# Characteristics of the Mean Water Vapor Transport over Monsoon Asia

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ABSTRACT

Based on ECMWF monthly mean data from January 1980 to December 1989, characteristics of the three–dimensional structure of the mean water vapor transport over Monsoon Asia are described, and the more important features of the different regional water vapor transport in the Indian Monsoon region and the East Asian Monsoon region are analyzed. It is found that there is a moist tongue extending from the equator poleward to the Asian Monsoon region. The three–dimensional distributions of the mean water vapor transport fields over the entire globe reflect clearly the asymmetry of the Asian Monsoon system, and the existence of a counter–Hadley monsoon circulation. The moisture conver–gence (divergence) area in Asia coincides with the confluent (diffluent) zone of the monsoon circulation. Furthermore, the moist features of the two sub–regions of the Asian Monsoon area are different both in their magnitudes and in their seasonal variations.

**Key words:** Water vapor transport, East Asian monsoon, Water balance

## I. INTRODUCTION

In the next five years there will be an ambitious and big program, the GEWEX Asian Monsoon Experiment (GAME). The aim of this experiment is to study the water and energy cycles in the Asian Monsoon region. Early in 1983 Peixoto and Oort(1983) pointed out that the study of the various fields which characterize the flow of water vapor in the atmosphere is essential for improving the under–standing of the water cycle and the earth's water balance on both regional and global scales; therefore in studying the water cycle in the Asian Monsoon region, the water vapor transport is one of the major components. During the past three decades some Japanese and Chinese researchers have done a lot of related work (Saito, 1966; Asakura, 1971; Lu and Gao, 1983). In this study by using the more extensive data (ECMWF monthly mean global analysis data from 1980–1989) we will investigate characteristics of the mean water vapor transport and expect to bring out additional significant features, particularly over the Asian Monsoon region. The data set has a grid point of 2.5x2.5 degree and data are available at 1000 hPa, 850 hPa, 700 hPa, 500 hPa, 300 hPa, 200 hPa and 100 hPa. We calculate the following parameters:

Mean precipitable water $\overline{W}=\frac{1}{g}\int_{p_t}^{p_s}\bar{q}dp$, where "–" refers to monthly mean.

Mean zonal transport of water vapor $\overline{Q}_\lambda=\frac{1}{g}\int_{p_t}^{p_s}\bar{q}\;\bar{u}dp$,

Mean meridional transport of water vapor $\overline{Q}_\varphi=\frac{1}{g}\int_{p_t}^{p_s}\bar{q}\;\bar{v}dp$,

Mean vertical transport of water vapor $\overline{Q}_p=\frac{1}{g}\int_{p_t}^{p_s}\bar{q}\;\bar{w}dp$, Mean divergence of water vapor flux $\nabla \cdot \overline{\mathbf{Q}} = \frac{1}{a\cos\varphi}\left(\frac{\partial \overline{Q}_\lambda}{\partial \lambda} + \frac{\partial \overline{Q}_\varphi \cos\varphi}{\partial \varphi}\right)$

In order to see the difference of the water vapor transport in the Indian Monsoon and the East Asian Monsoon, we define two areas, one is the Indian Monsoon region, northward from the equator to 25°N, and from 60°E to 100°E; the other is the East Asian Monsoon region, the four boundries of which are 100°E, 140°E, 20°N, 50°N.

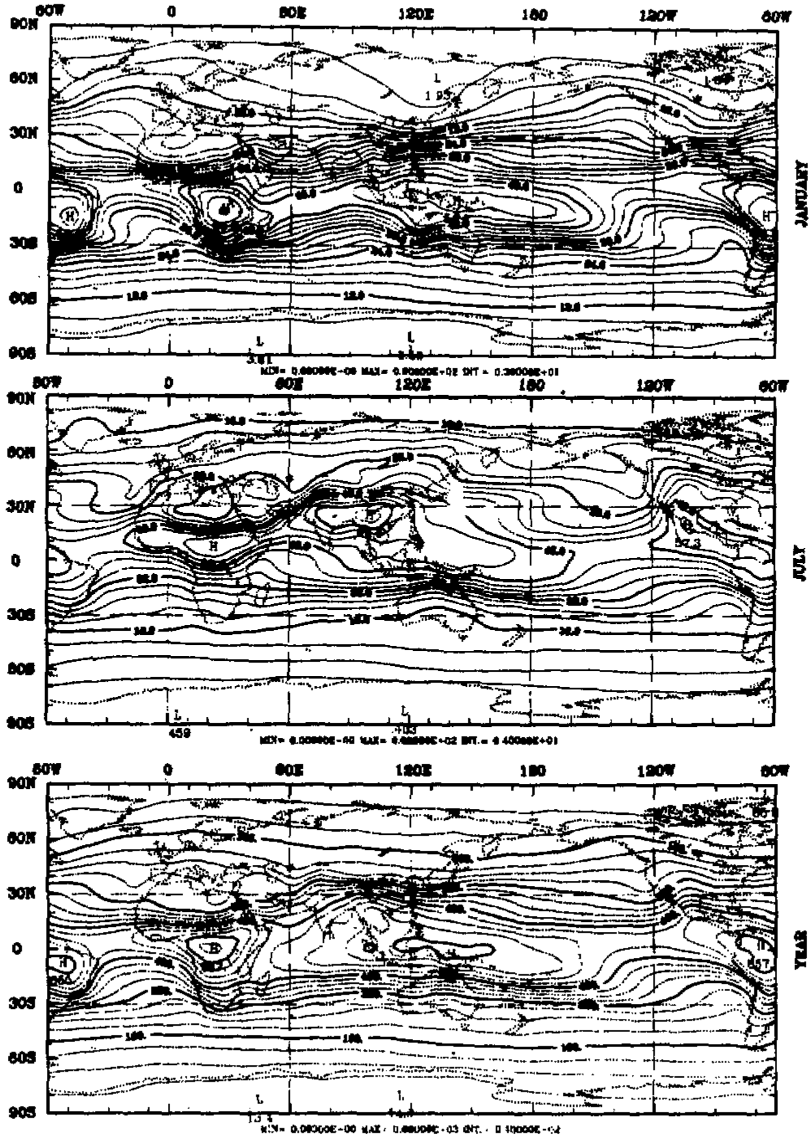


Fig. 1. Global distributions of column precipitable water. (a) January, (b) July, (c) year. unit: mm

According to the Gauss theorem, the areal–mean moisture divergence can be expressed as:

$$<\nabla \cdot \overline{\mathbf{Q}}> = \iint_A \nabla \cdot \overline{\mathbf{Q}} dA = \int_c \vec{n} \cdot \overline{\mathbf{Q}} dl \ .$$

II. CHARACTERISTICS OF MEAN PRECIPITABLE WATER

Fig. 1 (a, b and c) shows the global distributions of the 10yr–mean annual and seasonal precipitable water (PW) content. It is seen that there is a continuous decrease of precipitable water from the equatorial regions to the north and south poles. The PW content is higher over the oceans than over the continents. Near the western and eastern coasts of the continentsthe isolines are deflected and the deflection is reinforced by the topography and the presence of warm and cold ocean currents. The seasonal variations of precipitable water tend to be particurlarly evident in the Northern Hemisphere where the moist content is greater in summer than in winter at all latitudes, with the largest changes occurring in the 20°N–30°N latitude belt (especially in the monsoon regions). These changes must be associated with monsoon circulation over India, southeastern Asia and central Africa.

It is interesting to note that there is a moist tongue extending northward from the southern part of the South China Sea to the upstream areas of the Yantze River (Fig. 1c). In January the maximum centre of precipitable water locates in the Southern Hemisphere near the equator (Fig. 1a). It moves to the place near 30°N in summer and situates at the southeastern verge of the Tibetan Plateau, namely the Hengduan Mountains area (Fig. 1b). We can see that all over the world the Asian Monsoon region is the broadest region of highest water vapor content, which covers the northern part of the Arabian Sea, the whole Indian Subcontinent and East Asia. So it is inferred that the Asian Monsoon region is the potentially wettest region in the world in summer, and it has the largest seasonal variability because of the obvious seasonality of monsoon wind systems.

The annual marches of the areal–mean water vapor content in the Asian, the East Asian and the Indian Monsoon regions are shown in Fig. 2. The areal–mean precipitable water of the East Asian Monsoon region is larger in summer than that of the Indian Monsoon region, and also there is a bigger seasonal change in the East Asian Monsoon region. This is understandable since in the East Asian Monsoon region there are frequent outbreaks of cold air from the polar regions in winter months.

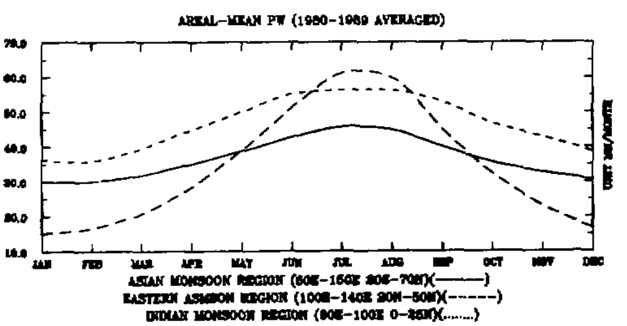


Fig. 2. Seasonal trends of areal–mean precipitable water.

## III. CHARACTERISTICS OF THE MEAN WATER VAPOR TRANSPORT FIELDS

### 1. *Mean Zonal Transport of Water Vapor*

The fields of mean vertically integrated zonal transport of water vapor $\overline{Q}_\lambda$ for yearly and seasonal conditions are presented in Fig. 3 (a,b and c). The general pattern of the $\overline{Q}_\lambda$ maps is consistent with the distribution of the mean global zonal circulation in the lower troposphere,

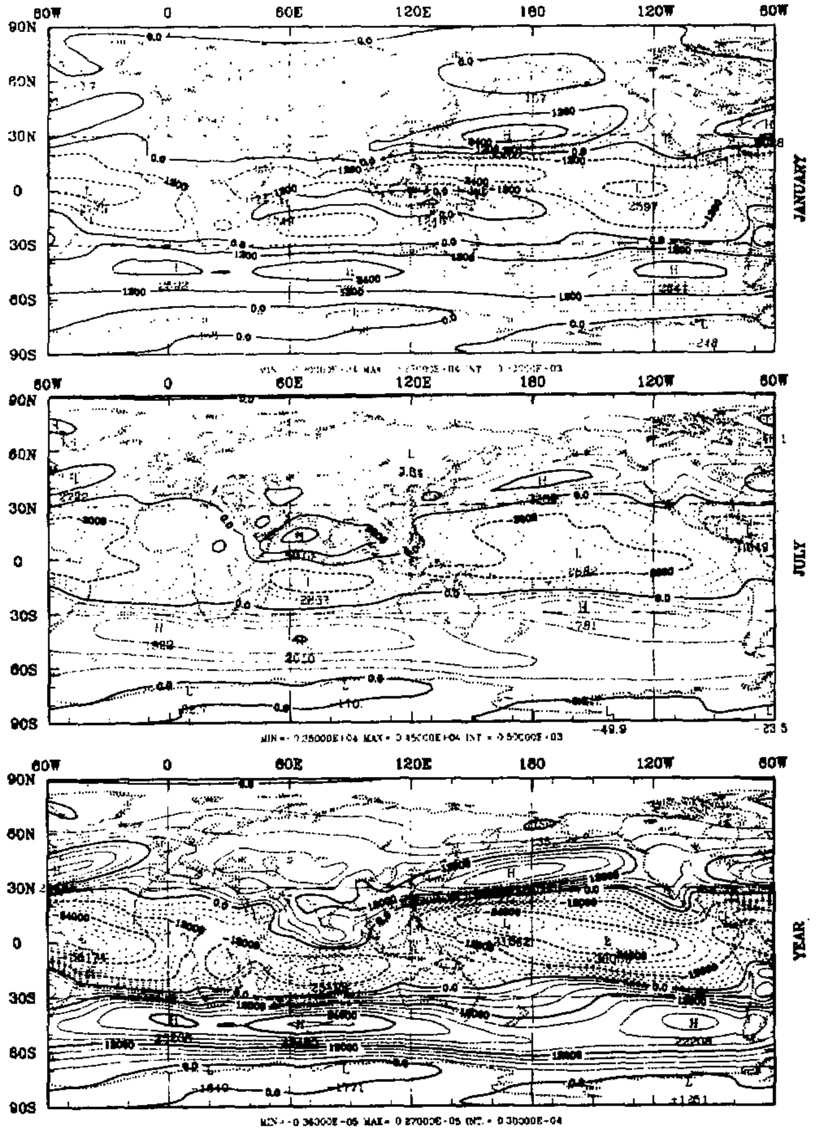


Fig. 3. Global distributions of zonal water vapor transport. (a) January, yrar. unit: g cm$^{-1}$s$^{-1}$.

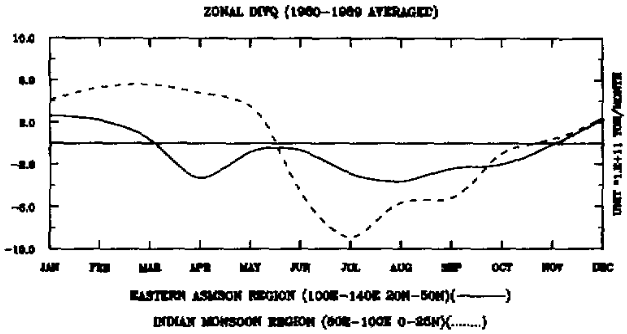


*Fig. 4. Seasonal trends of net moisture flux in the zonal direction of the two monsoon regions.*

i. e., westerlies in mid–latitudes, and easterlies in the tropical belt. But the westward transport in the tropics is interrupted over the Asian Monsoon region where there is actually eastward transport associated with the monsoon circulation and it is particularly pronounced in the summer season. This shows clearly the zonal asymmetry due to the Asian Monsoon circulation.

The differences of the water vapor fluxes between the eastern and western boundries of the two monsoon regions (as defined above) represent the water vapor divergences in the zonal direction; also the differences of water vapor transport between the northern and southern boundries of the two regions represent the water vapor divergences in the meridional direction.

From Fig. 4, we can see that both the Indian Monsoon region and the East Asian Monsoon region have net convergence of water vapor transport in the zonal direction in summer season. In the Indian Monsoon region, there is an abrupt change in sign (from divergence to convergence) between May and June showing the summer monsoon outburst and the start of the Indian Monsoon rainfall. In the East Asian Monsoon region the zonal convergence prevails from about March to November, and the seasonal trend is mild and the maximum value in July or August is not so high as that in the Indian Monsoon region.

2. *Mean Meridional Transport of Water Vapor*

The global distributions of the $Q$ fields are shown in Fig. 5 (a,b and c). The $\overline{Q}_\varphi$ values are about one time smaller than the corresponding $\overline{Q}_\lambda$ values, yet they play an essential role in maintaining the global water balance. The $\overline{Q}_\varphi$ fields reveal the main characteristics of the general circulation and also show the effects of the inhomogeneity of the surface of the globe, such as the land–sea contrast and variations of the topography. The most intense centres of the $Q$ fields are observed over the oceans and over the fringes of the continents.

The meridional flux of moisture over the Asian Monsoon region varies considerably with seasons. In winter the flux is predominantly equatorward in the Asian Monsoon region, while in summer it is predominantly poleward. Throughout the year along the latitude 35°N, there is a demarcation line between the southerly vapor transport from the oceans and the northerly vapor transport from the continent, which coincides with the climatological dividing line (along the Qinling Mountains) of the southern part and the northern part of China.

Fig. 6 presents the net meridional inflows of water vapor transport in both the Indian Monsoon region and the East Asian Monsoon region. It shows that from April to May there

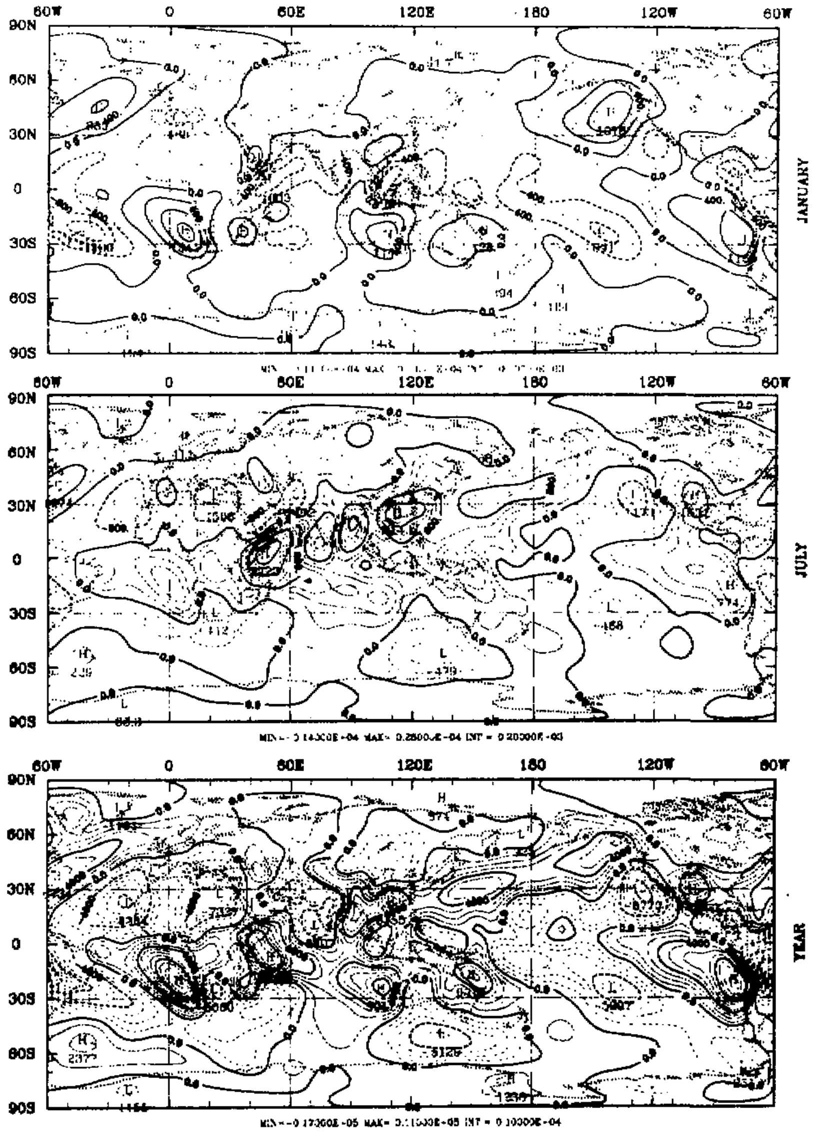


Fig. 5. Global distributions of meridional water vapor transport (a) January. (b) July, (c) year. unit $g\ cm^{-1}s^{-1}$.

is an obvious seasonal transition in the East Asian Monsoon region. The convergent values of the Indian Monsoon region are generally smaller than that of the East Asian Monsoon region. The maximum meridional convergence appears in May in the former region, while in the latter region it occurs later in June. It is found that in July there is even moisture divergence in the Indian Monsoon region.

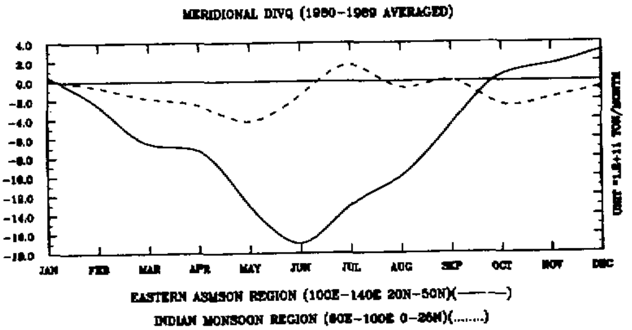


Fig. 6. Seasonal trends of net moisture flux in the meridional direction of the two monsoon regions.

It can be concluded from Fig. 4 and Fig. 6 that the meridional convergence of water vapor is the main source of water vapor for the East Asian Monsoon precipitation; while the zonal convergence of water vapor is the main source of water vapor for the Indian Monsoon rainfall. From winter to spring the seasonal transition of moisture convergence of the East Asian Monsoon occurs in the meridional direction about one month earlier than that of the Indian Monsoon in the zonal direction, but it is not so sharp as the latter. This suggests us that the onset of the Indian Monsoon and the East Asian Monsoon are from different origins. The onset of the East Asian Monsoon is possibly caused by the interaction between the tropical and the subtropical synoptic systems, while the onset of the Indian Monsoon may be due to the northward jump of the jetstream in westerlies which leads to the asymmetry of air flow in the zonal direction. The interaction and difference of characteristics of water vapor transport between the two subsystems of Asian Monsoon is a subject deserving of further investigation.

3. *Mean Vertical Transport of Water Vapor*

The vertical transport of water vapor links the terrestial and atmospheric branches of the hydrological cycle, so the analysis of $\overline{Q}_p$ is very important. Fig. 7 (a,b and c) shows that in general the vertical vapor flux is negative (upward) over the equatorial region associated with the ascending branches of the Hadley cell, and positive (downward) in the subtropics. There is a clear seasonal shift, generally northward to the summer pole. The seasonal shift is especially evident over the Asian Monsoon region where the downward vapor transport in January is almost wholly displaced by the upward vapor tran–sport till July. After April (not shown), over the Tibetan Plateau there is upward transport while over the areas to the south of the Plateau the vapor flux is downward, which demonstrates the existence of a counter–Hadley cell, and also reflects the vertical asymmetry of Asian Monsoon in the general circulation.

## IV. MEAN DIVERGENCE OF WATER VAPOR

Since $\nabla \cdot \overline{\mathbf{Q}} = \overline{E} - \overline{P}$, the analysis of water vapor flux divergence is of great interest for the study of water balance on both regional and global scales. The regions of mean positive divergence ($\overline{E} - \overline{P} > 0$) constitute the main sources of water vapor for the atmosphere, whereas the centres of convergence ($\overline{E} - \overline{P} < 0$) are regions of water vapor sinks.

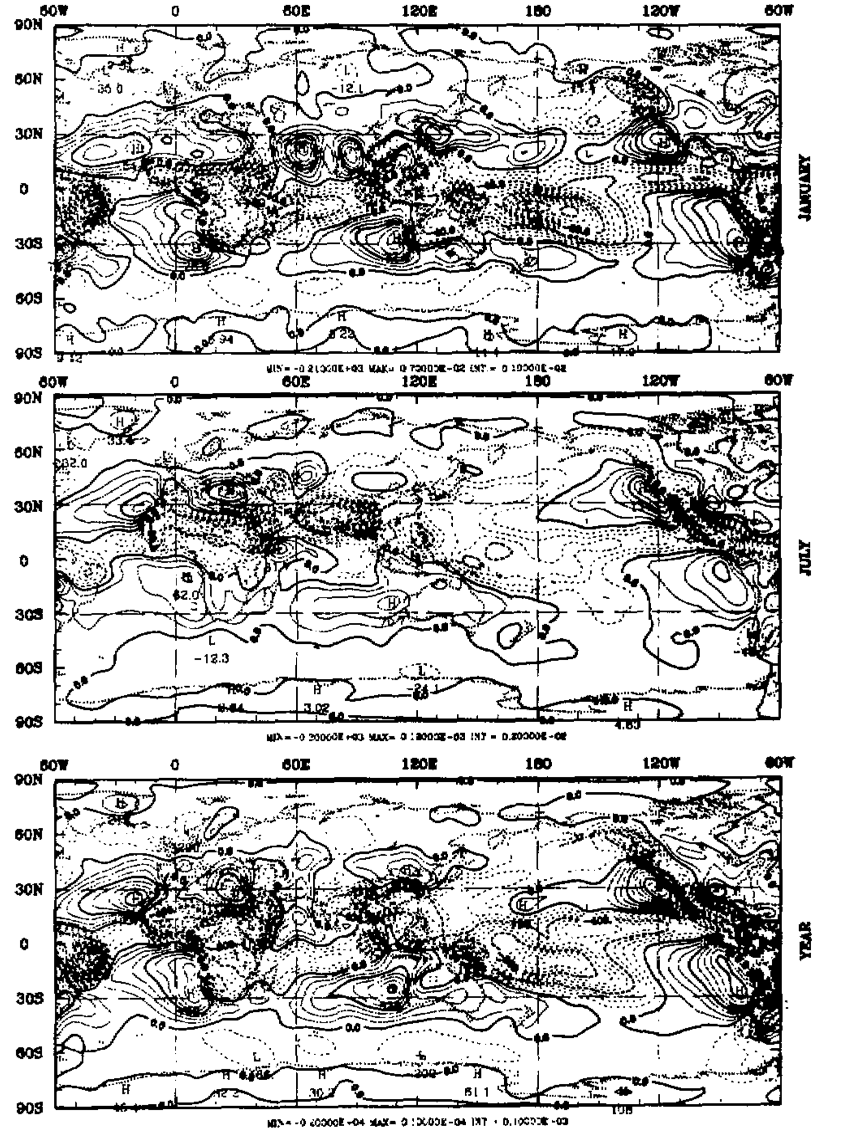


Fig. 7. Global distributions of vertical water vapor transport (a) January, (b) July, (c) year. unit: 0.01 hPa g cm$^{-2}$s$^{-1}$.

Fig. 8 (a,b and c) shows the vertically integrated water vapor flux diver–gence fields. We can see that convergence generally prevails over the equatorial and monsoon regions where precipitation is in fact larger than evaporation; while divergence mainly predominates in dry climate zones in the subtropics such as the desert areas of western Asia and northern Africa (Fig. 8c). The convergence and divergence centres are, as a rule, more intense over the oceans than over the land. In the equatorial region the convergence of water vapor is associated with the ITCZ. In the Asian Monsoon region over drainage basins of large rivers, such as the

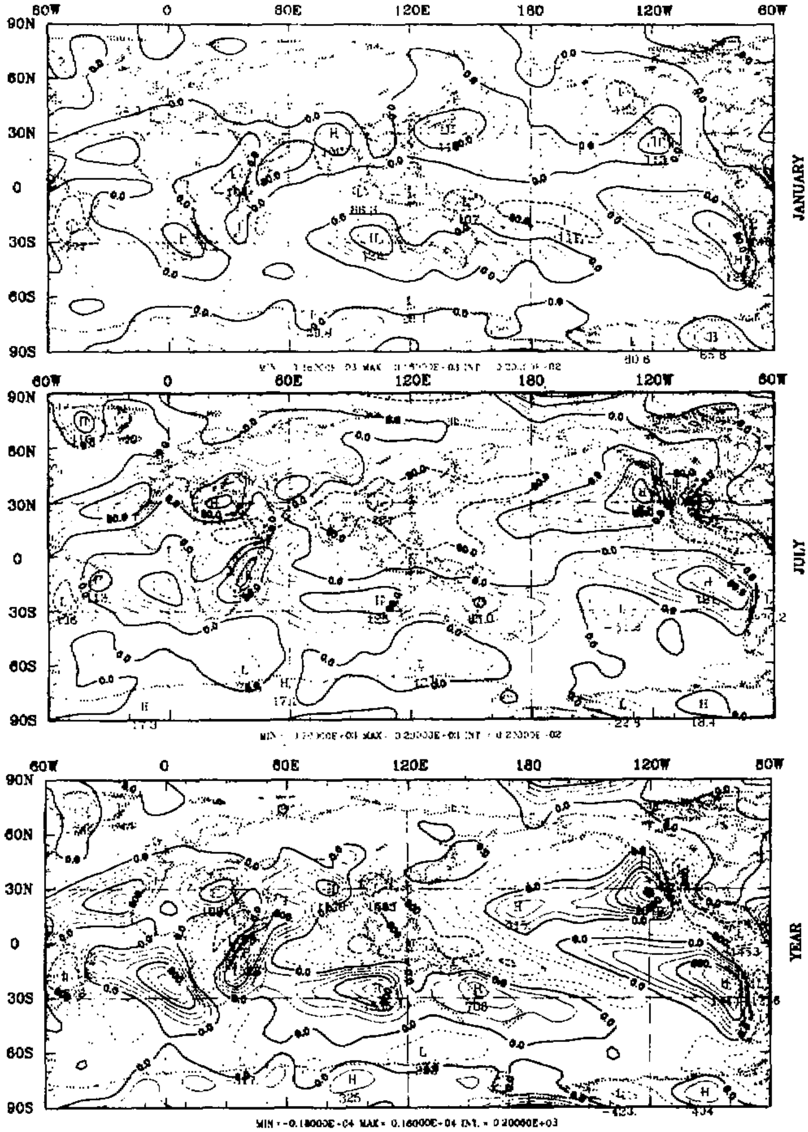


Fig. 8. Global distributions of water vapor divergence (a) January, (b) July, (c) year. unit: mm

Indus River and the Yangtze River, there is pronounced water vapor flux convergence. In the subtropical belts the divergence regions coincide largely with the arid zones of the globe. These regions constitute the main sources of moisture for the entire atmosphere. In July the moisture convergence zones extend northward. Over the eastern China and Japan there is moisture divergence in winter season, but in summer the strong moisture convergence prevails over there, showing a prominent seasonal shift. Compared with the moisture divergence maps done by Peixoto and Oort (1983) (not shown here), Fig. 8 (a,b and c) depicts much more details particularly over the Eurasian land areas.

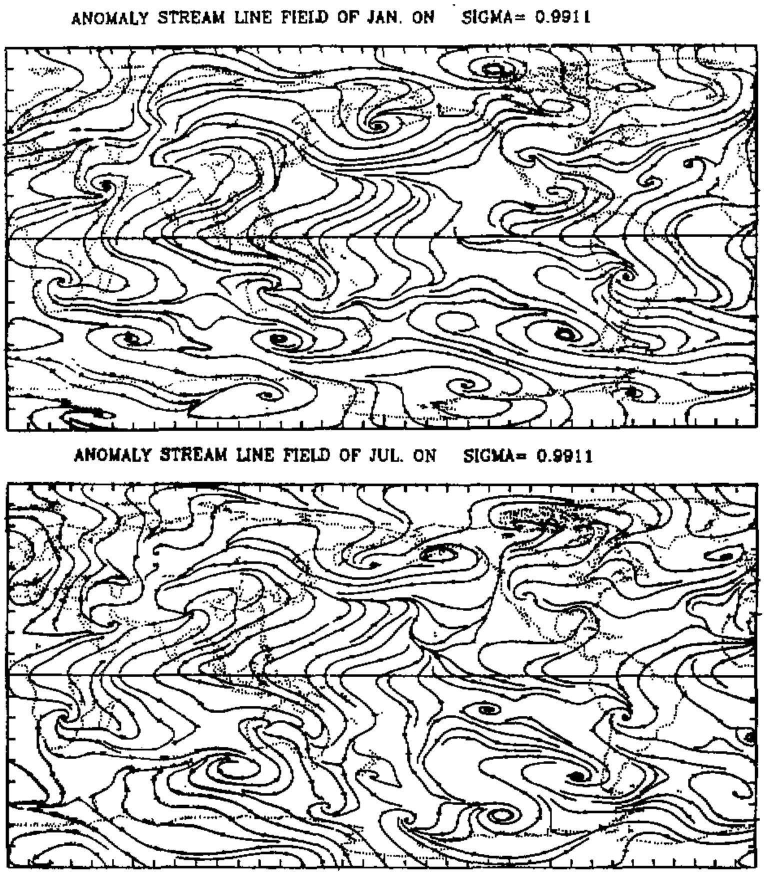


Fig. 9. Global distributions of wind anomaly stream line (a) January, (b) July. (Kind permission from Prof. Wu Guoxiong)

Comparison of Fig. 8 and Fig. 9 reveals relation between the fields of water vapor flux divergence and the monsoon circulation. In Fig. 9 (a and b) the wind vector is the difference between the monthly mean wind vector and the annual mean wind vector showing monsoonal flow in different seasons. We can see that during winter diffluent northernly flow prevails over the Asian Monsoon region and the moisture convergence zone occurs in the Australian Monsoon region; while in summer there is strong moisture convergence over southern Asia and western Africa where confluent flow exists.

Fig. 10 (a,b and c) reveals the areal-mean water vapor divergences in the whole Asian Monsoon region and the Indian and the East Asian Monsoon regions. There is moisture convergence for the whole Asian Monsoon region throughout the year, and it reaches the maximum value in July. In the Indian Monsoon region an abrupt change occurs in May, and the moisture convergence predominates from May to late October. In the East Asian Monsoon region there is moisture convergence from about February to October, and it attains the maximum value in June. The moisture convergence values of the East Asian Monsoon region are generally one time larger than that of the Indian Monsoon region.

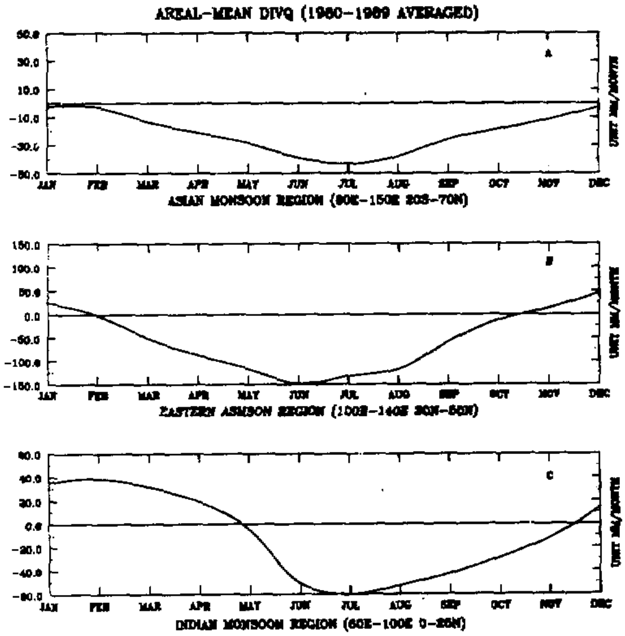


Fig. 10. Seasonal trends of areal–mean moisture divergence.

V. CONCLUSIONS

Based on ECMWF monthly mean data from January 1980 to December 1989, characteristics of the three–dimensional structure of the mean water vapor transport over Monsoon Asia are described, and the more important aspects of the different regional water vapor transport features between the Indian Monsoon region and the East Asian Monsoon region are analyzed. Major conclusions in this study are summarized as follows:

(1) There is a moist zone extending from the equator poleward to the Asian Monsoon region, so the Monsoon Asia is a major wet zone in the world. The PW content of the East Asian Monsoon seems to be influenced much more by cold air motions from high latitudes than that of the Indian Monsoon.

(2) The three–dimensional distributions of the mean water vapor transport fields over the entire globe reflect clearly the asymmetry of the Asian Monsoon system, and the existence of a counter–Hadley monsoon circulation. Furthermore, the moisture convergence (divergence) area in Asia coincides with the confluent (diffluent) zone of the monsoon circulation.

(3) The moist features of the two sub–regions of the Asian Monsoon area are different. In the East Asian Monsoon region the seasonal transition of moisture convergence occurs largely in the meridional direction from April to May. But in the Indian Monsoon region the seasonal transition occurs later (from May to June) and is more obvious, and it is manifested mainly in the zonal direction.

(4) The water vapor convergence in the meridional direction is the main source of water vapor for the East Asian Monsoon precipitation; while the water vapor convergence in the zonal direction is the main source of water vapor for the Indian Monsoon rainfall. In general

the East Asian Monsoon has a larger convergence of water vapor than the Indian Monsoon.

As a part of a more general study of the water cycle of Monsoon Asia, this study is preliminary. Ongoing studies are to calculate the eddy tran–sport of water vapor and to link the water vapor transport with precipitation, evaporation and surface runoff on the land areas of China particularly over the Tibetan Plateau and the Huaihe River Basin.

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