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Characteristics of the Water Vapor Transport in East Asian Monsoon Region and its Differences from that of South Asian Monsoon Region in Summer*

Huang Ronghui(黄荣辉), *Zhang Zhenzhou*(张振洲) and *Huang Gang*(黄 刚)
(Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100080)
Ren Baohua(任保华)
(Department of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026)

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The characteristics of the water vapor transport by the summer monsoon in the East Asian monsoon region are analyzed by using the daily data of water vapor and wind fields at various levels analyzed by ECMWF, and its differences from those in the Indian monsoon region are compared in this paper. The analyzed results show that there is an obvious difference between the characteristics of the water vapor transport in the East Asian monsoon region and those in the South Asian monsoon region. The meridional water vapor transport is larger than the zonal water vapor transport in the East Asian monsoon region, but the zonal water vapor transport is dominant in the Indian monsoon region. Moreover, the analyzed results also show that since the distribution of water vapor in the East Asian monsoon region is large in the south and small in the north, the water vapor advection by the southerly monsoon flow is wet advection. Therefore, the convergence of the water vapor transport is mainly due to the water vapor advection caused by the monsoon flow in the East Asian monsoon region. However, in the Indian monsoon region, the water vapor transport is dry advection, which is favorable to the divergence of water vapor, thus, the convergence of water vapor is mainly caused by the convergence of wind field.

Key words: monsoon; water vapor transport; flux; specific humidity.

1. INTRODUCTION

The hydrological cycle in climate system is related to each component in this system, which is not only an important one in the dynamical and thermodynamic processes of climate system, but also a complicated course associated directly with the human life and production. Therefore, the study of the hydrological cycle in climate system is one of major issues of the World Climate Research Plan(WCRP). The Global Energy and Water Experiment

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(GEWEX) ,which is being implemented in the world, recently, is aimed at increasing the understanding of the hydrological cycle in the air–land–ocean–biosphere coupled climate system and its effect on the climate change, so that to improve the description of the hydrological cycle in climate system.

Monsoon, especially the Asian summer monsoon, brings abundant water vapor to the monsoon region from the ocean. Thus, monsoon circulation will greatly influence the transport of water vapor, and thus it will greatly influence the precipitation. Zhu[1] firstly proposed that the rainfall in China has a close relationship with the East Asian monsoon. Starr et al.'s study indicated the important effect of water vapor advection on the local water balance[2]. Xu[3] discussed the transport and balance of water vapor in China. Xie and Dai[4] discussed the transport of water vapor in the heavy rainfall process in the Yellow River and the Huaihe River valley and pointed out that heavy rainfall process is closely associated with the convergence of water vapor. Lu and Gao[5] put forward that the transport of water vapor is associated with the advance and retreat of the East Asian summer monsoon. These studies revealed that the water vapor brought by the monsoon flow from the ocean plays an important role in the balance of water vapor in the monsoon region.

Tao and Chen[6,7] systematically studied the features of the East Asian monsoon circulation and pointed out that either its mean structures or its vertical meridional circulations are different from those in the Indian monsoon system. The East Asian summer monsoon is influenced not only by the Indian southwest monsoon, but also by the western Pacific subtropical high and the mid–latitude disturbances. Therefore, it can be expected that the characteristics of water vapor transport in the East Asian monsoon region differ largely from those in the Indian monsoon region.

In view of the above–mentioned discussion, the daily data of water vapor, wind and height fields at various levels from 1980 to 1989 analyzed by ECMWF were used to study the characteristics of water vapor transport in the East Asian monsoon region, and the comparison between it and that in the Indian monsoon region is made in this paper.

2. CHARACTERISTICS OF WATER VAPOR TRANSPORT IN THE EAST ASIAN MONSOON REGION AND ITS DIFFERENCES FROM THOSE IN THE INDIAN MONSOON REGION IN SUMMER

2.1 *Water Vapor Transport Vector and Flux*

Suppose that the water vapor in the atmosphere diminishes to zero above 100 hPa, then the flux vector of water vapor transport in a unit column of air $\vec{Q}=(Q_\lambda, Q_\varphi)$ can be estimated as follows:

$$\vec{Q}=\frac{1}{g}\int_{100}^{P_0}\vec{V}\cdot q\mathrm{d}p=\frac{1}{g}\int_{100}^{P_0}(u,v)q\mathrm{d}p. \tag{1}$$

Hence, the calculating formulas of the zonal and meridional component of water vapor transport flux Q_λ and Q_φ can be obtained as

$$Q_\lambda=\frac{1}{g}\int_{100}^{P_0}uq\mathrm{d}p, \tag{2}$$

$$Q_\varphi=\frac{1}{g}\int_{100}^{P_0}vq\mathrm{d}p, \tag{3}$$

where, $\vec{V}$ is the wind vector at various levels within the unit column of the air, u and v represent the zonal and meridional components of $\vec{V}$, respectively, q is the specific humidity at various levels of the unit column of air, P_0 is the sea surface pressure, and for simplicity, it is usually taken as 1000 hPa. Thus, by using Formulas (1)–(3), and ECMWF daily data of specific humidity and wind fields in June, July and August of 1980 to 1989, the vector of water vapor transport, the zonal and meridional component of water vapor transport flux for each month of 1980 to 1989 in the Asian monsoon region can be computed. Due to large variations of water vapor and wind field with time, for the sake of accuracy, we first calculated the daily water vapor transport in each month from 1980 to 1989, then the monthly mean data can be obtained from the daily flux of water vapor transport for each month of 1980 to 1989, and the climatological mean monthly data of water vapor transport may be calculated for each month.

2.2 *Mean Water Vapor Transport in Asia in Summer*

The mean distribution of water vapor transport vector in Asia's summer was calculated by using Formula (1) and ECMWF dataset and is shown in Figure 1. It may be seen from Fig.1. that the water vapor transport in the Indian monsoon region mainly comes from the water vapor transported along the Somali Jet, whose direction is changed over the Arabian Sea. And the source of water vapor transport in the East Asian monsoon region in summer is much more complex than that in the Indian monsoon region. It can be found that the water vapor transport in the East Asian monsoon region consists of four branches: The first is driven by the Indian southwesterly through the Bay of Bengal and transported to the Yangtze River and Huaihe River valleys, the second is brought by the southeast monsoon along the southwest side of the western Pacific subtropical high, the third results from the cross–equatorial flow along 105°E by the South China Sea, and the fourth branch is due to the disturbances in the westerly zone of mid–latitudes. All these four flows converge in the Yangtze River and Huaihe River valleys of China and then flow to the Korean Peninsula and Japan.Therefore, the interannual and intraseasonal variabilities of water vapor transport in the East Asian monsoon region in summer are more complicated than those in the Indian monsoon region. The distribution of water vapor transport vector in the East Asian monsoon region in summer, as shown in Fig.1, is in accordance with the East Asian summer monsoon circulation system proposed by Tao Shiyan and Chen Longxun[6].

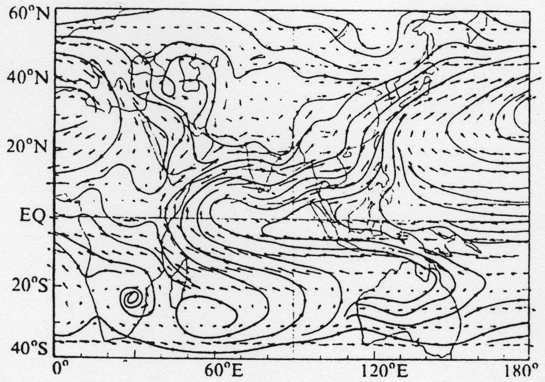

FIGURE 1. The distribution of water vapor transport vectors in summer, averaged for 1980–1989. Units: g / (s • cm).

It can be also seen from Fig.1 that the water vapor transport in the East Asian monsoon region in summer differs distinctly from that in the Indian monsoon. In summer, the airflow in the Indian monsoon region flows from the Arabian Sea to the Indian Peninsula, and the zonal transport of water vapor is dominant. In the East Asian monsoon region, however, the southerly flow prevails in summer, and the meridional component of water vapor transport is very large. These differences will be clearly seen from the computation of zonal and meridional transport flux of water vapor illustrated in next section.

2.3 *Mean Zonal Transport Flux of Water Vapor*

Figs.2a–c are the distributions of climatological–mean zonal transport flux of water vapor in June, July and August averaged from 1980 to 1989, respectively. It may be found that in June, an area of positive zonal transport flux of water vapor locates in the Arabian Sea, India and the Indo–China Peninsula, which stretches eastward to the east to the Philippines in July and August, but its center is still located over the Arabian Sea and India. The maximum zonal transport of water vapor is in July. It is obviously shown in Fig.2 that the precipitation in the Indian monsoon region may originate from the water vapor, which is carried by the Somali–Jet from the south Indian Ocean and evaporated from the Arabian Sea. Moreover, it is also seen that in June, another positive zone of water vapor transport flux appears from the Korean Peninsula to the east of Japan, and it moves westward to the east of China in July and August.

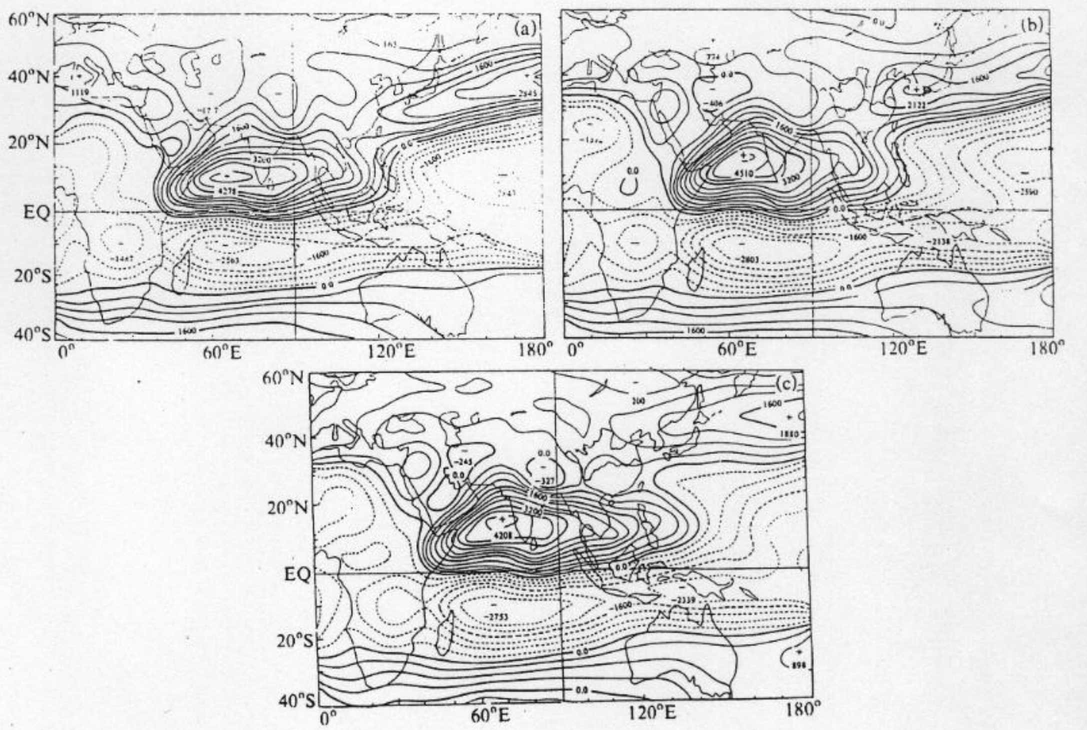

FIGURE 2. Distribution of the zonal transport flux of water vapor in June (a), July (b) and August (c), averaged for 1980–1989. Units: g / (s • cm).

In comparison of these two positive centers, it may be found that the zonal transport flux of water vapor over the Arabian Sea and India is much larger than that over the Korean Peninsula and the south of Japan, particularly in the eastern part of China, the zonal transport flux of water vapor is much smller than that over South Asia.

2.4 *Mean Meridional Transport Flux of Water Vapor*

Figs.3a–c represent the mean meridional transport flux of water vapor for June, July and August averaged from 1980 to 1989, respectively. It can be seen that there is a positive center of water vapor transport flux (northward transport) in an area from the Somali–Jet to the Arabian Sea, a negative region of water vapor transport flux over the Indian Peninsula and another positive center over the Bay of Bengal, which forms a dipole structure. Furthermore, there is another positive region of water vapor transport flux in the area from the South China Sea, South China to the south of the Yangtze River valley and the south of Japan, whose center is located over the South China Sea in June, and it moves northward to South China with its value reaching the maximum in July.

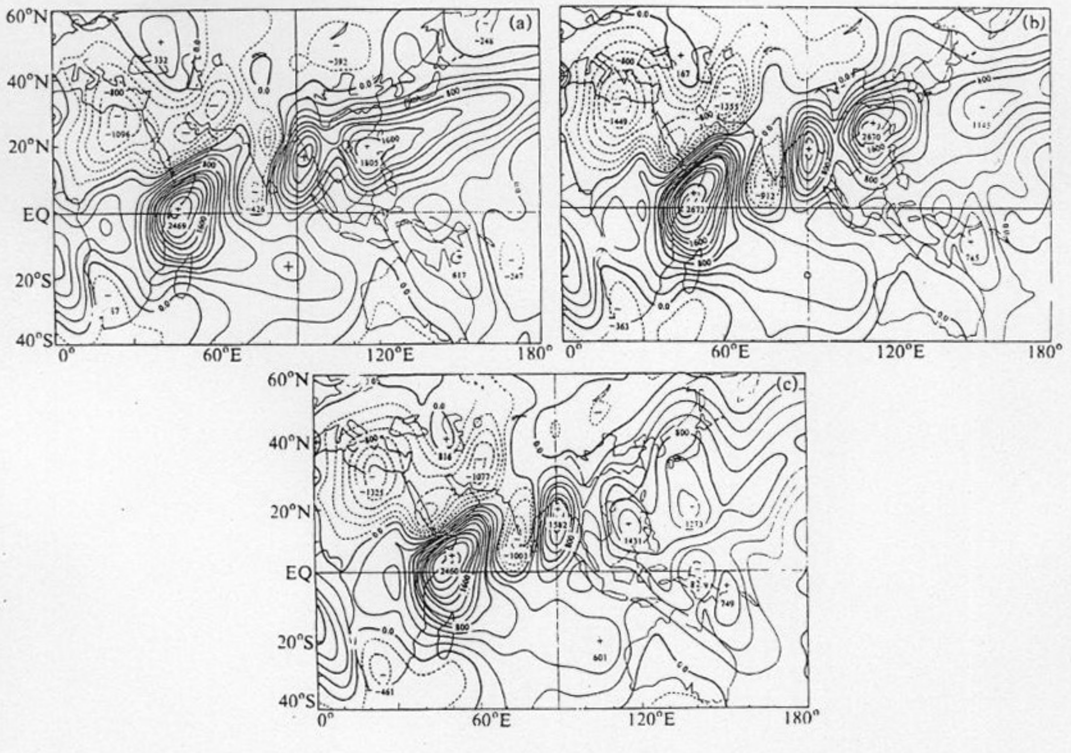

FIGURE 3. Same as in Fig.2 but for the meridional transport flux.

Comparing Fig.3 with Fig.2, we can find that the zonal transport flux of water vapor over South Asia and the Arabian Sea is larger than the meridional transport flux of water vapor along the west coast of the Arabian Sea and the east coast of Africa, while over the South China Sea, the south of the Yangtze River and Huaihe River valleys, the meridional transport flux of water vapor is greater than the zonal component, especially in July. So it can be seen that during the mid–summer, the meridional transport flux of water vapor from the South China Sea and the tropical western Pacific as well as the Bay of Bengal is the main source of water vapor for the East Asian summer monsoon rainfall, which is in agreement with that analyzed by Luo[8] and Chen[9]. Therefore, the summer precipitation in the East Asian monsoon region mainly originates from the water vapor brought by the southwest monsoon from the Bay of Bengal and by the southeast monsoon from the tropical western Pacific, and carried by the cross–equatorial flow from the South China Sea.

It may be concluded from the above analyses that the zonal transport of water vapor, i.e. the transport from west to east, is dominant in the water vapor transport of the Indian monsoon region in summer. However, in the East Asian monsoon region in summer, though the zonal transport flux of water vapor is not less, the meridional transport flux of water vapor, i.e., the transport from south to north, is much larger than the zonal component.

3. CONVERGENCE (DIVERGENCE) OF WATER VAPOR TRANSPORT IN THE EAST ASIAN MONSOON REGION AND ITS DIFFERENCE FROM THAT IN THE INDIAN MONSOON REGION

As early as in the 1950's, Starr[10] pointed out that the local content of water vapor is associated closely with the convergence (divergence) of water vapor transport flux. The study by Chen[11] also indicated that the convergence (divergence) of water vapor transport flux in the East Asian monsoon region is in good agreement with the distribution of OLR. Therefore, the convergence (divergence) of water vapor transport flux in the East Asian monsoon region is an important physical indicator of the variation of monsoon precipitation.

3.1 *Divergence of Water Vapor Transport Flux*

In spherical coordinates, the divergence of water vapor transport flux vector can be calculated as follows:

$$\nabla \cdot \vec{Q} = \frac{1}{a\cos\varphi}\left(\frac{\partial Q_\lambda}{\partial \lambda} + \frac{\partial Q_\varphi \cos\varphi}{\partial \varphi}\right), \tag{4}$$

where λ and φ are the longitude and latitude, respectively. a is the earth radius.

Combining (4) and (1), the following formula can be derived:

$$\nabla \cdot \vec{Q} = \frac{1}{g}\int_{100}^{P_0} \nabla \cdot (\vec{V}q)\mathrm{d}p = \frac{1}{g}\int_{100}^{P_0} \vec{V} \cdot \nabla q\mathrm{d}p + \frac{1}{g}\int_{100}^{P_0} q \cdot (\nabla \cdot \vec{V})\mathrm{d}p. \tag{5}$$

It is seen from the right side of Eq.(5) that the divergence of water vapor transport is made up of two parts. Part one (the first term of the right side of Eq.(5)) is the divergence of water vapor due to the water vapor advection, and part two (the second term on the right side of Eq.(5)) is the divergence of water vapor due to the divergence of wind field.

From the first term of right side of Eq.(5), it may be seen that when the wind flows from the high specific humidity zone to the low specific humidity zone, this term is negative and may be called as the wet advection, which is advantageous to the convergence of water vapor transport. On the contrary , when the wind flows from the low specific humidity zone to the high specific humidity zone, this term is positive and may be called the dry advection, which is favorable to the divergence of water vapor transport. Similarly, from the second term of the right side of Eq.(5), it is also seen that when the wind field is convergent, it has a positive contribution to the convergence of water vapor transport. On the contrary, when the wind field is divergent, it is advantageous to the divergence of water vapor transport.

If the liquid water and solid water in the atmosphere are omitted, then, the water balance in a unit column of air could be expressed as

$$\frac{\partial W}{\partial t} = -\nabla \cdot \vec{Q} + (E - P), \tag{6}$$

where W reprensents the precipitable water, i.e., storage water vapor in a unit column of air; P is precipitation, and E is evaporation. Formula (6) shows that the variation of the water vapor content in a unit column of air is associated with the convergence (divergence) of water vapor in the column, the water vapor evaporated from the underlying surface of the air column as well as the rainfall in the air column.

If we integrate Formula (6) for a longer time period, for example, a month or a quarter, the saturation and condensation water vapor in the air column is changed continuously into precipitation. Therefore, when $t-t_0$ is large enough, the following formula can be obdained:

$$\int_{t_0}^{t_1} \frac{\partial W}{\partial T} \mathrm{d}t \approx 0,$$

thus, Eq.(6) can be changed into Eq. (7),

$$\int_{t_0}^{t_1} P\mathrm{d}t = -\int_{t_0}^{t_1} \nabla \cdot \vec{Q}\mathrm{d}t + \int_{t_0}^{t_1} E\mathrm{d}t. \tag{7}$$

Eq. (7) explains that the precipitation at a certain place for a month or a quarter is dependent on the convergence of water vapor flowed into the region and the evaporation from the surface of the region for this period of time. Of course, the water vapor evaporated from the surface of this region comes mostly from the precipitation within this region.

3.2 *Convergence (Divergence) of Water Vapor Caused by the Water Vapor Advection*

The investigation by Huang Ronghui and Sun Fengying[12] revealed that in the summers of 1980, 1982, 1983 and 1987, the rainfalls in the Yangtze River and the Huaihe River valleys were above normal and floods happened there; whereas in the summers of 1981, 1984, 1985 and 1988, the rainfalls in the Yangtze River and the Huaihe River valleys were below normal and droughts happened there. This is associated closely with the convergence of water vapor transport by the East Asian summer monsoon. For this reason, by utilizing the observational data from 1980 to 1989 and the first term on the right side of Eq. (5), the divergence of water vapor transport due to the water vapor advection in summer was computed. Fig.4 and Fig.5 show the divergence of water vapor transport flux caused by the water vapor advection for the drought summers (1981, 1984, 1985 and 1987) and in the flood summers (1980, 1982, 1983 and 1987) in the Yangtze River and the Huaihe River valleys, respectively. It may be found from Fig.4a and Fig.4b that either in the drought summer or in the flood summer in the Yangtze River and the Huaihe River valleys, a divergent region of water vapor caused by the large dry advection situates in the area from the Somali–Jet zone to the west of the Indian Peninsula by the Arabian Sea, another divergent region of water vapor by the larger dry advection is located in the west of the Indo–China Peninsula. Under these two circumstances, the Indian Peninsula lies in the divergent region of water vapor transport due to the smaller dry advection, while the East Asian monsoon region is located in the convergent zone of water vapor transport caused by the wet advection. Moreover, comparing Fig.4a with Fig.4b, it may be seen that the convergence of water vapor caused by the wet advection in the East Asian monsoon region in the flood summer is much stronger than that in the drought summer. These evidences show that the summer rainfall in East Asia is prominently due to the water vapor advection by the summer monsoon.

3.3 *Convergence (Divergence) of Water Vapor Transport Caused by the Convergence (Divergence) of Wind Field*

By using the observed data from 1980 to 1989 and the second term of the right side of Eq.(5), the divergence of water vapor transport flux caused by the convergence (divergence) of wind fields can also be estimated. Fig.5a and Fig.5b exhibit the divergence of water vapor caused by the convergence (divergence) of wind field for the summers of flood and drought in the Yangtze River and the Huaihe River valleys, respectively. It can be seen from Fig.5a and

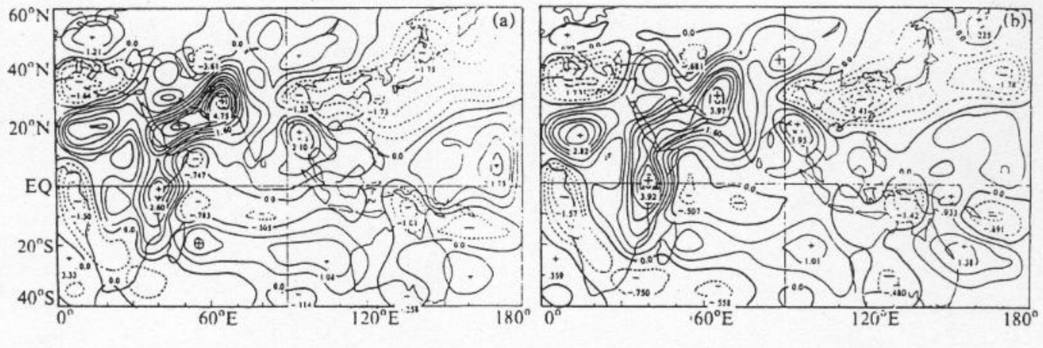

FIGURE 4. Distributions of the divergence of water vapor transport flux due to the water vapor advection in summer. (a) in the summer of drought in the Yangtze River and the Huaihe River valleys; (b) in the summer of flood in the Yangtze River and the Huaihe River valleys. Units: mm / d.

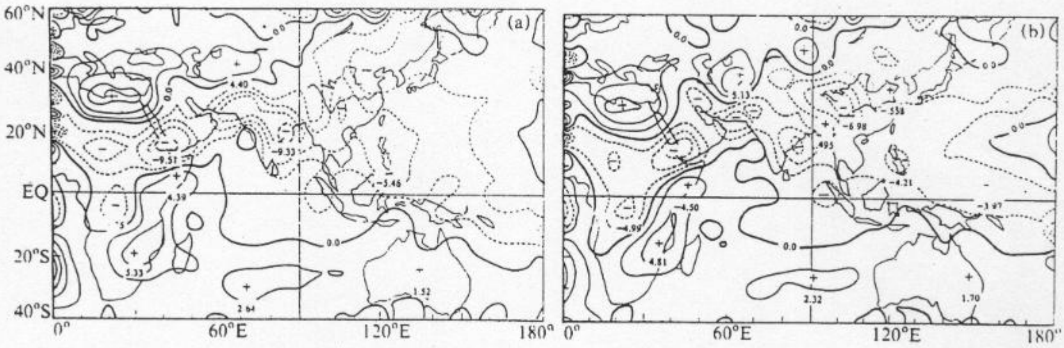

FIGURE 5. Same as in Fig.4 but for the divergence of water vapor transport due to the divergence of wind field.

Fig.5b that either for the drought or flood summer in the Yangtze River and the Huaihe River valleys in China, the Indian monsoon region and the East Asian monsoon region are all situated in the convergence zone of wind field. However, in the summer of drought in the Yangtze River and the Huaihe River valleys, the maximum convergence of water vapor transport due to the convergence of wind field is found in the Indian monsoon region, while the convergence of water vapor transport caused by the convergence of wind field is relatively smaller in the East Asian monsoon region. On the other hand, in the summer of flood in the Yangtze River and the Huaihe River valleys, the convergence of water vapor transport due to the wind in the East Asian monsoon region is the same as that in the Indian monsoon region.

Comparing Fig.5 with Fig.4, it may be seen that in the Indian monsoon region, the convergence (divergence) of water vapor transport caused by the convergence (divergence) of wind field is more than that by the water vapor advection. The above analysis shows that the mechanism for the convergence (divergence) of water vapor transport in the East Asian monsoon region differs from that in the Indian monsoon region in summer. The convergence (divergence) of water vapor transport in the Indian monsoon region in summer is primarily due to the convergence (divergence) of wind field in the monsoon circulation system; while in the

East Asian monsoon region, the convergence (divergence) of water vapor transport is mainly caused by the water vapor advection (wet advection) by the monsoon flow. Moreover, besides the wet advection, the convergence of wind field is also important in the flood summer in the Yangtze River and the Huaihe River valleys.

4. CHARACTERISTICS OF SPECIFIC HUMIDITY IN THE EAST ASIAN MONSOON REGION AND ITS DIFFERENCE FROM THAT IN THE INDIAN MONSOON REGION IN SUMMER

It has been known from last section that the convergence (divergence) of water vapor transport in the East Asian monsoon region in summer is mainly due to the water vapor advection; while it is largely caused by the convergence (divergence) of wind field in the Indian monsoon region. Why is it so? We will explain this problem in the following.

The first term in Eq.(5) can be written as

$$\frac{1}{g}\int_{100}^{P_0}\vec{V}\cdot\nabla q\mathrm{d}p=\frac{1}{g}\int_{100}^{P_0}\left(u\frac{\partial q}{a\cos\varphi\partial\lambda}+v\frac{\partial q}{a\cos\varphi\partial\varphi}\right)\mathrm{d}p. \tag{8}$$

The climatological–mean specific humidity q at various levels can be computed by using the observational data from 1980 to 1989. Figs.6a–c give the latitude–altitude cross–sections of the climatological–mean q along 80°E for June, July and August, respectively. Since the Indian monsoon region situated to the south of the Tibetan Plateau, i.e., between 10~30°N, it is seen from Figs.6a–c that the term $\partial q / a\cos\varphi\partial\varphi$ is positive but smaller. Therefore, the southwest monsoon has a negative contribution to the convergence of water vapor transport

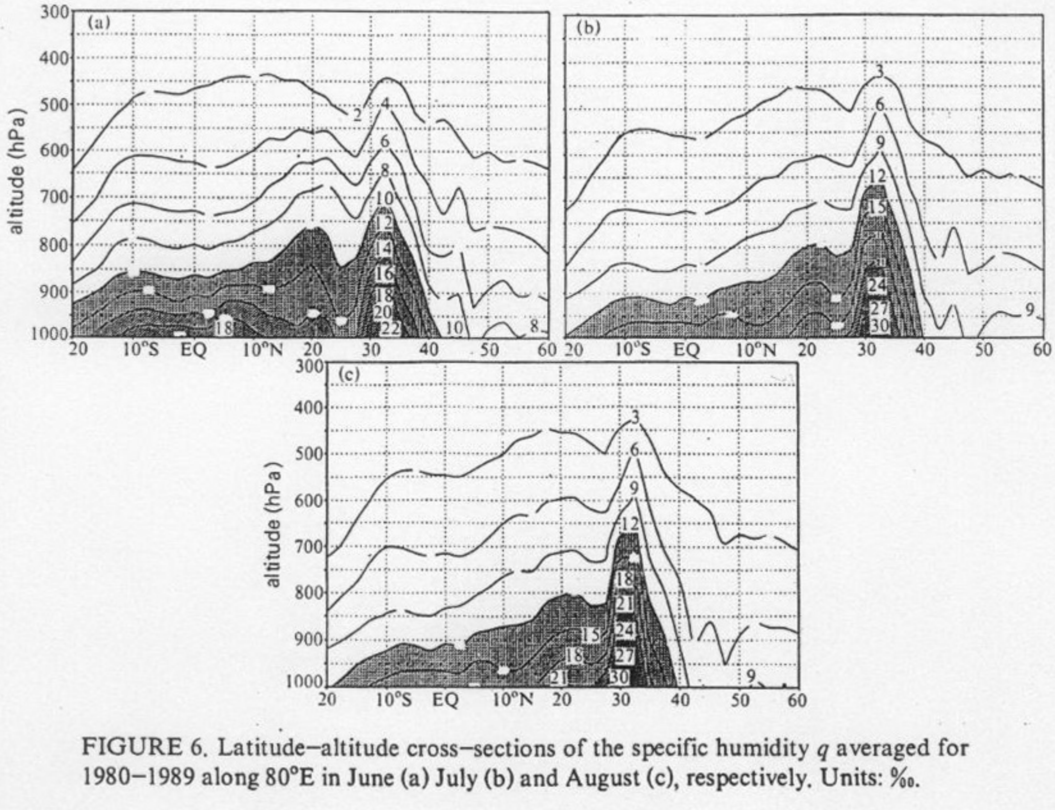

FIGURE 6. Latitude–altitude cross–sections of the specific humidity q averaged for 1980–1989 along 80°E in June (a) July (b) and August (c), respectively. Units: ‰.

in the Indian monsoon region, i.e., $v(\partial q / a\cos\varphi\partial\varphi) > 0$, which is advantageous to the divergence of water vapor. Figs.7a–c are the latitude–altitude cross–sections of the climatological–mean q along 115°E for June, July and August, respectively. It shows that, in the East Asian monsoon region (25–40°N), the term $\partial q / a\cos\varphi\partial\varphi$ is of great negative value, hence, the southwest and southeast monsoons play a positive effect on the convergence of water vapor in the East Asian monsoon region, i.e. $v(\partial q / a\cos\varphi\partial\varphi) < 0$, which is in favor of the convergence of water vapor there.

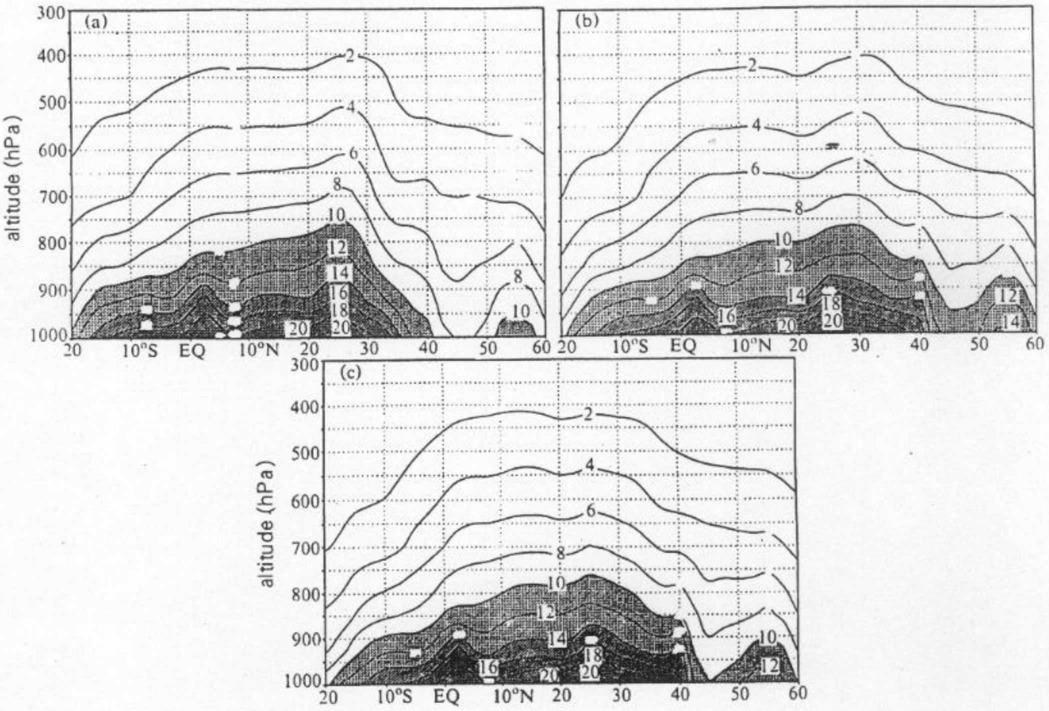

FIGURE 7. Same as in Fig.6 but for the case along 115°E.

Fig.8a and Fig.8b are the longitude–time cross–sections of q at 700 hPa for each month averaged from 1980 to 1989 along 25°N and 30°N, respectively. It shows that, in the Indian monsoon region, $\partial q / a\cos\varphi\partial\lambda \approx 0$, the southwest monsoon contributes little to the convergence of water vapor, while in the East Asian monsoon region, $\partial q / a\cos\varphi\partial\lambda < 0$, therefore, the southwesterly is favorable to the convergence of water vapor there.

From the above analysis, it may be found that the water vapor advection by the monsoon is advantageous to the convergence of water vapor in the East Asian monsoon region and disadvantageous to that in the Indian monsoon region. Consequently, in summer, the water vapor advection induced by the southwest and southeast monsoon is favorable to the monsoon precipitation in the East Asian monsoon region. However, the water vapor advection induced by the southwesterly is not favorable to the monsoon precipitation in the Indian monsoon region, and the rainfall may be caused by the convergence (divergence) of wind field there. Thus, the Indian monsoon low may paly an important role in the convergence of water vapor and the precipitation in the Indian monsoon region.

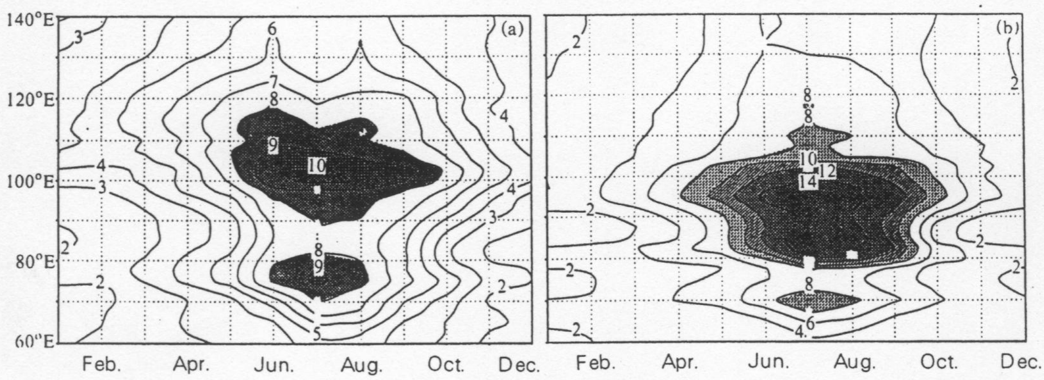

FIGURE 8. Longitude–time cross–sections of the specific humidity q averaged for 1980–1989 at 700 hPa along 25°N (a) and along 30°N (b). Units: ‰.

5. CONCLUSIONS AND DISCUSSION

In this paper, by using ECMWF daily data of water vapor and wind at various levels from 1980 to 1989, the characteristics of water vapor transport in the East Asian monsoon region in summer are analyzed and compared with that in the Indian monsoon region.

The analyzed results reveal that the characteristics of water vapor transport in summer in the East Asian monsoon region are different distinctly from that in the Indian monsoon region. In the East Asian monsoon region, the meridional transport of water vapor is larger than the zonal transport; while in the Indian monsoon region, the zonal transport of water vapor is dominant. The results also show that since the distribution of water vapor in the East Asian monsoon region is large in the south and small in the north, the water vapor advection by the southerly monsoon flow is the wet advection, which is important for the convergence of water vapor there. However, in the Indian monsoon region, the water vapor advection by the monsoon flow is the dry advection, which is favorable to the divergence of water vapor transport, thus, the convergence of water vapor is primarily caused by the convergence of wind field there. These may explain that the summer monsoon rainfall in the East Asian monsoon region basically results from the water vapor advection by the summer monsoon, whereas in the Indian monsoon region, the summer rainfall is mainly due to the convergence of wind field in the summer monsoon circulation system. But in the summer of flood in the Yangtze River and the Huaihe River valleys, the convergence of wind in the monsoon circulation system is of great importance as well.

The analyzed results in this paper may explain that the East Asian monsoon is different from the Indian monsoon not only in the horizontal circulation structure and meridional circulation, but also in the water vapor transport. Therefore, the East Asian monsoon and the Indian monsoon are two subsystems of the Asian monsoon system, which are related to each other on one hand, but are independent of each other on the other.

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