N in the region (120°E-150°E) of western pacific Ocean. In association there is strong southwesterly wind system (system B) in the region centered at (130°E, 45°N)—Northeast China, south to it there is southeasterly wind, and over whole south China (south to 30°N in the normal year, but slightly more south in 1992) southwestly wind is prevailing from surface to the level higher than 850hPa (the wind field is not given here, it is similar to Fig. 2). The precipitation region jumps to North China or even Northeast China, Mei-yu is stopped, and hot weather occupies south China (see Fig. 7c), except for the case that typhoon is formed in the ITCZ and moves into mainland.

(*d*) *Autumn with Clear Sky Stage*

In August the subtropic high as well as the major precipitation region moves to or remains at their extreme north location, and due to ITCZ activities including typhoons there is another but separated precipitation zone in the tropic-subtropic zone over western Pacific Ocean and extended to the coast region of southeast China. Starting from September the summer monsoon regresses southward and weakens down, cool air mass with westerly-to-northwesterly wind component at the surface and in the lower troposphere frequently moves from the north to East Asian continent and completely occupies it in the late September. There is cool weather with clear sky and no or very few precipitation. Fig. 6*c* and Fig. 7*d* are the typical patterns (September 16-30).

The Structure of Mei-yu Weather System

The synoptic structures of East Asian summer monsoon have been thoroughly analyzed by Hsieh *et al.*[10,11] and many Chinese meteorologists. It is revealed

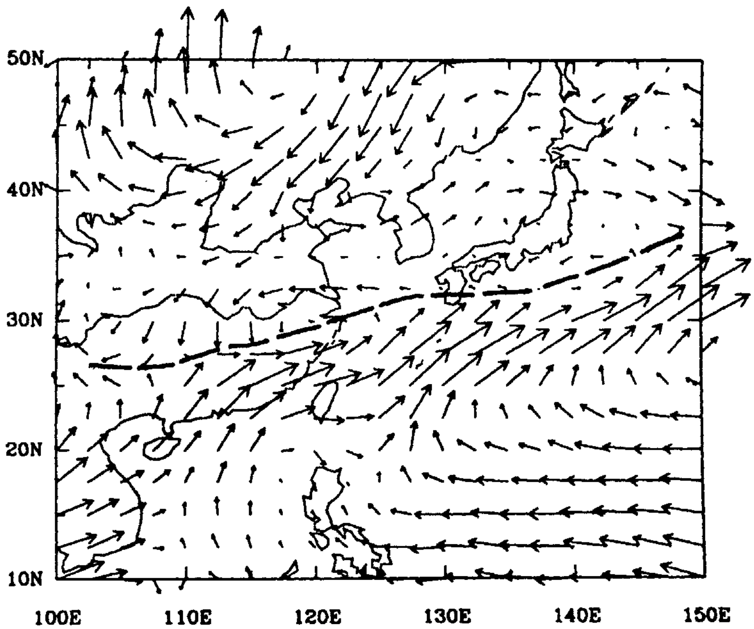

Fig 8 The wind field at 850hPa for 12Z, 16 June, 1992. The heavy dashed is the shear line.

that the structure of Mei-yu weather system is very unique. A typical example is given by Figs. 8-10 (for June 16, 1992), although the quasistationary front is located slightly south to the mean case.

It can be seen at 850hPa wind field (Fig. 8). There is a very narrow zone with very large wind shear and large convergence. This is called as shear line in Chinese literature. It is elongated from Japan vicinity to Southwest China and with almost east-westwards orientation. South to this line there is southwesterly wind system, whose western part comes from Indian Ocean and South China Sea area and is of tropical origin, but the eastern part can be tracked back to the easterly wind in the south and southwest sides in the subtropic region of western Pacific Ocean. North to the shear line there are southeasterly wind in some part and wind with northly component in other part, and at surface this wind system clearly comes from the cool air mass (it can be seen also in Fig. 9).

Fig. 9 shows the vertical structure across Mei-yu front. It is seen that the θ_{se} isolines are very dense and very cruted in the vicinity of Mei-yu front (shear line) due to the large contract of moisture, although the horizontal temperature gradient is only moderate or weak. In the lower troposphere, south to the front this is tongue of maximum θ_{se} representing the very wet summer monsoon air mass, but north to the front this is a shallow shield of minimum θ_{se} with northly wind representing the dry air mass of middle-high latitude origin. In both sides the upper troposphere is dry due to the lack of ascending motion except for the direct vicinity of Mei-yu front and the convection area in the south.

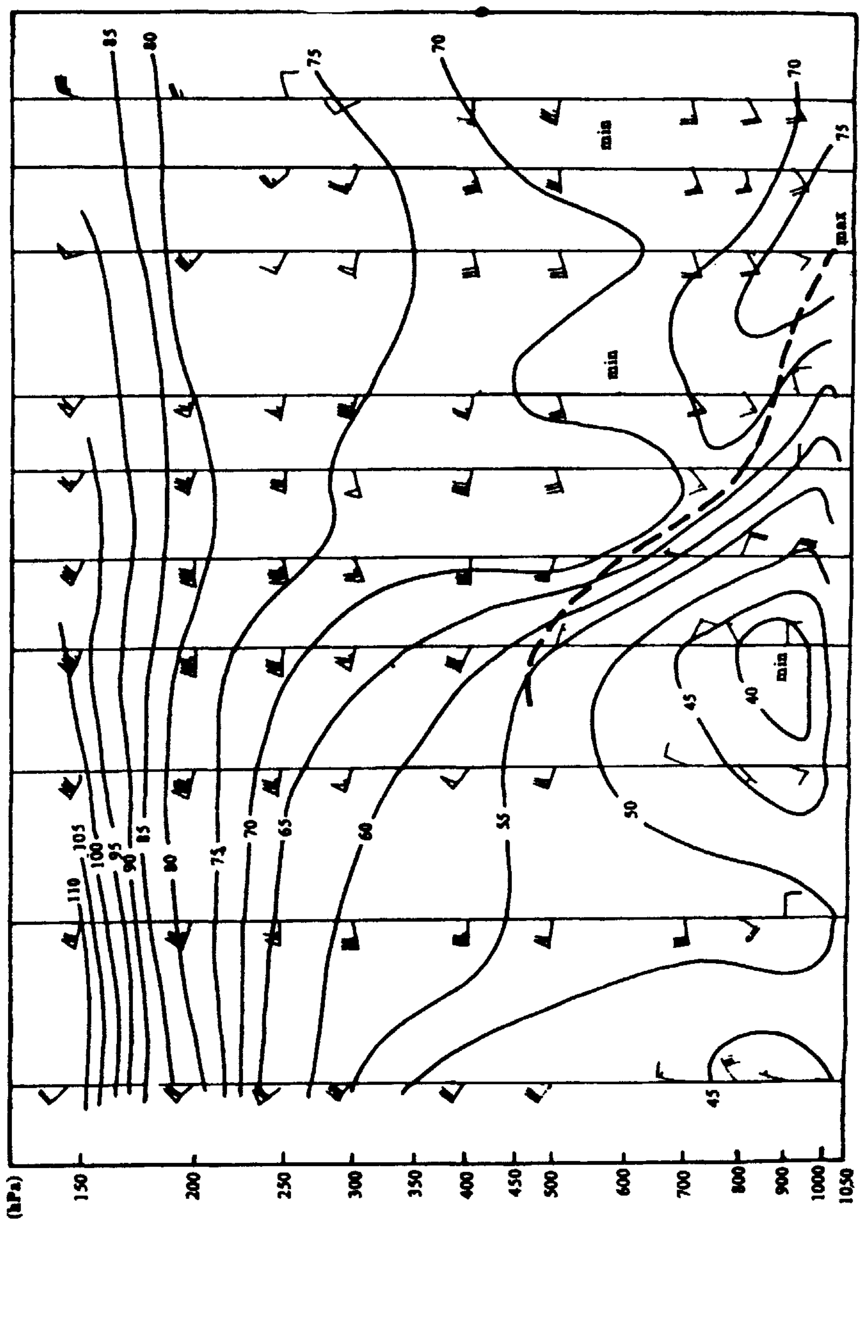

Fig 9 The vertical cross section along 120°E for 00Z, 16 June 1992. The solid lines for θ_{se} and the heavy dashed indicates the shear line.

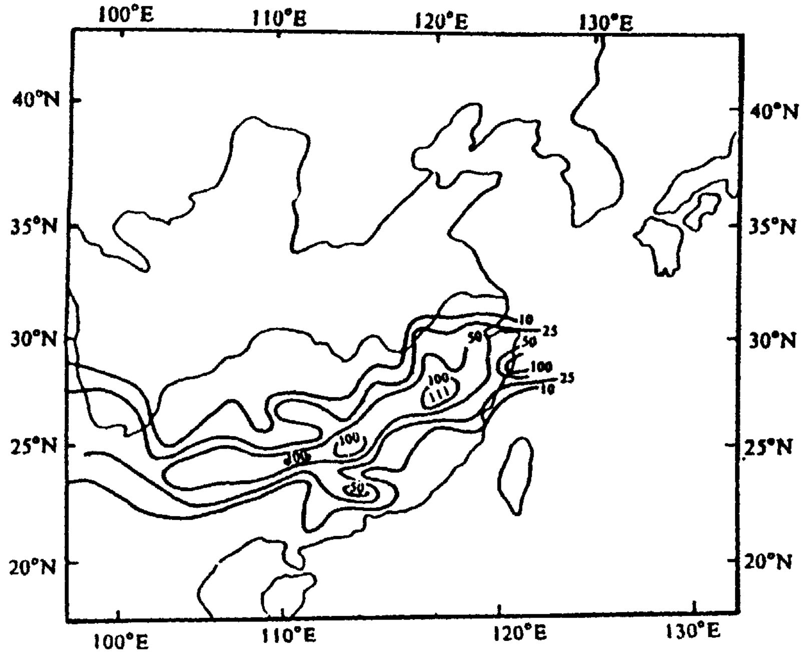

Fig 10 24 hour precipitation for 16-17, June, 1992. The unit is mm.

Fig. 10 shows the 24 hour accumulated precipitation. The region with heavy precipitation is just along the shear line, but there are a lot of mesoscale extreme centers representing the mesoscale feature. It is also revealed that the mesoscale and synoptic scale systems are very important in the maintenance of large scale monsoon flow as well as its super-geostrophic feature due to the eddy transport of momentum and energy (see also Zhao, 1988)[12]. Note the release of latent heat is also very important during the onset of summer monsoon as it has been emphasized by Krishnamurti and Ramanathan[13] and Zeng *et al.*[9].

Summary

Based on the analysis of observational data for 1992, the East Asian summer monsoon can be tracked back to the cease of Asian winter monsoon (northeastly wind at the surface and in the lower troposphere), to the creation of "Southeast monsoon" (southeasterly wind at the surface but southwesterly wind in the lower troposphere) during spring in the coastal region of southeast China and the adjacent ocean due to the large seasonal variation of atmospheric general circulation over the South China Sea and the tropical and subtropical western Pacific Ocean. The "southeast monsoon" is gradually extended into larger area, modified and intensified during early and middle summer by the Indian summer monsoon, cross equatorial flow over South China Sea and the vicinity of Philippines, and the subtropic flow due to the intensification and northwestward marching of subtropic high over Pacific Ocean in the Northern Hemisphere. After middle summer the East Asian summer monsoon reaches even 50°N, but its northern part is clearly connected with the westerly wind of subtropic high.

Based on the similarity of patterns, the division of seasons of atmospheric general circulation shows that the spring and summer come first in the tropical region of western Pacific Ocean, propagate northwestward into South China Sea and the vicinity. The summer (i.e., typical summer monsoon) comes to India and East Asia almost simultaneously.

There are two channels of cross equatorial air flow in the lower troposphere. One is located over the Indian Ocean and associated with Indian summer monsoon, the other is located over South China Sea and the vicinity of Philippines and associated with Asian winter monsoon and also influencing East Asian summer monsoon.

According to the computed seasonality (normalized seasonal variation), the Indian monsoon region and the East Asian monsoon region do indeed possess large seasonality. The East Asian monsoon region is closely connected with other regions of large seasonality, which are located in the tropical western Pacific Ocean and Australian monsoon region.

East Asian summer monsoon brings bulk precipitation in a large area, although nonuniformly with mesoscale structure. During the raining season (Mei-yu) along about 30°N in the East Asia the precipitation in along the shear line which is an elongated narrow zone with large wind shear due to the confluence of southeasterly wind from tropics, southeasterly wind from tropical and subtropical western Pacific Ocean, and northly wind from middle-high latitude in the lower troposphere. The shear line is associated with the Mei-yu quasistationary front with large contract of moisture in the cross section.

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