Precipitation and Moisture Balance of the Asian Summer Monsoon in 1991

Part II: Moisture Transport and Moisture Balance

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Abstract

Features of the moisture transport and the moisture balance within the Asian summer monsoon region in 1991 are studied utilizing the 24-hour prediction data by a global weather prediction model in relation to changes of precipitation and the major circulation systems (CSs) defined in Part I of the present paper.

The change during May, June and July is characterized by a shift of the intense rainfall areas, with the strong moisture sink from the equatorial zone over the Indian Ocean and Indonesia, to the subtropical area of the Indian subcontinent and East Asia. The southwesterly moisture transport in 30–80°E is mainly due to CS-3 (the clockwise circulation over the Indian Ocean), whereas the southwesterly moisture transport in 80–110°E and 110–140°E is mainly due to CS-4 (clockwise circulation around Indonesia) and CS-5 (circulation around the Pacific subtropical anticyclone), respectively. The confluence between the adjacent CSs yields strong southerly moisture transport into the monsoon rainfall areas and large moisture-flux convergence.

It is an important fact that the seasonal variation of the moisture flux crossing the boundary of a large domain, which is bounded by 10°S, 40°N, 35°E and 140°E, and the variation of cross equatorial moisture transport from the southern hemisphere, are significantly smaller than the variations of the moisture transport within the domain. The moisture balance calculation also indicates that the essential feature of the summer monsoon is the formation of a pair of moisture source region, and the adjacent moisture sink region, within the large domain. The moisture source regions form under the subsidence and convective stable stratification. The moisture sink regions appear under the ascent motion and convective unstable stratification.

Several parameters such as “moisture influx ratio” and “rainfall production ratio” are defined to discern the characteristics of the moisture balance. The temporal and spatial variations of these parameters depict well the features of moisture balance within the Asia summer monsoon region.

1. Introduction

Various studies have been extensively made about the moisture transport and moisture balance in relation to the Asia monsoon rainfalls from the various viewpoints. The important results of previous studies will be briefly summarized.

Murakami *et al.* (1984) pointed out the following features of the moisture balance in the 1979

summer monsoon. In May, the moisture supply for the rainfall near the west coast of Burma and Malaysia comes primarily from the Bay of Bengal, not from the Southern Hemisphere. In JJA, the cross-equatorial moisture flux off the east coast of Kenya is not large enough to maintain the rainfalls over South and Southeast Asia. Evaporation over the Arabian Sea is the key contribution to the moisture supply for monsoon rains. The northward and eastward passage of 40–50 day perturbations is related to the phase changes between active and break monsoons over the central South and Southeast Asia. When the active monsoons begin, the

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moisture sinks become above normal over the Arabian Sea. About 5–7 days later, the moisture sink reaches its maximum over the Bay of Bengal. This is followed by the intensification of the moisture sink over the South China Sea region about 5 days later.

Pearce (1992) discussed the water balance of the Asian summer monsoon for JJA of 1990. The amount of latent heat supply from the Indian Ocean is $\sim 180 \text{ W m}^{-2}$. As for the domain bounded by 22.5°S – 32.5°N and 37.5°E – 117.5°E , most of the moisture is carried by the low-level flow. It enters in this region on the eastern edge between Australia and the equator, and leaves it through Bangladesh and the South China Sea. The latent heat net transport from the domain is $\sim 8 \times 10^{14} \text{ W}$, which is $\sim 10\%$ of the latent heat supply from the sea surface within the domain. He inferred that the variability of rainfall, on a time-scale of one month, is determined by feed back mechanisms within this region.

Cadet and Greco (1987a) stated the following features of the water vapor flux over the Indian Ocean during the 1979 summer monsoon. After the monsoon onset, while the cross-equatorial vapor flux does not vary much west of $\sim 50^{\circ}\text{E}$, it undergoes significant fluctuation east of 50°E . The vapor flux across the west coast of India undergoes a large variation with the active-break cycle of the monsoon. The bulk of water vapor crossing the western coast of India comes from the southern hemisphere, where the major moisture source region is seen in the 10 – 20°S latitude belt. The major moisture supply for the west coast of Burma and Thailand is advected over the Bay of Bengal from the Arabian Sea branch of the monsoon.

Cadet and Greco (1987b) calculated the water budget over the Arabian Sea and the Bay of Bengal for the 1979 monsoon. Water vapor from the southern hemisphere is the major moisture source for Indian rainfall. During the active phase, total evaporation is 30–40 % of the total eastward flux across the west coast of India. This ratio increases to 40–50 % during the break conditions, but falls below 20 % during the revival period. The convergence of water vapor flux is limited to the eastern part of the Arabian Sea, whereas evaporation exceeds precipitation in the western Arabian Sea. The moisture supply from the southern hemisphere via cross-equatorial flux at the latitude of the Bay of Bengal is very weak. In the active phase, large evaporation from the Bay enhances transport from the Bay area to Indochina.

Luo and Yanai (1984), He *et al.* (1987) and Yanai *et al.* (1992) discussed the seasonal and regional characteristics of the moisture sink/source in relation to the seasonal heating of the Tibetan Plateau. The moisture sink is small over the western Tibetan Plateau throughout the summer monsoon, while the large moisture sink continues over the east-

ern Plateau after mid-June. The significantly large moisture sinks appear over southern Asia, south China and southwestern India concurrent with the commencement of rain periods, *i.e.*, mid-May, late-May and mid-June, respectively. The maximum value of the vertically integrated moisture sink in these regions exceeds $\sim 300 \text{ W m}^{-2}$ ($\sim 10 \text{ mm/day}$). On the other hand, the Arabian Sea is characterized by the moisture source associated with the subsidence yielded by radiative cooling throughout the monsoon season.

Many authors (*e.g.*, Tao and Chen, 1987; Ding, 1991) pointed out that the large southwesterly moisture transport from the Bay of Bengal and the South China Sea is one of the important conditions for the occurrence of intense monsoon rainfall over China. The southwesterly over these areas is significantly intensified when the Indian westerly monsoon and the cross-equatorial flow from Australia converge.

Several authors (*e.g.*, Akiyama, 1973 and 1975; Ninomiya, 1984; Ninomiya and Murakami, 1987; Ninomiya and Akiyama, 1992) stated that the major part of the monsoon rainfall over East Asia occurs within the Baiu/Meiyu front. This front is sustained by the low-level southwesterly prevailing along the rim of the North Pacific subtropical anticyclone through the frontogenesis in the deformation field, and the generation of convective instability due to the differential advection. The moisture budget analysis indicates that the intense rainfall with strong moisture convergence in the frontal zone is always accompanied by the strong southwesterly moisture inflow into the frontal zone. Thus, the circulation around the subtropical anticyclone is inferred to be one of the key factors sustaining the East Asia monsoon rainfall.

In spite of these extensive studies, the following problems have not been fully explicated;

- (1) Variations of the moisture balance over the whole monsoon region.
- (2) The characteristics of moisture balance in monsoon sub-regions.
- (3) Relations among the moisture balance, moisture transport, precipitation and the major circulation systems in and around the monsoon region.

Since features of the Asian summer monsoon vary significantly year to year, studies of the monsoon for various years are needed to fill the remaining problems. As the first step, we will study the moisture transport and moisture balance of the Asian summer monsoon for May, June and July (MJJ) 1991 in relation to the precipitation variation and the major circulation systems elucidated in Part I of the present study (Ninomiya and Kobayashi, 1998).

2. Data utilized for the present study and outline of the analysis

The 24-hour prediction data obtained for 00 and 12 UTC by a global spectral model (GSM T106) of the Numerical Prediction Division, JMA, which is stored in the latitude and longitude grid system with 2.5° interval, are utilized for the present study. The brief description of GSM T106 and the reason of using the prediction data have already been given in Part I. The daily analyzed global sea surface temperature is used for the numerical prediction. The land surface temperature and soil moisture are evaluated by SiB included in the model (Numerical weather prediction Division, JMA, 1993). Here we note again that every predicted meteorological quantities, such as the vertical velocity, moisture, precipitation and the moisture supply from the underlying surface are consistent with each other, because they are adjusted in the process of time integration according to the physical laws incorporated in the model.

Notations used in the present study will be defined here; The precipitable water W and the vertically integrated moisture transport $\mathbf{Q}$ is calculated at each grid point for every 12-hour by

$$W = 1/g \int q dp, \text{ and } \mathbf{Q} = 1/g \int q \mathbf{v} dp,$$

where q and $\mathbf{v}$ are the mixing ratio of the water vapor and wind velocity, respectively. The vertical integration is made for the layer between the surface pressure (the grand surface pressure in case over the land) and 300 hPa. The zonal and meridional component of the vertically integrated moisture transport, Qu and Qv , are also obtained respectively by

$$Qu = 1/g \int q u dp, \text{ and } Qv = 1/g \int q v dp.$$

The moisture balance equation is given by

$$(\partial W / \partial t) + \text{div } \mathbf{Q} = e - r,$$

where e and r indicates the evaporation from the underlying surface and the rainfall amount, respectively. If the 10-day mean field is discussed, the magnitude of the first term in the left hand side is negligibly smaller than other terms in the equation. Therefore, the positive value of $\text{div } \mathbf{Q}$ indicates the net moisture source ($e > r$), while the negative value means net moisture sink ($e < r$).

For the most simple expression of the moisture balance, the whole monsoon region is divided into sub-areas, and the zonal and meridional moisture flux (Fu and Fv) crossing the boundary of each sub-area are calculated by,

$$Fu = \int Qu Re d\psi, \text{ and}$$

$$Fv = \int Qv Re \cos \psi d\lambda,$$

where Re , ψ and λ are radius of the earth, latitude and longitude, respectively.

The area integration of $\text{div } \mathbf{Q}$ is obtained by

$$D = \int \text{div } \mathbf{Q} dS = \oint \mathbf{Q}_n ds$$

$$= \Sigma (Fu \text{ and } Fv) = Fo - Fi,$$

where dS , ds , Fo and Fi are the area element, the line element along the boundary of the relevant sub-area, moisture efflux and the moisture influx, respectively. $\mathbf{Q}_n$ is the normal component of $\mathbf{Q}$ to ds .

The area integrated precipitable water M , precipitation R and the evaporation from the underlying surface E are respectively defined as

$$M = \int W dS, R = \int r dS, \text{ and } E = \int e dS.$$

The area element is given by

$$dS = Re \cos \psi d\psi d\lambda.$$

The increment of M is then defined as

$$Mt = \partial M / \partial t.$$

The moisture balance equation for the sub-area is given by $\Delta = D + Mt = E - R$.

Since Mt is negligibly smaller than other terms, as for the 10-day averaged field, we have $D = Fo - Fi \doteq E - R$.

In the following sections, the features of the 10-day averaged field of aforementioned quantities are discussed for nine sub-periods in MJJ 1991.

3. Overview of the Asian summer monsoon in 1991

Features of the Asian summer monsoon in 1991 referring the results of Part I of the present study, are presented. Table 1 summarizes the large-scale features over 40–110°E and 110–150°E for nine 10-day subperiod in MJJ 1991.

The most remarkable change around early June over the Indian Ocean and Southeastern Asia is the rapid displacement of the major precipitation areas from the equatorial zone to the Indochina Peninsula and Indian subcontinent. The notable change over the East Asia is the formation of a precipitation belt, which corresponds to the Meiyu/ Baiu frontal zone.

In order to clearly express the relation between the variations of precipitation with those of the low-level circulation, we defined eight major circulation systems (CSs) in the lower troposphere, and illustrated them schematically in Fig. 1. The location and extension of CSs indicate certain variations with time. Among them, variations of the clockwise circulation over the Indian Ocean (CS-3), and a cyclonic circulation over the Indian subcontinent (CS-6), are closely related with variations of the Indian monsoon rainfalls. The cross-equatorial flow from

Table 1. Sub-periods in MJJ of 1991 and the main features in these sub-period.

Period	Date	Features in 40–110°E	Features in 110–150°E
May-I	1–10 May	pre monsoon period	pre-monsoon rainfall
May-II	11–20 May	pre monsoon period	pre-monsoon rainfall
May-III	21–30 May		formation of Baiu rainfall zone
June-I	1–10 June	onset of the Indian monsoon	intensification of Baiu rain
June-II	11–20 June	break of the Indian monsoon	1st monsoon westerly burst
June-III	21–30 June		peak period of Baiu rainfall
July-I	1–10 July	second onset of the monsoon	peak period of Baiu rainfall
July-II	11–20 July	second onset of the monsoon	2nd monsoon westerly burst
July-III	21–30 July		disappar. of Baiu rainfall zone

Fig. 1. The schematic illustration of the eight major circulation systems in and around the Asian summer monsoon region.

the Australia anticyclone (CS-4), and the circulation around the North Pacific subtropical anticyclone (CS-5), are the major systems related with East Asia rainfalls.

The mixing ratio of water vapor, equivalent potential temperature, vertical stability and vertical motion also vary in association with the variations of precipitation and CSs. During the Asian summer monsoon season, the gradual decrease of mixing ratio and increase of the vertical stability in association with the subsidence are significant features over the western tropical Indian Ocean, while the increase of the mixing ratio and vertical instability are the notable features over the Indian sub continent, Indochina Peninsula and the southern part of China.

The features of the sea surface water temperature (SST) will be very briefly noted. In the Pacific and Indian Ocean bounded by 40°N, 20°S, 30°E and 180°E, any significant SST anomaly is not found throughout the 1991 MJJ.

4. Moisture transport and major circulation systems

The 10-day mean field of vertically integrated moisture transport Q for May-II and July-II are pre-

sented in Fig. 2 as examples. The Q -field indicates significant seasonal change during MJJ 1991. With the seasonal march of the monsoon, the clockwise moisture transport by CS-3 and CS-4 become predominant over 40–80°E and 80–120°E, respectively. Over the western North Pacific, the clockwise moisture transport accompanied by CS-5 is a predominant feature.

In order to extract the key features of the moisture transport from Q -field we will present “the axis of maximum zonal and meridional moisture transport” in Fig. 3 by plotting the maximum value of 3-grid average of Qu and Qv along the respective meridional and latitude circle. In these maps, the areas with rainfall more than 10 mm/day are indicated by hatching. It is obvious that “the axes of the moisture transport” are closely related to the major circulation systems. From these maps, following temporal variations of the moisture transport are pointed out:

a. Pre Indian monsoon period

In May-II (Fig. 2A and Fig. 3A), the easterly transport predominates over the tropical and subtropical latitude in both the southern and northern hemisphere, except the small areas over the equatorial African coast, whereas the westerly moisture

Fig. 2. The 10-day mean maps of Q for May-II and July-II. A wind barb indicates the moisture transport of $20 \text{ g (m/sec) cm}^{-2}$.

transport predominates over the middle latitudes north to $\sim 25^\circ\text{N}$.

The southerly moisture transport over the Bay of Bengal ($\sim 85^\circ\text{E}$) is not associated with southwesterly of CS-3 but southerly flow CS-4, which is enhanced by the development of the tropical disturbance over the southern part of India.

b. The first onset of the Indian monsoon

The westerly moisture transport by CS-3 begins to intensify in the northern equatorial zone over the Indian Ocean in May-III (map is not shown). In June-I (Fig. 3B), the westerly transport covers large parts of the Arabian Sea and the northern Indian Ocean. The first onset of the Indian monsoon in June-I is identified as the maximum of the westerly moisture transport ($\sim 60 \text{ g m s}^{-1} \text{ cm}^{-2}$) and precipitation over the western India (maximum $\sim 30 \text{ mm/day}$, figure is not shown).

The westerly moisture flow of CS-3 extends eastward, merging with that of CS-4, and intensifies the southwesterly transport over the Bay of Bengal and

the South China Sea. The development of the monsoon depression over the Indian subcontinent also attributes the intensification of the southerly transport over the Bay of Bengal. The confluence of the intensified westerly moisture flow of CS-3 and CS-4 with the easterly moisture flow of CS-5 in the monsoon trough region results in the strong southerly moisture transport over the South China Sea and the coastal area of China.

c. Break of the Indian monsoon

The westerly moisture transport over the southern Arabian Sea and the northern Indian Ocean decrease rapidly in the break period of the Indian monsoon (June-II, Fig. 3C) to $\sim 30 \text{ g m s}^{-1} \text{ cm}^{-2}$. The precipitation over the western coast of India decreases concurrently to $\sim 5 \text{ mm/day}$ (figure is not shown). The southerly moisture transport over the Bay of Bengal in the onset period turns to the southwesterly transport in the break period, with the weakening of the monsoon depression over India.

Fig. 3. The distribution of the maximum zonal and meridional moisture transport (max. Q_u and max. Q_v) for May-II, June-I, June-II, July-I and July-II 1991. The hatched areas indicate the areas of precipitation more than 10 mm/day.

d. Variation of the moisture transport over East Asia

With the first westerly burst into the western North Pacific in June-II (Fig. 3C), "the axis of maximum meridional moisture transport in the monsoon trough region" which is abbreviated as monsoon trough hereafter, moves eastward to $\sim 125^\circ\text{E}$ in $5-25^\circ\text{N}$. The increase of the precipitation in the Meiyu/Baiu frontal zone is concurrent with the intensified southerly moisture inflow toward $\sim 30^\circ\text{N}$.

However, with the weakening of the monsoon westerly, the monsoon trough shifts westward to $\sim 110^\circ\text{E}$ in July-I (Fig. 3D). The southerly moisture transport over the South China Sea and southern China increases around the westward moving monsoon trough. The full extension of the Meiyu/Baiu frontal precipitation belt with maximum precipitation of ~ 25 mm/day (figure is not presented) is seen in this phase.

Fig. 3. (Continued)

e. Second onset of the Indian monsoon

The westerly moisture transport begins to increase over the Arabian Sea and the northern Indian Ocean in July-I (Fig. 3D). Around July-II (Fig. 2B and Fig. 3E), the large zonal moisture transport of $\sim 70 \text{ g m s}^{-1} \text{ cm}^{-2}$ is found around 15°N from the African coast to the Bay of Bengal. In this period, the precipitation around the west coast of India and Bangladesh reaches ~ 30 and $\sim 35 \text{ mm/day}$, respectively (figure is not shown). With propagation of the second westerly burst to $\sim 140^\circ\text{E}$, the monsoon trough in Q field is remarkably intensified in July-II as it shifts eastward. The area of the southerly flux extends from the monsoon trough region to $\sim 35^\circ\text{N}$ over China and the Japan Sea.

In addition to the aforementioned temporal variations of the moisture transport, we include the following important features in the moisture transport;

1) The spatial stepwise northward jump of moisture transport

We can point out “the spatial stepwise northward jump of moisture transport” as a characteristics in the monsoon period (see Fig. 3B and Fig. 3D for examples). The first (west-most) northward step of the moisture transport from the southern hemi-

sphere to $\sim 10^\circ\text{N}$ over the western Indian Ocean is accompanied by the cross equatorial flow of CS-3. The second (central) northward step of the transport from $\sim 10^\circ\text{N}$ to $\sim 20^\circ\text{N}$ in $90\text{--}110^\circ\text{E}$ is owing the southerly flow of CS-4, while the third (east-most) step of the transport from $\sim 20^\circ\text{N}$ to the Baiu/Meiyu frontal zone ($\sim 30^\circ\text{N}$) is due to the southerly flow of CS-5.

The large southerly moisture transport in $80\text{--}130^\circ\text{E}$ appears only when and where the moisture flows of the adjacent major circulation systems form significant convergence and confluence in the moisture flux field. The large southerly moisture transport is not necessarily accompanied by the larger moisture transport from the southern hemisphere, but is mainly associated with the zonal moisture flux convergence in the tropical zone in the northern hemisphere. The typical situations are seen in June-I (Fig. 3B) over $\sim 85^\circ\text{E}$, where the westerly moisture flow of CS-3 converges with the southerly flow of CS-4, and in July-II (Fig. 2B and Fig. 3E) over $\sim 115^\circ\text{E}$, where the westerly moisture flow of CS-4 converges with the easterly flow of CS-5. The main precipitation areas also shift in association with the aforementioned variations of the confluence and con-

Fig. 4. The latitude-time section of the 10-day averaged moisture transport Q along 70°E during MJJ 1991.

vergence area in the moisture flux field.

2) The seasonal stepwise changes in the moisture transport

The seasonal stepwise changes in the moisture transport are seen as the northward shift of the zonal moisture transport axis. Figure 4 presents the 10-day averaged Q on the latitude-time section along 70°E . In this figure, the axis of the westerly transport in May-III appears over $\sim 2.5^\circ\text{N}$. The onset of the Indian monsoon is seen in June-I as the rapid intensification of the westerly transport in 0 – 15°N with the maximum of $\sim 60 \text{ g m s}^{-1} \text{ cm}^{-2}$ at $\sim 5^\circ\text{N}$. It decreases once in the monsoon break period in June-II to $\sim 35 \text{ g m s}^{-1} \text{ cm}^{-2}$. It increases again rapidly around July-II with the second monsoon onset. In this period the maximum transport of $\sim 70 \text{ g m s}^{-1} \text{ cm}^{-2}$ appears at $\sim 15^\circ\text{N}$. The seasonal northward propagation speed of the maximum moisture transport belt is $\sim 10^\circ$ latitude/50-day on the average, although the seasonal shift is by no means continuous. Over East Asia (110 – 140°E , figure is not shown), the axis of westerly moisture transport appears at $\sim 30^\circ\text{N}$ with the first onset and jumps to $\sim 40^\circ\text{N}$ after the second onset.

3) Intraseasonal variation in the moisture transport

The longitude-time section of the 10-day averaged Q along 10°N latitude circle is shown in Fig. 5. The first monsoon onset is identified as the appearance of the strong westerly transport in June-I. The

Fig. 5. The longitude-time section of the 10-day averaged moisture transport Q along 10°N during MJJ 1991.

eastward expansion of the westerly transport toward $\sim 140^\circ\text{E}$ occurs in June-II, ~ 10 -day after the first onset. In July-I, the eastern tip of the westerly flux retreats westward to $\sim 115^\circ\text{E}$. The eastward intrusion of the westerly flux to $\sim 140^\circ\text{E}$ takes place again following the second monsoon onset.

Figure 6 shows the time variation of the northward and eastward moisture transport crossing a few selected longitudinal and latitudinal sections. The moisture transport labeled by A, B and C represents the northward moisture transport by CS-3, CS-4 and CS-5, whereas the transport labeled by a, b, and c stands for the eastward moisture transport by CS-3, CS-4 and CS-5, respectively. The first and second monsoon onset appears as the maximum of these moisture transports. Especially, the increase of the moisture transport in the first onset is very large. The time lag of ~ 20 days between the peak in the transport in CS-3, and that in CS-5 is also evident. This indicates the eastward and northward propagation speed of $\sim 40 \text{ km/day}$ and $\sim 15 \text{ km/day}$, respectively.

5. Spatial and temporal variations of the precipitable water

The 10-day mean maps of precipitable water W for May-II, June-I, June-II, July-I and July-II of 1991 are presented in Fig. 7.

In May (see Fig. 7A for May-II), the area of small W less than 3 g cm^{-2} covers the northern part of Africa, the Arabian Peninsula, northern part of the Indian subcontinent and the zone north of $\sim 30^\circ\text{N}$. The area of W more than 5 g cm^{-2} is restricted generally within the equatorial belt over the oceans. The appearance of wet areas over the Bay of Bengal and southern China precedes about a half month to the onset of the monsoon rainfall over the western

Fig. 6. The time variation of meridional and zonal moisture transport crossing several latitudinal and longitudinal section as indicated in the figure. The moisture transport is given in units of 10^9 ton/day.

coast of India.

The moist area protrudes gradually from the tropical zone to the Bay of Bengal, the Indochina Peninsula and the South China Sea in late May (map is not shown). In the first onset of monsoon rainfall period over the western coast of India (June-I, Fig. 7B), the area of large W more than 5 g cm^{-2} covers a wide area from the eastern part of the Arabian Sea to the southern China in addition to the tropical belt. The area of largest W more than 6 g cm^{-2} appears over the west coast of India, the Bay of Bengal and the South China Sea. The northern limit of the moist area along the coast of the Arabian sea is bounded by the northerly wind of CS-7, whereas the limit in $70\text{--}100^\circ\text{E}$ is seen along the southern rim of the Tibetan Plateau.

The decrease of W over the western Indian Ocean due to the dry advection and subsidence in the southerly flow of CS-3 is also a notable feature. The area of relatively small W less than 4 g cm^{-2} elongates northward from the southern Indian Ocean along the east coast of Africa.

The pattern of W shows significant variations in the monsoon period. In the break period of rainfall

over the western coast of India (June-II, Fig. 7C), the moist area ($W > 5 \text{ g cm}^{-2}$) over the Arabian Sea and the western Indian Ocean shrinks once eastward. The moist area, however, expands westward to the central part of the Arabian Sea concurrent with the increase of the westerly around the second onset period of the Indian monsoon rainfall (July-I and July-II, Fig. 7D and Fig. 7E).

The notable changes in W field are also seen over East Asia and the western North Pacific. The westerly burst intrudes into the tropical North Pacific about 10 days after the first onset of the monsoon (see Section 4). Simultaneously, the Pacific subtropical anticyclone retreats eastward. With the intensification of the monsoon trough over the South China Sea, which is due to the confluence of the monsoon westerly of CS-3 and CS-4 to the easterly of CS-5, the high moisture area shifts northward from the tropical zone to the East China Sea and southern China (June-II, Fig. 7C). With the weakening of the monsoon westerly, the Pacific subtropical anticyclone extends westward again. In July-I (Fig. 7D, the peak period of the Baiu/Meiyu rainfall), the tongue shaped zone of high W , which corresponds to the Baiu/Meiyu frontal rain belt, indicates full extension from the Yangtze valley to the Japan Islands along the southwestern rim of the westward expanding Pacific subtropical anticyclone. In middle July (Fig. 7E), the moist area expands northward in $110\text{--}150^\circ\text{E}$, when the second westerly burst reaches to the western North Pacific up to $\sim 140^\circ\text{E}$, and the Pacific subtropical anticyclone shifts north-eastward.

6. Moisture balance in the Asian summer monsoon region

The 10-day mean maps of $\text{div } Q$ for May-II and July-II are shown in Fig. 8 as examples. The feature in the pre-monsoon period (May-II, Fig. 8A) is characterized by a moisture sink zone over the equatorial belt. A strong moisture sink region is seen over the $\sim 60^\circ\text{E}$ at equator. The $\text{div } Q$ field indicates significant changes with the onset of monsoon. The strong moisture sink disappears from the tropical Indian Ocean, while the moisture sink is sustained over the equatorial zone over the Pacific to the east of $\sim 150^\circ\text{E}$ in the monsoon period. The onset of the monsoon is accompanied by the shift of the strong moisture sink from the equatorial zone to the Indian subcontinent and the Indochina Peninsula (Fig. 8B). The formation of the moisture sink belt over the Baiu/Meiyu frontal zone in June and July is also a notable feature.

During the monsoon period, a significant moisture source is found over the western Indian Ocean and the Arabian Sea under the cross equatorial flow of CS-3 and CS-4. The moisture sources also appear over the vast oceanic areas under the southern hemi-

Fig. 7. The 10-day mean maps of the precipitable water (W in g cm^{-2}) for May-II, June-I, June-II, July-I and July-II of 1991. The isopleth is given at 1 g cm^{-2} interval. The blacked and hatched areas indicate the area of W larger than 6 and 5 g cm^{-2} , respectively.

sphere subtropical high belt and the North Pacific subtropical anticyclone. These moisture source regions coincide with the areas of subsidence and the stable stratification shown in Part I of the present paper.

Another moisture source region is seen over the southwestern part of the Bay of Bengal throughout the monsoon season. Weak subsidence, which

is inferred to be due to the descending motion over the lee side of India, is sustained over this moisture source region during the monsoon season.

In order to elucidate the feature of the moisture balance in the most simple expression, the whole monsoon region is divided into sub-areas of $10^\circ \text{ lat.} \times 15^\circ \text{ long.}$ dimension, and the zonal and meridional moisture flux (F_u and F_v) crossing the

Fig. 7. (Continued)

boundary of each sub-area are calculated as in Fig. 9. The features of the moisture balance will be described on the basis of Fig. 9.

a. Pre-monsoon period

In May (Fig. 9A for May-II), the easterly moisture flux of CS-1 and CS-2 predominates in the large portion of the equatorial zone, while the westerly moisture flux of CS-8 is seen over the mid latitudes. The appearance of a strong southerly flux in 90–120°E in May, which is due to southerly winds of CS-4 and CS-5, results in the moisture flux convergence and intense pre-monsoon rainfall around 30°N. In the pre-monsoon period, significant moisture convergence over the equatorial Indian Ocean forms between the easterly flux of CS-2, and the westerly flux of CS-3, which is still restricted in the equatorial zone during May.

b. The first onset of the Indian monsoon

In June-I (Fig. 9B), the westerly moisture flux within 0–10°N zone in 50–80°E increased abruptly with the increase of the cross equatorial flux in 35–50°E. However, the increase of the westerly flux

crossing 65°E meridian in 0–20°N is not fully accounted for by the increase of the cross equatorial moisture flux. The large moisture source in 0–20°N, 50–65°E contributes greatly to increase the moisture flux toward India. The northerly moisture flux crossing 20°N latitude circle in 65–80°E, which is due to the northerly wind in the west side of the monsoon onset depression, also contributes to the large moisture flux convergence over western India.

In this period, the large southerly moisture flux across the 10°N latitude circle in 80–95°E (over the Bay of Bengal) is mainly due to the confluence of the monsoon westerly of CS-3 with the southerly flow of CS-4, whereas the cross equatorial moisture flux of CS-4 in 80–110°E is relatively small. In 0–10°N and 80–110°E area, the meridional moisture flux increases northward (the meridional moisture flux divergence) at the expense of the westerly flux decrease (the zonal moisture flux convergence). Thus, the southerly winds of CS-4 transport the moisture mainly from the monsoon westerly zone to the subtropical area in 80–95°E, not only from the southern hemisphere.

Fig. 8. The 10-day mean maps of $\text{div } Q$ for May-II, June-I and July-II. The isopleth is given at 1×10^{-5} (g/sec) cm^{-2} interval. The dotted areas indicate the convergence of moisture flux. The hatched areas indicate convergence of moisture flux less than -1×10^{-5} (g/sec) cm^{-2} .

The clockwise moisture flow in $110\text{--}140^\circ\text{E}$ is associated with CS-5. The zonal moisture flux convergence between CS-4 and CS-5 in $0\text{--}20^\circ\text{N}$ results in the increase of the northeastward moisture transport, and the net moisture flux convergence over the wide area in $10\text{--}30^\circ\text{N}$, $80\text{--}125^\circ\text{E}$, as well as in the Baiu frontal zone. These three-cell moisture circulations and the associated moisture flux convergence over the monsoon rain area, are seen as the basic features throughout the monsoon period. They indicate significant seasonal and intraseasonal variations.

c. Break period of the Indian monsoon rainfall

The maximum zone of F_u in $50\text{--}80^\circ\text{E}$, which is located over $0\text{--}10^\circ\text{N}$ in June-I (Fig. 9B), moves to $10\text{--}20^\circ\text{N}$ in July-I (Fig. 9D) with the northward shift of the CS-3. In addition to this seasonal change, the break and the second onset of the Indian monsoon appear as the intraseasonal variations in the maps of moisture transport and the moisture balance.

The westerly moisture flux in $0\text{--}20^\circ\text{N}$ zone cross-

ing the 65°E meridian decreases from $\sim 72 \times 10^9$ ton/day of June-I (Fig. 9B) to $\sim 58 \times 10^9$ ton/day of June-II (Fig. 9C), whereas the cross equatorial moisture flux in $35\text{--}65^\circ\text{E}$ decreases a little from $\sim 39 \times 10^9$ ton/day (June-I) to $\sim 37 \times 10^9$ ton/day (June-II). In this period, the northerly moisture inflow into this domain crossing 20°N latitude circle in $35\text{--}65^\circ\text{E}$ also decreases from $\sim 14 \times 10^9$ ton/day to $\sim 7 \times 10^9$ ton/day with weakening of the monsoon onset depression over India. The moisture flux divergence in $0\text{--}20^\circ\text{N}$, $35\text{--}65^\circ\text{E}$ decreases from $\sim 27 \times 10^9$ ton/day to $\sim 22 \times 10^9$ ton/day. This indicates that the decrease of the westerly moisture flux of the Indian monsoon in the break period is not due to the decrease of the cross equatorial moisture transport alone, but also to the decrease of the northerly moisture inflow and the decrease of evaporation from the northwestern Indian Ocean and the Arabian Sea (see Fig. 11 in Section 7). With the disappearance of the monsoon onset depression, the meridional moisture flux convergence and rainfall over the Indian subcontinent also weaken abruptly.

Fig. 9. The moisture balance for each sub-area of 10° lat. $\times$ 15° long. dimension within the monsoon region for May-II, June-I, June-II, July-I and July-II. The arrows indicate the meridional and zonal moisture flux crossing the boundary of these sub-areas. The amount of moisture flux is given in units of 10^9 ton/day. The italic numeral indicates the area integrated moisture flux divergence.

d. Variations of the monsoon westerly and peak of East Asia monsoon rainfall

The Indian monsoon westerly, which abruptly intensified in the onset period, propagates toward the western North Pacific as the monsoon westerly burst in June-II (Fig. 9C), about 10 days after the on-

set. In association with the westerly burst, the zonal moisture flux in 0 – 20° N remarkably increases over the wide area from the Bay of Bengal to the western North Pacific. With the eastward retreat of the Pacific subtropical anticyclone, which occurs simultaneously with the westerly burst, the northward

Fig. 9. (Continued)

moisture transport increases in 125–140°E.

After the largest eastward extension of the monsoon westerly up to $\sim 140^\circ\text{E}$ in June-II (Fig. 9C), it retreats westward in June-III (map is not shown) and July-I (Fig. 9D). In this period, the Pacific subtropical anticyclone protrudes westward to $\sim 120^\circ\text{E}$. The southerly moisture flux along the western rim of the Pacific subtropical anticyclone attains its largest magnitude in 110–140°E. The moisture inflow into the Baiu/Meiyu frontal zone, as well as the moisture flux convergence in the frontal zone, also show maximum intensity in this period. It is an important fact that the peak of the East Asia rainfalls (Fig. 9D) is by no means accompanied by the increase of the cross-equatorial moisture transport of CS-3 nor CS-4.

e. The second onset of the Indian monsoon

The westerly moisture flux in 0–20°N across the 65°E meridian abruptly increases from $\sim 61 \times 10^9$ ton/day in July-I (Fig. 9D) to the maximum value of $\sim 94 \times 10^9$ ton/day in the second onset period in July-II (Fig. 9E). This maximum of the westerly moisture transport occurs simultaneously with the

increase of the cross equatorial moisture flux in 35–65°E from $\sim 40 \times 10^9$ ton/day (July-I) to $\sim 54 \times 10^9$ ton/day (July-II) and that of the moisture source in 0–20°N, 35–65°E from $\sim 13 \times 10^9$ ton/day to $\sim 20 \times 10^9$ ton/day. It is also noted that the northerly moisture transport crossing 20°N latitude circle in 35–65°E also changes from $\sim -15 \times 10^9$ ton/day to $\sim -22 \times 10^9$ ton/day, whereas the easterly moisture efflux crossing 35°E meridian in 0–20°N changes from $\sim -7 \times 10^9$ ton/day to $\sim -2 \times 10^9$ ton/day. This indicates that the increase of the cross-equatorial moisture transport in 35–65°E accounts for only 40 % of the increase in the moisture transport within the monsoon westerly zone.

The cross equatorial moisture flux in 80–110°E due to CS-4 increases from $\sim 22 \times 10^9$ ton/day (July-I, Fig. 9D) to $\sim 29 \times 10^9$ ton/day (July-II, Fig. 9E). This is mainly attributed to the increase of the moisture source over the domain bounded by 10°S–0° and 80–110°E. During this period, the westerly moisture transport crossing 110°E meridian in 0–20°N increases from $\sim 15 \times 10^9$ ton/day (July-I) to $\sim 42 \times 10^9$ ton/day (July-II). Therefore, the increase of the cross-equatorial moisture transport of CS-4

Fig. 10. The schematic illustration of the basic feature of the moisture transport and the moisture balance of the Asian summer monsoon. The large arrows indicate very large moisture transport, while the small arrows indicate relatively weak moisture transport. The southerly moisture transport is enhanced over the moisture source region and the area of strong zonal moisture flux convergence.

is not enough to explain the increase of the westerly moisture transport crossing the 110°E meridian. Not only the increase of the cross-equatorial moisture transport of CS-3 and CS-4, but also the increase of moisture source over the tropical oceanic area in the northern hemisphere together with the increased moisture flux convergence, contribute to enhance the westerly moisture transport.

With the second westerly burst following the second monsoon onset, the Pacific subtropical anticyclone shifts northeastward in late July (figure is not presented). The southwesterly flow of CS-5 around the western rim of the subtropical anticyclone transports moisture beyond 40°N latitude circle and 140°E meridian.

To summarize the discussions in Section 6, the basic feature of the moisture transport and the moisture balance of the Asian summer monsoon are schematically illustrated in Fig. 10. The large arrows indicate very large moisture transport, while the smaller arrows indicate relatively small moisture transport. This illustration stresses that the moisture transport is enhanced over the area of moisture source region and the area of strong zonal moisture flux convergence.

7. Moisture balance over several sub-domain in the Asia summer monsoon region

The time series data of R , E and $-\Delta = -(D + Mt)$ are obtained for five selected sub-domains of $\sim 10 \times 10^6 \text{ km}^2$ dimension.

As the typical example of the monsoon moisture source region, the time series data over Area-1, which includes the western tropical Indian Ocean

Fig. 11. The time variation of terms in the moisture balance equation over Area-1. R , E and $\Delta = D + Mt$ is the area integrated rainfall, evaporation and "moisture flux divergence+increment of the precipitable water," respectively. The variation of the area averaged convective stability $-\partial\theta_e/\partial p$ in 850–500 hPa layer except its high-land areas in the northwestern part of the domain is also presented.

and the Arabian Sea, is presented in Fig. 11. The variation in the convective stability $-\partial\theta_e/\partial p$ in 850–500 hPa layer averaged over Area-1, except its northwestern high-land area is also presented in Fig. 11. While the large excess of the rainfall over the evaporation and the large moisture flux convergence are seen in May, the large excess of the evaporation over the rainfall and the large moisture flux divergence are found in June and July. In MJJ, the variation of the evaporation is considerably smaller than that of the rainfall and moisture flux divergence. The increase of the moisture flux divergence is strongly correlated with the decrease of rainfall. The subsidence and stable stratification over this domain suppress the rainfall and thus sustain large moisture flux divergence, i.e., the moisture source, throughout the monsoon period.

The variations of the moisture balance, and the convective stability over the Indian subcontinent and the Indochina Peninsula (Area-2), are presented in Fig. 12 as the typical example over the monsoon moisture sink region. While evaporation in this domain increase slightly with time, both the moisture

Fig. 12. The time variation of terms in the moisture balance equation over Area-2. The variation of the area averaged convective stability $-\partial\theta_e/\partial p$ in 850–500 hPa layer is also presented.

flux convergence and the rainfall indicate very large temporal variations. The weak moisture source seen in the pre-monsoon period abruptly changes to the strong moisture sink in June-I concurrently with the first onset of the monsoon. The monsoon break and the second monsoon onset corresponds to the minimum and the second maximum of the moisture sink, respectively. It is an important fact that the increase of precipitation on the peak periods of monsoon is not accompanied by the peak of evaporation within this domain but with the moisture flux convergence, which is due to the large moisture influx from the adjacent region. In this domain, the convective unstable stratification is sustained not only in the monsoon period but also in May.

In order to elucidate the regional characteristics of the moisture balance, F_u , F_v , D , R , E and M averaged for May (the pre-monsoon period) and for two monsoon sub-periods (A and B) over the five areas are presented in Figs. 13, 14, 15, 16 and 17. The monsoon sub-period A and B of each respective sub-domain is defined based on the features in large-scale moisture flux field as indicated in these figures.

Figure 13 presents the moisture balance over Area-1 (the western tropical Indian Ocean and the Arabian Sea). The pre-monsoon period is characterized by the easterly moisture flux and a large excess of rainfall over evaporation, whereas the Indian

Fig. 13. The moisture balance in May and the active and inactive monsoon period over the Area-1, which includes the western tropical Indian Ocean and the Arabian Sea. The moisture flux F_u and F_v crossing the boundary of the area are indicated by arrows. R , E , D (shown by italic form) and M (shown in parenthesis) is the area integrated rainfall, evaporation, moisture flux divergence and precipitable water, respectively. The unit is in 10^9 ton/day except for M . The unit for M is in 10^9 ton .

monsoon period, especially in the active phase (A period; June-I, July-II and July-III), is characterized by the large eastward moisture efflux and the large excess of evaporation over rainfall.

Moisture balance over Area-2 (Indian subcontinent and the Indochina Peninsula, Fig. 14) also shows a large seasonal variation. In the pre-monsoon period, both the moisture influx and the efflux are

Fig. 14. The moisture balance over the Area-2, which includes the Indian sub-continent and the Indochina Peninsula.

small, and the evaporation is almost offset by the rainfall. In the Indian monsoon period, especially in the active phase (A period; June-I, July-II and July-III), the westerly and southerly moisture influx are very large. The excess of rainfall over evaporation ($\sim 50\%$ of the precipitation) is also found.

Figure 15 presents the situation in Area-3 (the East Asia and its adjacent oceanic areas). The southwesterly moisture transport around the northwestern rim of the Pacific subtropical anticyclone has a strong influence on the moisture balance in this area. Therefore, the monsoon period in this area is subdivided into the A period (June-III, July-II and July-III) of the strong southerly moisture influx crossing 20°N and the B period (June-I, June-II and July-I) of relatively weak southerly influx crossing 20°N . The southerly moisture influx crossing 20°N in the A period is ~ 3 times larger than that in May. This period corresponds to the period of intense precipitation, in which the precipitation is ~ 2 times larger than that in May. The comparison between the moisture balance in A period and B period indicates that the magnitude of the moisture influx across 20°N is the key factor to decide precipitation in this region.

Fig. 15. The moisture balance over the Area-3, which includes the east Asia.

Moisture balance in Area-4 (the tropical Indian Ocean) is presented in Fig. 16. In May, the easterly moisture influx and the relatively large moisture sink are seen. The situation in the monsoon period is characterized by the large westerly moisture influx, large moisture southerly efflux and weak moisture source. The monsoon period is divided into A period (June-I, June-II and July II) with strong westerly moisture transport after the first and the second onset, and B period (June-III, July-I and July-III) with less strong westerly moisture transport. It is a notable fact that the variation of the moisture source/sink is relatively small over this area in spite of the large variations in the moisture influx and efflux crossing the boundary of the area.

Figure 17 shows the moisture balance in Area-5, which includes the monsoon trough region. In May, moisture flux convergence in the easterly flow is very weak and the evaporation in this area is almost offset by the rainfall. The "westerly period" (A period; June-II, July-II and July-III) means the period with monsoon westerly burst extending to 110°E , whereas the "easterly period" (B period; June-I, June-III and July-I) is the period of the easterly moisture transport. In spite of the significant difference in the zonal moisture flux, both A and B pe-

Fig. 16. The moisture balance over the tropical Indian Ocean (Area-4).

riod show common features of the large zonal moisture flux convergence with the meridional moisture flux divergence. The monsoon trough region thus exports the moisture northward, in addition to the moisture sink in this domain, at the expense of the zonal moisture flux convergence.

Figure 18 presents the moisture balance over the whole Asian monsoon region for the pre-monsoon (May) and the monsoon period (June and July). Since there are different moisture flows crossing the eastern boundary of this domain, the easterly (influx) and westerly (efflux) moisture flux is shown separately. Both the influx and the efflux indicate relatively small changes throughout the pre-monsoon and the monsoon period, whereas both the evaporation and precipitation indicate larger variation from the pre-monsoon to the monsoon period. This means that the considerable part of variation in the moisture balance proceeds in association with the variations of circulation within this domain.

At the end of this section, we will list the moisture influx F_i , the moisture efflux F_o and the area integrated moisture flux divergence ($F_o - F_i$) obtained for each sub-area and each subperiod in Table 2 to summarize the features of the Asian summer monsoon moisture balance.

In Area-1 (the southwestern Indian Ocean and

Fig. 17. The moisture balance over the Area-5, which includes the South China Sea, Indonesia and the western Pacific.

the Arabian Sea), the seasonal change from the pre-monsoon to monsoon period is characterized by the remarkable increase of F_o , whereas the amount of F_i does not increase significantly.

In Area-2 (Indian subcontinent and Indochina Peninsula) and Area-3 (the Meiyu and Baiu region), the seasonal change from May to the rainy season is accompanied by the explosive increase of F_i , while the change of F_o is very small.

It is an interesting fact that large F_o is maintained in Area-5 (the south China Sea and Indonesia region, *i.e.*, the monsoon trough region) throughout MJJ. As already mentioned in Fig. 17, the F_o of this domain is southerly moisture efflux crossing its northern boundary. The monsoon trough region thus plays the role of the effective channel transporting moisture to the East Asia rainy area from the

Fig. 18. The moisture balance over the Asia summer monsoon region.

tropical and subtropical zone.

8. Characteristics of the moisture balance parameters in the Asian summer monsoon

In order to characterize the features of moisture balance in each period as well as each sub-area, we further define the following parameters:

- $Fi/(Fi + E)$; moisture influx ratio to the total moisture input,
- $R/(Fi + E)$; rainfall production ratio to the total moisture input,
- Fo/Fi ; moisture efflux ratio to moisture influx, and
- $(Fi + E)/M$; moisture exchange ratio (in the unit of 1/day),

where $(Fi + E)$ means the total moisture input into the atmosphere over the area under consideration. The ratios evaluated over these sub-areas for each sub-period are presented in Table 3.

The “moisture efflux production ratio to the total moisture input” and “moisture storage ratio to the total moisture input” is also defined by $Fo/(Fi + E)$ and $Mt/(Fi + E)$, respectively. However, we do not present these ratio in Table 2, because the former is approximated as $Fo/(Fi + E) \doteq (1 - R/(Fi + E))$ by using the relation of $Fo - Fi \doteq E - R$, and the latter is usually very small as far as the moisture balance in the 10-day mean field over the area of $10 \times 10^6 \text{ km}^2$ dimension is discussed.

It should be noted that these ratios vary according to the time- and space-scale of the phenomenon under the consideration (Ninomiya and Akiyama, 1976). For example, the contribution of Fi and Fo to the precipitation decrease whereas the contribution of evaporation increase when the moisture balance over a very large region is considered. On the contrary, the role of the moisture flux convergence becomes predominant, if the meso-scale intense rainfall event is considered. We note again that the results shown in Table 3 are obtained in the moisture balance analysis over the area of $\sim 10 \times 10^6 \text{ km}^2$ dimension for the 10-day mean field.

The scatter diagram in Fig. 19 expresses the relation between $Fi/(Fi + E)$ and $R/(Fi + E)$, whereas Fig. 20 shows the relation between Fo/Fi and $(Fi + E)/M$. The numeral by the side of the plotted data indicates the area number, while P , A , and B indicate the pre-monsoon and sub-monsoon periods defined in section 7, respectively. The difference of these parameters between the pre-monsoon period and the monsoon period is significantly larger than the difference within the monsoon period, in spite of the large intra-monsoon variation of the moisture flux field and rainfall. The change of these parameters in the scatter diagram from the pre-monsoon period to the monsoon period is indicated by arrows.

On Fig. 19 and Fig. 20, changes from the pre-monsoon period to the monsoon period over Area-1 are characterized by the remarkable decrease in the rainfall production ratio, and a large increase of moisture efflux ratio with a slight increase of the moisture exchange ratio, and a slight decrease of the moisture influx ratio. Similar tendencies are also found over Area-4, although the variations of these parameters over Area-4 is much smaller than that over Area-1.

The change over Area-2 is characterized by the large increase of the rainfall production ratio, the moisture influx ratio, the moisture exchange ratio, and the remarkable decrease of the moisture efflux ratio. The same changes are almost seen over Area-3 and Area-5, although the variations in these areas are smaller than that over Area-2.

In short, the moisture balance in the moisture source region of the Asian summer monsoon, as typically seen over Area-1, is characterized by a very small rainfall production rate and consequently by

Table 2. Moisture influx Fi and moisture efflux Fo obtained for the monsoon sub-areas and the sub-periods. Unit is in 10^9 ton/day

Area	sub-period		Fi	Fo	$Fo - Fi$
Area-1	pre-monsoon	May	54	27	-27
	active period	June-I, Jul-II, III	60	83	23
	break period	Jun-II, III, Jul-III	47	63	16
Area-2	pre-monsoon	May	20	21	1
	active period	June-III, Jul-II, III	94	33	-61
	break period	Jun-II, III, Jul-III	78	41	-37
Area-3	pre-monsoon	May	39	30	-9
	strong southerly	Jun-III, Jul-II, III	72	44	-28
	weak southerly	Jun-I, II, Jul-I	66	45	-21
Area-4	pre-monsoon	May	35	23	-12
	strong westerly	Jun-I, II, Jul-II	36	43	7
	weak westerly	Jun-III, Jul-I, III	35	34	-1
Area-5	pre-monsoon	May	53	51	-2
	westerly burst	Jun-II, Jul-II, III	68	57	-11
	easterly	Jun-I, III, Jul-I	65	50	-15

Table 3. Parameter related to moisture balance obtained for various sub-domains and the sub-periods of the Asian summer monsoon in 1991

Area	sub-period		$Fi/Fi + E$	$R/Fi + E$	Fo/Fi	$Fi + E/M$
Area-1	pre-monsoon	May	0.60	0.70	0.50	0.19
	active period	Jun-I, Jul-II, III	0.59	0.19	1.38	0.24
	break period	Jun-II, III, Jul-III	0.57	0.22	1.34	0.20
Area-2	pre-monsoon	May	0.38	0.55	1.05	0.14
	active period	Jun-I, Jul-II, III	0.67	0.75	0.35	0.26
	break period	Jun-II, III, Jul-III	0.63	0.67	0.52	0.24
Area-3	pre-monsoon	May	0.70	0.41	0.77	0.25
	stron. southerly	Jun-III, Jul-II, III	0.78	0.51	0.51	0.30
	weak southerly	Jun-I, II, Jul-I	0.80	0.43	0.68	0.29
Area-4	pre monsoon	May	0.41	0.74	0.66	0.15
	stron. westerly	Jun-I, II, Jul-II	0.38	0.55	1.19	0.17
	weak westerly	Jun-III, Jul-I, III	0.38	0.63	0.97	0.17
Area-5	pre monsoon	May	0.54	0.45	0.96	0.19
	westerly burst	Jun-II, Jul-II, III	0.57	0.53	0.84	0.22
	easterly	Jun-I, III, Jul-I	0.58	0.54	0.77	0.22
Asia monsoon	pre monsoon	May	0.32	0.79	0.55	0.13
	monsoon	Jun, Jul	0.31	0.84	0.47	0.13

the large moisture efflux ratio. This situation appears under the large-scale condition of strong subsidence, and stable stratification in the lower troposphere. Meanwhile, the moisture balance over the area of maximum monsoon rainfall, as typically found in Area-2, is characterized by the large rainfall production ratio, the large moisture influx ratio and very small moisture efflux ratio. These particular features occur under the large-scale condition of the strong upward motion and the convectively unstable stratification.

The moisture exchange ratio over the intense rainfall area (Area-2 and Area-3) in the peak rainfall period indicates a large value of 0.25–0.30/day, while a relatively smaller value of 0.15–0.20/day is seen in the moisture source region and the pre-monsoon dry period. It is added for the comparison that the global and annual mean moisture exchange ratio E/M , where Fi does not appear in the closed domain of the global atmosphere, is estimated to be ~ 0.11 /day from the global averaged annual precipitation of 970 mm/year, and the global averaged precipitable water of 25 mm.

Fig. 19. The scatter diagram showing the relation between the $R/(F_i + E)$ and $F_i/(F_i + E)$. The numeral by the plotted circle indicates the area number, while P, A and B indicates the pre-monsoon period and two monsoon sub-period. The arrow shows the change from the pre-monsoon period to the monsoon period.

9. Concluding remarks

The results of the present study will be compared with those of the previous studies mentioned in the introduction.

The statement by Murakami *et al.* (1984) and Peace (1992) that the cross-equatorial moisture transport over the western Indian Ocean is not enough to sustain the moisture sink in the Asian monsoon region, coincides with the result of the present analysis. The important role of circulation variations within the Asian monsoon region and that of evaporation from the Indian Ocean, the Arabian Sea and the Bay of Bengal for the moisture balance pointed out by Murakami *et al.* (1984), Pearce (1992), Cadet and Greco (1987a), are also consistent with the present study. However, we do not necessarily agree with the conclusion of Cadet and Greco (1987b) that water vapor from the southern hemisphere is the major moisture source for Indian rainfall, since the variation of the Indian monsoon rainfall is much larger than that of the cross-equatorial moisture transport.

The spatial and temporal variations of the moisture sink and source, related with the large-scale monsoon vertical circulation described by Yanai *et al.* (1992) concurs with the present paper. The influence of the 40-50 day oscillation on the moisture sink/source found by Murakami *et al.* (1984) is confirmed by the present analysis.

Fig. 20. The scatter diagram showing relation between $(F_i + E)/M$ and F_o/F_i .

The important role of the cross-equatorial moisture transport from Australia and its adjacent sea area, and that of convergence between the cross-equatorial flow and the monsoon westerly in the monsoon rainfalls over China discussed by several Chinese authors, and that of the moisture transport along the western rim of the Pacific subtropical anticyclone for the Baiu frontal precipitation, stated by Japanese authors, agree with the present analysis.

The aforementioned coincidences for various years, indicates that these features appear in many years as the common basic features of the Asian summer monsoon.

The significance of the present study is not only in confirming previous studies, but in elucidating relations among variations of the moisture transport, moisture balance, precipitation, and the major circulation systems in the whole Asian summer monsoon region more qualitatively and synthetically. The main results of the Part II are summarized below:

- (1) The seasonal change from the pre-monsoon to the monsoon period is characterized by the distortion of the south-north axis symmetric pattern of precipitation with the symmetric axis over the equator. That is, the zone of intense precipitation with a strong moisture sink moves from the tropical belt over the Indian Ocean to the subtropical area of the Asian continent south of the Tibetan Plateau;
- (2) The important role of the major circulation systems in moisture transport is pointed out. The stepwise northeastward moisture transport

is carried out by CS-3, CS-4 and CS-5. The southerly moisture transport from the southern hemisphere over the Indian Ocean is due to CS-3, whereas the southerly moisture transport toward the Bay of Bengal and the Indochina area is due to CS-4. The moisture transport from the subtropical zone to the Baiu/Meiyu frontal zone is mainly carried out by CS-5;

- (3) The moisture transport in the monsoon westerly (CS-3), which is the key factor of the Indian monsoon rainfall, is not only sustained by moisture transport from the southern hemisphere, but also greatly by the moisture supply from the Indian Ocean, Arabian Sea and the Bay of Bengal as well as the significant northerly moisture transport crossing 20°N latitude circle;
- (4) The large southerly moisture transport around 90–110°E, which is the key factor of rainfalls over the Myanmar and Indochina Peninsula, is produced in the confluence/convergence area between CS-3 and CS-4. The confluence/convergence of moisture flux between CS-4 and CS-5 is also the essential condition for the intense rainfall over East Asia;
- (5) The moisture balance calculation indicates that the appearance of the pair of adjoining strong moisture source and sink region is the key feature of the Asian summer monsoon, rather than the moisture inflow from the southern hemisphere. The strong moisture source region over the tropical and subtropical oceans formed under the condition of strong subsidence and stable stratification, which suppress the consumption of moisture supplied from the underlying surface, and thus enable moisture export to the down stream moisture sink region. The moisture sink region is characterized by moisture inflow from the upstream moisture source region, and upward motion as well as the convective instability;
- (6) The aforementioned inference is also supported by the fact — pointed out in the analysis for the wide area, bounded by 10°S, 40°N, 35°E and 140°E — that the moisture flux crossing the boundary of this area indicates a relatively small seasonal increase of $\sim 12 \times 10^9$ ton/day (it is by no means due to the increase of the moisture influx through the southern boundary, but mainly due to the decrease of moisture efflux crossing the western boundary) from the pre monsoon to the monsoon period as compared with the increase of precipitation ($\sim 38 \times 10^9$ ton/day) within the domain.
- (7) A few parameters such as “moisture influx ratio,” “rainfall production ratio,” “moisture ef-

flux ratio” and “moisture exchange ratio” are defined to discern regional and seasonal characteristics of the moisture balance. These parameters also indicate larger variations within the monsoon region from the pre-monsoon to monsoon period.

Although the present study shows many important features in the moisture transport and the moisture balance in the Asian summer monsoon, the features in and around the North Pacific subtropical anticyclone has not been fully examined. The smaller scale aspect of the moisture balance around the Baiu/Meiyu frontal zone are not yet fully explored. These remaining problems will be further studied in a separate paper.

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1991 年アジア夏季モンスーン期の降水と水蒸気収支

II: 水蒸気輸送と水蒸気収支

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本報告では、全球数値予報モデルの 24 時間予想値を使用して 1991 年アジア夏季モンスーンにおける降水と水蒸気収支の特徴を調べる。第 I 部では、アジア夏季モンスーン域の主要の循環系を定義し、その変動との関連において降水分布の時間的変化を調べた。第 II 部では、それらの循環系の変化に注目して水蒸気輸送と水蒸気収支の特徴を調べる。

春季からモンスーン期への主要な変化は、水蒸気シンクを伴う降雨域のインド洋・西太平洋赤道域からアジア大陸亜熱帯域への移動、及び、熱帯・亜熱帯海洋域における水蒸気ソース域の形成によって特徴づけられる。南半球及び低緯度帯からこのモンスーン雨域への大きな水蒸気輸送は主として東西に並んだ三つの時計回りの循環系 (CS-3, インド洋; CS-4, インドネシア域; CS-5, 太平洋亜熱帯域) による。

モンスーン雨域を含む大領域 (10°S–40°N, 35–140°E) に出入りする水蒸気流束の春季からモンスーン期への変化は、その内部における水蒸気流束・降水量の変化に比して、はるかに小さい。この事実は、領域内変動の重要性を示している。

この大領域を細分した各小領域についての水蒸気収支解析の結果も、相隣る水蒸気ソース域とシンク域の形成がモンスーン降雨に重要である事を示した。

更に、 $10 \times 10^6 \text{ km}^2$ 程度の領域の水蒸気収支状態を示すパラメーターとして「流入水蒸気流束比」、「流出水蒸気流束比」、「降水生成比」、などを定義し、各領域の特徴を対比した。西部インド洋・アラビア海に代表される水蒸気ソース域では強い下降流と安定成層が降水による水蒸気消費を抑制し、その結果として域外への大きな水蒸気流束を生じる。その風下に位置する水蒸気シンク域は上昇流と不安定成層が見られ、ソース域から流入する水蒸気の多くが降水として消費され、従って、シンク域からの流出水蒸気流束は相対的に小さい。