Moisture Balance over China and the South China Sea during the Summer Monsoon in 1991 in Relation to the Intense Rainfalls over China

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Abstract

The moisture balance over the central part of China in May, June and July (MJJ) of 1991 is studied by utilizing the 24-hour prediction data of a global weather prediction model of JMA, in relation with the heavy rainfalls over China.

The moisture balance over a domain bounded by 20–40°N and 110–125°E (Area-C, main part of China) indicates that the moisture flux convergence within this domain is mainly due to the southerly moisture inflow across the southern boundary. The precipitation in this domain increases in the early June with the abrupt increase of the southerly moisture inflow. The precipitation within this domain is highly correlated with the southerly moisture inflow crossing 20°N.

To relate the southerly moisture flow into Area-C with the moisture balance in the tropical zone, the moisture balance in a domain bounded by 0–20°N and 110–125°E (Area-S, the South China Sea including the monsoon trough region) is further studied. The variation of the cross-equatorial moisture inflow in Area-S is significantly smaller than that of the moisture efflux across the northern boundary of Area-S. In Area-S, the strong correlation is found between the zonal moisture flux convergence and the southerly moisture flux across the 20°N latitude circle. This zonal moisture flux convergence is seen within the monsoon trough region between the monsoon westerly and the easterly flux in the southern rim of the Pacific subtropical anticyclone. The monsoon trough region plays the role of the channel to transport the moisture from 0–20°N zone toward north, although Area-S itself is not a moisture source region. The west-east intraseasonal oscillation of the monsoon trough, monsoon westerly and the North Pacific subtropical anticyclone have strong influence on the precipitation and westerly moisture transport over China.

The features of precipitation over China in early July are characterized by a narrow intense rainfall zone over the Yangtze River Valley. The moisture flux field during this period indicates the strong moisture flux convergence within the precipitation zone.

1. Introduction

Large amount of rainfall is brought out over the various parts of Asia during the Asian summer monsoon season. The summer monsoon rainfalls over East Asia is identified as Meiyu in China, and Baiu in Japan. The summer monsoon rainfalls over these areas are signified by the intense rainfalls concentrated in the west to east oriented narrow rain band forms within the stationary front, which is called the Meiyu/Baiu front. Extensive studies have been made on the Meiyu/Baiu rainfalls from the various view point, such as the large- and meso-scale circulation systems, and the moisture balance in the hemispheric and regional scale. We will summa-

rize briefly some important results of the previous studies, related to the East Asia summer monsoon rainfalls.

Many authors (*e.g.*, Tao and Chen, 1987; Ding, 1991 and 1992) pointed out the important role of the cross equatorial flow in 90–110°E on the summer monsoon over China, though it is considerably weaker than the Somalia jet. This cross equatorial flow has a close connection with circulation over Australia and East Asia. During the period of strong cross-equatorial flow, the cold anticyclone over Australia is strong, and the monsoon trough is identifiable over the South China Sea. It has been also 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 the intense rainfalls over China in the monsoon period. The southwesterly moisture transport over these areas is significantly intensified

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when the Indian monsoon westerly, and the cross-equatorial flow from Australia, converge.

Lau *et al.* (1988) identified two major monsoon rainfall onsets over China from the climatology of precipitation and OLR (outgoing long-wave radiation) over East Asia. The first one, Meiyu, occurs over central China around early June, whereas the second one over northern China around late July. These onsets are related with the phase-locking between the intraseasonal oscillation and the seasonal variation. Similar findings on the seasonal transition in the summer monsoon rainfalls over China and Japan have been reported by several authors (*e.g.*, Ding, 1992; Hirasawa *et al.*, 1995; Kato, 1985 and 1989; Murakami *et al.*, 1984; Nakazawa, 1992; Ninomiya, 1989; Ninomiya and Muraki, 1986; Ueda *et al.*, 1995; Ueda and Yasunari, 1996).

Several authors (*e.g.*, Akiyama, 1973 and 1975; Matsumoto *et al.*, 1971; Ninomiya, 1984; Ninomiya and Akiyama, 1992; Ninomiya and Murakami, 1987) pointed out that the major part of the summer monsoon rainfalls over China and Japan occurs within the Baiu/Meiyu front. The front and the intense rainfalls are sustained by the low level southwesterly prevailing along the periphery of the Pacific anticyclone through the frontogenesis in the deformation field, the generation of the convective instability due to the differential thermal advection, and the moisture flux convergence associated with the strong moisture influx toward the front. The circulation around the Pacific subtropical anticyclone, is inferred to be one of the key factor to sustain the East Asia summer monsoon rainfalls. Many papers (*e.g.*, Akiyama, 1984 and 1989; Ninomiya and Akiyama, 1992; Ninomiya *et al.*, 1988) further stressed the multi-scale features of the summer monsoon rainfalls, from the fact that the intense rainfall in the Baiu/Meiyu front is generated in association with the meso-scale convective disturbances, which develop under the influence of the various larger circulation systems.

In the recent studies on the large-scale circulation systems, and the large-scale moisture balance in the Asia summer monsoon of 1991, Ninomiya and Kobayashi (1998 and 1999) pointed out that the two clockwise circulation systems centered over the tropical Indian Ocean, and Indonesia area, play an important role in transporting the moisture from the tropical belt to the Indian subcontinent and the southeastern Asia. The circulation around the Pacific subtropical anticyclone transports the moisture from the tropical area, to the East Asia monsoon rainfall zone. They also pointed out that the moisture supply from the southern hemisphere to the whole monsoon region is not large to explain the increase of the precipitation in the monsoon period. They stressed that the formation of the moisture source region in the large-scale subsiding area is an

Fig. 1. Comparison of the 10-day and area averaged observed precipitation over the HUBEX area with that of the predicted precipitation during MJJ in 1991.

important features of the summer monsoon.

Since the summer monsoon of 1991 is characterized by the very intense rainfalls over China (Ding, 1993; Si *et al.*, 1995), the present author intends to study the characteristics of the moisture transport and the moisture balance over China for May, June and July (MJJ) 1991 in more detail.

2. Data and its quality

Like the previous large-scale studies, the data of 24-hour numerical prediction obtained twice a day 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, are given in Ninomiya and Kobayashi (1998). Here we only note that every predicted meteorological parameters, such as the vertical velocity, mixing ratio of the water vapor, precipitation and the moisture supply from the underlying surface to the atmosphere, are consistent with each other. They are adjusted in the process of the time integration according to the physical laws incorporated in the numerical model, if the prediction would be accurate.

Since the present study is made over the relatively small domain, as compared with that in Ninomiya and Kobayashi (1999), some verification about the prediction data will be required to support the validity of utilizing the prediction data. The area averaged precipitation over HUBEX (Huaihe River Basin Experiment) area of $\sim(500 \text{ km})^2$ dimension

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 peak of the monsoon	peak period fo Baiu rainfall
July-II	11–20 July	second peak of the monsoon	2nd monsoon westerly burst
July-III	21–30 July		disappar. of Baiu rainfall zone

centered over $\sim 34^{\circ}\text{N}$ and 117°E presented by Si *et al.* (1995) is used for the verification of the predicted data. Figure 1 compares the area averaged 10-day (see Table 1 for the notation of the 10-day subperiods in MJJ) observed precipitation over the HUBEX area, and that of the predicted precipitation during MJJ in 1991. Good agreement of the predicted precipitation with the observed one will support the validity of utilizing numerical prediction data for the present study, as far as the averaged values for 10-day and over $\sim 10^6\text{ km}^2$ are discussed.

3. Notations used in the present study and outline of the analysis

Notations used in the following discussion are defined in the present section.

The precipitable water W is calculated by $W = 1/g \int q dp$, where q indicates the mixing ratio of the water vapor and the vertical integration is made for the layer between the surface pressure and 300 hPa.

The vertically integrated moisture transport Q and its zonal and meridional component Qu and Qv are defined as

$Q = 1/g \int v q dp$, $Qu = 1/g \int u q dp$ and $Qv = 1/g \int v q dp$, where v , u and v are the wind velocity, zonal and meridional wind speed, respectively.

The moisture balance equation at a certain point is given by

$(\partial W/\partial t) + \text{div}Q = e - r$, where e and r indicates the evaporation from the underlying surface and the precipitation, respectively.

For the analysis over an area bounded by two meridians and two latitude circles, the area integrated moisture balance equation is obtained by

$\Delta = Mt + D = E - R$, where area integrated precipitable water M , precipitation R , evaporation E and Mt are defined by

$M = \int W dS$, $R = \int r dS$, $E = \int e dS$ and $Mt = \partial M/\partial t$, respectively.

The area integrated moisture flux divergence D is defined by

$D = \int \text{div}Q dS = \oint Q_n ds = \Sigma (Fu \text{ and } Fv),$

where Q_n is the component of Q normal to ds . The area element dS is given by $dS = Re \cos \psi d\psi d\lambda$, where Re , ψ and λ is the radius of the earth, the latitude and the longitude, respectively.

The zonal and meridional moisture flux across the boundary of the area, Fu and Fv , are calculated by $Fu = \int Qu Re d\psi$, and $Fv = \int Qv Re \cos \psi d\lambda$. The total moisture influx into the area under consideration is noted by Fi , whereas the total moisture efflux from the area is labeled by Fo .

In the following sections, we will discuss the time-averaged features of the moisture balance for the nine 10-day subperiod presented in Table 1. This table summarizes characteristics in the large-scale situation of Asian summer monsoons during MJJ of 1991.

4. Temporal and meridional variations of the rainfall over China in 1991

The meridional distribution of the 10-day mean precipitation averaged for $110\text{--}125^{\circ}\text{E}$ in nine subperiod, during MJJ of 1991 is presented in Fig. 2. Although the occurrence of the Meiyu rainfall around the early June, and the seasonal northward shift of the precipitation zone are seen in this figure, the increase of the rainfall in association with the commencement of Meiyu is rather gradual in this year, since significant precipitation occurs over $20\text{--}30^{\circ}\text{N}$ zone already in May. The northward shift of the rainfall zone is also gradual in this year. Instead, the north-south oscillation of the maximum rainfall zone within $20\text{--}30^{\circ}\text{N}$ in June, the occurrence of the intense rainfall over $\sim 30^{\circ}\text{N}$ in July-I, and that at $\sim 15^{\circ}\text{N}$ in July-II, are the notable features. At present, it is not clear whether this situation is particularly seen in 1991, or seen occasionally in other years. We know from experience that the “typical pictorial seasonal change” occurs rarely.

5. Rainfall and the southerly moisture influx over China

The close relation between the rainfall over China and the southerly moisture transport from the South

Fig. 2 The meridional distribution of the 10-day mean precipitation averaged for 110–125°E during MJJ of 1991.

Fig. 3. The zonal and meridional moisture flux, F_u and F_v , across the boundary of Area-C and Area-S. The italic numeral shows the area integrated moisture flux convergence.

Fig. 4. Topographic map of the East Asia. The areas higher than 6000 m, 3000 m and 1000 m above the sea level are indicated by the blacked area, cross hatched area and hatched areas, respectively.

China Sea, has been pointed out by many papers. In order to realize the aforementioned features, the moisture balance not only over China, but over the South China Sea should be elucidated. We will therefore study the moisture balance over Area-C, which is bounded by 20–40°N and 110–125°E (area dimension $\sim 3.2 \times 10^6 \text{ km}^2$, main part of China) and Area-S, which is bounded by 0–20°N and 110–125°E (area dimension $\sim 3.6 \times 10^6 \text{ km}^2$, the South China Sea). The zonal and meridional moisture flux, F_u and F_v , crossing the respective boundary of Area-C and Area-S are presented in Fig. 3.

The features over Area-C will be first discussed. The moisture flux crossing the northern boundary (40°N) of Area-C is very small throughout MJJ of 1991, whereas the southerly flux crossing the southern boundary (20°N) increases rapidly around June-I. As for Area-C, the southerly influx across the southern boundary is predominantly larger than the westerly influx across the western boundary (110°E) throughout MJJ. It is inferred from the topographic map (Fig. 4), that mountain ranges to the west of Area-C block the direct intrusion of low level moist westerly from the Bay of Bengal and the western Indian Ocean. This will be the main reason why the southerly moisture influx crossing the southern boundary of Area-C is predominantly larger than the westerly moisture influx into Area-C.

The scatter diagram in Fig. 5 shows the relation between the area integrated precipitation over Area-C and the moisture flux crossing the southern boundary of this area for MJJ of 1991. As far as the overall situation is concerned, the high correlation between these quantities is evident. The seasonal change from May to June/July greatly contributes to the high correlation, whereas data for June-I and June-II deviate significantly from the regression line.

Fig. 5. The scatter diagram showing the relation between the area integrated rainfall over Area-C and the moisture transport across the southern boundary of Area-C.

Fig. 6. The scatter diagram showing the relation between the area integrated moisture flux convergence over Area-C and the moisture transport across the southern boundary of Area-C.

We further find high correlation between the area integrated moisture flux convergence over Area-C and the southerly moisture inflow into the area in the scatter diagram (Fig. 6), although the data for July-II indicates significant deviation from the regression line. The coefficient of the linear regression equation in Fig. 6 indicates that about 30 % of the moisture influx through the southern boundary is consumed as rainfall through the moisture flux convergence. Figure 3 also indicates that about 2/3 of the southerly moisture influx is offset by the zonal moisture divergence in Area-C. It is also clear from Fig. 5 and Fig. 6 that the rainfall, moisture flux convergence, and the southerly moisture inflow increase remarkably in June-I with the commencement of the East Asia summer monsoon.

The moisture balance over Area-S is discussed next. The moisture flux crossing the southern boundary of Area-S (equator) does not vary significantly throughout MJJ of 1991. Whereas southerly moisture flux crossing 20°N, the zonal moisture flux

Fig. 7. The scatter diagram showing the relation between the meridional moisture flux across the northern boundary of Area-S and the zonal moisture flux convergence in Area-S.

crossing the western ($110^{\circ}E$) and eastern ($125^{\circ}E$) boundary change widely. It is seen in Fig. 3 that the southerly moisture flux across $20^{\circ}N$ increases in association with the increase of the zonal moisture flux convergence. The scatter diagram in Fig. 7 confirms the relation between the zonal moisture flux convergence in Area-S and the meridional moisture flux across the northern boundary of Area-S, although the data for June-I deviates significantly from the regression line. The coefficient of the linear regression equation in Fig. 7 indicates that about 70 % of the area integrated zonal moisture flux convergence in Area-S was transported northward across the $20^{\circ}N$ latitude circle.

Figure 5, Fig. 6 and Fig. 7 imply that the zonal moisture flux convergence in Area-S plays an important role to enhance the rainfalls over Area-C, through the intensification of the northward moisture transport into Area-C. This inference is actually certified in the scatter diagram in Fig. 8, which shows the relation between the zonal moisture flux convergence in Area-S and the area integrated precipitation over Area-C. It is an interesting fact that the zonal moisture transport in the tropical belt has strong influence on the rainfall over China, ~ 2000 km north from the tropical belt.

6. Moisture balance over China and the South China Sea

As for Area-S, the three month period of MJJ is reasonably subdivided into three periods (Period-P, Period-A and Period-B) according to the fea-

Fig. 8. The scatter diagram showing the relation between the area integrated precipitation over Area-C and the zonal moisture flux convergence in Area-S.

tures of the zonal moisture transport in $0-20^{\circ}N$ (see Fig. 3). The Period-P (May-I, II and III) is signified by the easterly moisture transport seen in the pre-monsoon period. Period-A (June-I, III and July-I) is identified by the westerly moisture transport at $110^{\circ}E$ with the easterly moisture transport at $125^{\circ}E$, whereas Period-B (June-II, July-II and III) is characterized by the westerly moisture transport at both the western and eastern boundaries. From the large-scale view point, Period-P corresponds to the pre-monsoon period, in which the easterly moisture flow predominates over the South China Sea. Period-A corresponds to the period when the monsoon trough is located within Area-S, while Period-B corresponds to the phase when the monsoon trough is located to the east of $125^{\circ}E$, or in other words when the monsoon westerly burst reaches to the east of $125^{\circ}E$.

The composite situation of moisture balance over Area-C, and Area-S for Periods-P, A and B is presented in Fig. 9. The arrows across the respective boundaries of the domains indicate moisture flux F_u or F_v , whereas the arrow within each domain labeled by R and E indicates the area integrated precipitation and the evaporation from the underlying surface, respectively. The italic numeral shows the area integrated moisture flux convergence.

The most significant seasonal change from the pre-monsoon period (Period-P), to the monsoon period, (Periods-A and B) seen over Area-S is the abrupt increase of the zonal moisture flux convergence, which results in the remarkable intensification of the northward moisture transport crossing $20^{\circ}N$ in addition to the enhancement of the rainfall within Area-S. The increase of the evaporation in Area-S associated with the strong low-level westerly wind in the phase of the intense monsoon westerly burst, is also a notable feature.

Fig. 9. The composite features of moisture balance in Area-C and Area-S for the three periods categorized based on the large-scale moisture transport in 0–20°N. The cross equatorial moisture flux in 95–110°E for the three periods is also presented in the lower part of figure, respectively. Left panel: For the period of easterly moisture flux (Period-P; May-I, II and III). Middle panel: For the period of the westerly moisture flux at 110°E with the easterly moisture flux at 125°E (Period-A; June-I, III and July-I). Right panel: For the period of the westerly moisture flux (Period-B; June-II, July-II and III).

Table 2. Parameters related to the moisture balance obtained for Area-C and Area-S for Period-P, Period-A and Period-B

Area	Period	$F_s/F_i + E$	$F_i/F_i + E$	$R/F_i + E$	F_o/F_i	$F_i + E/M$
Area-C	Period-P	0.24	0.80	0.28	0.89	0.37
	Period-A	0.55	0.85	0.31	0.68	0.48
	Period-B	0.55	0.79	0.42	0.72	0.32
Area-S	Period-P	0.24	0.68	0.34	0.95	0.24
	Period-A	0.65	0.76	0.42	0.77	0.31
	period-B	0.35	0.70	0.39	0.91	0.41

The evaporation in Area-C does not vary significantly during MJJ, while the precipitation increases considerably with commencement of the East Asia summer monsoon. This increase of the precipitation in Area-C is mainly owing to the increase of the moisture flux convergence, which occurs simultaneously with the intensification of the southerly moisture transport across 20°N.

Ninomiya and Kobayashi (1999) defined the following parameters to characterize the moisture balance over a certain domain;

$F_i/(F_i + E)$; moisture influx ratio to the total moisture input,

$R/(F_i + E)$; rainfall production ratio to the total moisture input,

F_o/F_i ; moisture efflux ratio to the moisture influx, and

$(F_i + E)/M$; moisture exchange ratio (in the unit of 1/day).

They also noted that the “moisture efflux production ratio to the total moisture input” is approximated by $F_o/(F_i + E) \approx 1 - R/(F_i + E)$.

In the present paper we define further “southerly moisture flux ratio” by $F_s/(F_i + E)$, where F_s is defined by $F_s = |F_v(20^\circ\text{N})|$.

The value of these parameters obtained for the respective area and period are presented in Table 2. The rainfall production ratio in both areas indicates the considerable seasonal increase from the pre-monsoon period to the monsoon period. The moisture influx ratio in Area-C is significantly larger than that in Area-S. This indicates that the moisture influx has strong influence as compared with evaporation in the Area-C, whereas the role of the evaporation in Area-S, which includes vast oceanic

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

area, has larger influence in the moisture balance. However, the most important feature found in these area is the abrupt and very large seasonal increase of the southerly moisture flux ratio, with the commencement of the East Asia summer monsoon. It should be added that Area-S plays the role of the effective channel to transport the moisture northward from the $0-20^\circ\text{N}$ zone, although Area-S itself is not a so-called moisture source region, since the rainfall exceeds the evaporation in this area.

The results of the present section indicate that the increase of the southerly moisture flux across 20°N , accompanied by the strong zonal moisture flux convergence in the tropical zone between the equator and 20°N , is the key feature of the summer monsoon rainfalls over China.

It should be noted that variation of the cross equatorial moisture influx in $110-125^\circ\text{E}$ is negligibly small, as compared with southerly moisture transport across the 20°N latitude circle. Since several

previous papers (see introduction) discussed some close relation between the precipitation over China and the cross equatorial moisture flux in $90\text{--}110^\circ\text{E}$, we should present the cross equatorial moisture flow in $95\text{--}110^\circ\text{E}$, in respective period in the lower part of Fig. 9. It is clear that variations of the cross equatorial moisture flux in $95\text{--}110^\circ\text{E}$, is also significantly small as compared with the southerly moisture transport across the 20°N latitude circle in $110\text{--}125^\circ\text{E}$.

7. Large-scale circulation associated with the strong southerly moisture transport

The situation in the large-scale circulation, favorable to the occurrence of the strong southerly moisture transport over the South China Sea, is discussed in the present section. The maps of the 10-day mean moisture transport Q for May-II, June-II and July-I are presented in Fig. 10 as the typical example for Period-P, Period-B and Period-A. The features in these period are discussed in relation to the major circulation systems in the lower troposphere, defined by Ninomiya and Kobayashi (1998), and illustrated schematically in Fig. 11.

The features in May-II (Fig. 10A) are characterized by the almost zonal pattern of easterly moisture flow within CS-2 in $0\text{--}15^\circ\text{N}$, and that of the westerly moisture flow in $20\text{--}40^\circ\text{N}$ (CS-8). The northward moisture transport into East Asia from the tropical zone is small, except weak southerly transport along the western rim of the westward protruding tip of the Pacific subtropical anticyclone. The monsoon trough, which is the confluence/convergence zone between the easterly flow of CS-5 and the westerly of CS-3/CS-4, does not form in the pre-monsoon period.

The map for June-II (Fig. 10B) represents the situation of the monsoon westerly burst, following the first onset of the summer monsoon. The eastern tip of the monsoon westerly in $0\text{--}15^\circ\text{N}$ reaches to $\sim 135^\circ\text{E}$, and forms an intense monsoon trough in Q field between the monsoon westerly and the easterly flow of CS-5 around 130°E . The strong zonal moisture flux convergence, and the associated large southerly moisture flux, are seen over $120\text{--}130^\circ\text{E}$.

The map for July-I (Fig. 10C) shows the typical situation associated with the westward protruding Pacific subtropical anticyclone. The predominant monsoon trough in this period forms over the South China Sea, between the monsoon westerly of CS-4 and the easterly of CS-5. The strong zonal moisture flux convergence in the monsoon trough region results in the very strong southerly moisture transport around 115°E .

To demonstrate the relation among the southerly moisture transport over the South China Sea, the monsoon westerly burst and west-east oscillation of the Pacific subtropical anticyclone, the longitude-

Fig. 11. The schematic illustration of the major circulation systems in the lower troposphere of the Asian summer monsoon.

time sections of 10-day mean Q along 10°N and 20°N latitude circles are presented in Fig. 12 and Fig. 13, respectively. In these time sections, the boundary between the westerly and easterly moisture transport is indicated by the thick broken line. The zonal moisture flux convergence is strong in the monsoon trough at 10°N , whereas the southerly moisture transport is large in the monsoon trough region at 20°N .

Since the monsoon trough forms in the southwestern periphery of the Pacific subtropical anticyclone, the variation of the monsoon trough is closely related with the west-east oscillation of the Pacific subtropical anticyclone, and the extension of the monsoon westerly zone. In the present paper, the subsidence area in the anticyclone is identified by "the clear area," which corresponds to the area where Ch (amount of cloud higher than 400 hPa level, estimated from Geostationary Meteorological Satellite IR observation) is less than 0.1. Then, the time and space averaged clear area coverage is obtained for each 10-day subperiod, and domain with 10° latitude width in $10\text{--}30^\circ\text{N}$ latitude zone. Table 3 presents the space and temporal variation of the clear area ratio thus obtained. In the pre-monsoon period (May) the western border of the clear area extends to 110°E . The significant eastward shrink of the clear area occurs in June-II with the first monsoon westerly burst. In July-I, after the first westerly burst, the western tip of the clear area again protrudes westward to 120°E . The second eastward shrink of the clear area in July-III occurs with the second monsoon westerly burst.

It is clear on these time sections (Fig. 12 and Fig. 13) and Table 3, that the intraseasonal variations of the southerly moisture transport with the zonal moisture flux convergence around the South China Sea, is associated with the intraseasonal west-east oscillation of the monsoon trough, monsoon westerly extension and the Pacific subtropical anticyclone.

At the end of this section, we will discuss again

Fig. 12. The longitude-time section of the 10-day averaged moisture transport Q along 10°N . The boundary between the westerly and easterly moisture transport is indicated by a broken line.

Fig. 13. The longitude-time section of the 10-day averaged moisture transport Q along 20°N . The boundary between the westerly and easterly moisture transport is indicated by a broken line.

the difference between Period-A and Period-B by looking at Figs. 2 and 9. It is clear that the westerly moisture efflux crossing the easterly boundary of Area-C in Period-A, is significantly larger than that in Period-B. It is also found in Fig. 2 that the maximum zone of precipitation in Period-A tends to appear in $22.5\text{--}30^\circ\text{N}$, while that in Period-B tends to occur around $15\text{--}17.5^\circ\text{N}$. Thus, the intraseasonal variation, *i.e.*, west-east oscillation of the monsoon trough, has a strong influence not only on the southerly moisture flux across 20°N and the amount of rainfall over China, but also the north-south oscillation of the maximum rain zone and the westerly moisture transport in $20\text{--}40^\circ\text{N}$ zone.

8. Features of intense rainfall zone over the Yangtze River Valley in July-I

The precipitation over China in July-I of 1991 is characterized by the persistent rainfall concentrated in a narrow rain band over the Yangtze River Valley and the Huaihe River Basin (Ding, 1993; Ninomiya and Kobayashi, 1998). In the present section, the relation between the rain band and the southerly moisture transport along the western-northwestern rim of the Pacific subtropical anticyclone will be briefly noted. The 10-day averaged precipitation, the vertical velocity ω at 700 hPa and the vertical stability ($-\partial\theta_e/\partial p$) in the layer between 500 and 850 hPa for July-I are presented in Fig. 14. The distribution of the 10-day averaged Ch (coverage of cloud higher than 400 hPa level) is also shown in Fig. 15.

The area of subsidence (Fig. 14B) corresponds to the clear area (Fig. 15) under the Pacific subtropical anticyclone. The extension of the persistent

rain band is seen as a zone of maximum precipitation in Fig. 14B, and also as a zone of maximum cloud amount in Fig. 15. The rain/cloud band extends along the northwestern rim of the clear area with subsidence in the Pacific subtropical anticyclone. It is also found that the large southwesterly moisture transport predominates along the western and northwestern rim of the anticyclone (Fig. 10C).

The map of ω at 700 hPa (Fig. 14B) shows that the subsiding motions occurs not only in the south side (in the Pacific subtropical anticyclone), but also in the north side of the rain band. This suggests the concentrated upward motion in the rain band and the compensating downward motion in both sides of the rain band. Another important fact is that the condition within the rain band is not characterized by the strong convective instability, but characterized by the weak convective instability or almost moist neutral stratification, as pointed out for many cases of the heavy rainfall event in the Baiu frontal zone (Akiyama, 1984; Ninomiya, 1984; Ninomiya and Akiyama, 1992). This indicates the release of convective instability due to the successive development of convective clouds in the heavy precipitation zone.

In addition to the study on the moisture balance in the large domain such as Area-C, more detailed features on the moisture transport around the rain band is desired. The normal and tangential component of 10-day averaged moisture transport relative to the axis of the rain band are presented in Fig. 16 and Fig. 17. It is an interesting fact that the lateral moisture flux convergence is large in the southern side of the maximum rainfall zone, whereas the lon-

Table 3. Area ratio (%) of the clear area in each of 10° long. ×20° lat. area.

	90–100E	100–110E	110–120E	120–130E	130–140E	140–150E	150–160E	160–170E	170–180E	180–170W
May-I	0	4	58	74	94	86	62	86	90	90
May-II	2	38	86	58	66	98	94	100	98	88
May-III	8	48	78	84	78	66	68	88	70	76
Jun-I	0	0	4	70	90	68	84	92	94	50
Jun-II	0	0	2	44	54	44	56	78	56	32
Jun-III	0	0	0	8	78	100	98	74	54	66
Jul-I	0	8	40	58	82	94	92	92	90	92
Jul-II	0	0	0	12	36	48	70	64	92	90
Lul-III	0	0	0	0	16	52	42	58	70	56

gitudinal moisture flux divergence is seen ahead of the core of the heavy rainfall. The large longitudinal moisture transport in the rain band ahead of the maximum rainfall area, indicates that the rain band plays the role of the channel for the eastward moisture transport from the intense rainfall area.

The time series data of precipitation (Si *et al.*, 1995), and the satellite cloud images, indicate that the intense rainfalls in the present period are caused by the successive passage of the meso-scale, and/or subsynoptic-scale precipitation systems within the precipitation belt. Therefore, the moisture balance analysis in the 10-day averaged field does not necessarily represent the essential feature of the extreme rainfall event. More detailed analysis of the moisture balance is required to elucidate the nature of this heavy rainfall event.

9. Concluding remarks

Features of the moisture balance over the central part of China and the South China Sea in MJJ of 1991 are studied, in relation with the heavy rainfalls over China, by utilizing the data of 24-hour prediction by a global numerical weather prediction model of JMA.

The study on moisture balance over a domain bounded by 20–40°N and 110–125°E (Area-C) indicates that the moisture inflow into this domain during MJJ in 1991, is mainly due to the southerly moisture transport across its southern boundary at 20°N. The seasonal variation of the moisture flux convergence, and the precipitation within this domain, are highly correlated with that of the southerly moisture inflow.

In order to find the relation between the southerly moisture inflow into Area-C and the moisture transport in the monsoon trough region over the South China Sea, the moisture balance in a domain bounded by 0–20°N and 110–125°E (Area-S), is further studied. In Area-S, the variation of the cross equatorial moisture flux is very small as compared with that of the southerly moisture flux crossing

20°N. In Area-S, the significant correlation is found between the southerly moisture flux across the 20°N latitude circle and the zonal moisture flux convergence in 0–20°N. This zonal moisture flux convergence is seen within the confluence area between the monsoon westerly and the easterly flow in the southern rim of the Pacific subtropical anticyclone. The monsoon trough region plays the role of the channel to transport the moisture from the 0–20°N zone toward north, although Area-S itself is not characterized by the moisture source region. It is also shown that the west-east intraseasonal oscillation of the monsoon trough has strong influence on the monsoon rainfall over China and the westerly moisture transport in 20–40°N. We show that the variation of the cross equatorial moisture flux in 95–110°E is also significantly smaller than that of the southerly moisture flux crossing 20°N in 110–125°E.

We should compare the results of the present study with those of the previous studies cited in the introduction. Against the previous studies, we conclude that the influence of the cross equatorial moisture flux in 95–110°E and 110–125°E on the precipitation over China, is significantly smaller than that of the zonal moisture convergence in 0–20°N zone.

The basic features of the intraseasonal variation of the monsoon westerly and that of the North Pacific subtropical anticyclone seen in 1991 are consistent with that found in other years. In addition, we stress the important relation between the precipitation over China and the intraseasonal variation of the monsoon trough over the South China Sea.

It will be asked whether the features of the precipitation, and the moisture balance over China and the South China Sea found in 1991, are seen commonly in other summers. Features similar to 1991 have been found in the East Asia summer monsoon periods in 1979 (Ninomiya and Muraki, 1986), and also in 1982 (Akiyama, 1989). The influence of topography on the moisture transport (see Fig. 4) does not change, of course, with time. From above, the present author infers that the fundamental features

Fig. 14. A: The 10-day averaged precipitation for July-I. The isohyet is given at 5 mm/day interval. Areas of precipitation larger than 10 mm/day are indicated by hatch marks. B: The 10-day averaged vertical velocity ω at 700 hPa for July-I. The blacked area indicates highland area higher than 3000 m. The isopleth is given at 4 hPa/hour interval. The areas of ascending motion are indicated by stipples. The areas of ascending motion larger than 4 hPa/hour are indicated by hatching. C: The 10-day averaged vertical stability $(-\partial\theta_e/\partial p)$ in the layer between 500 and 850 hPa for July-I. The blacked areas indicate highland areas higher than 1500 m. The isopleth is given at 1 K/(100 hPa) interval. The areas of convective instability are indicated by stipples. The area with stability lower than -2 K/(100 hPa) are indicated by hatching.

seen in 1991 will be found in other years. However, we need the studies for various years to confirm this question, since features of moisture balance vary year by year.

Although the 10-day averaged moisture flux field during the intense rainfall period in July-I indicates the concentration of the moisture flux convergence in the southwest side of a persistent narrow rain

Fig. 15. Distribution of 10-day mean Ch, the amount of cloud whose top is higher than 400 hPa level, for July-I. The black area, stippled area, dense hatched area and thin hatched area indicates the area of Ch more than 0.7, 0.5, 0.3 and 0.1, respectively. The blank area indicates the area with Ch less than 0.1, which is defined as clear area in the present paper.

Fig. 16. The normal component of the 10-day averaged moisture transport Q relative to the axis of the rainfall zone in July-I. The axis of the maximum rainfall zone is indicated by a thick broken line. The isohet of 24 and 16 mm/day are shown by thin dashed lines in this map.

band, more detailed meso-scale study is needed to understand the essential nature of the rain band.

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Fig. 17. The tangential component of the 10-day averaged moisture transport Q relative to the axis of the rainfall zone in July-I. The axis of the maximum rainfall zone is indicated by a thick broken line. The isohet of 24 and 16 mm/day are shown by thin dashed lines in this map.

this study.

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1991 年夏期の中国の強い降雨に関わる中国及南シナ海上の水蒸気収支

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気象庁全球数値予報モデル (T106) の 24 時間予報値を使用し、1991 年夏季モンスーン季の中国及南シナ海上の水蒸気収支を中国上の強い降雨との関連において解析した。

大雨域を含む $20\text{--}40^\circ\text{N}$ 及び $110\text{--}125^\circ\text{E}$ の領域-C への水蒸気流束の大部分は、 20°N を横切る南風水蒸気流束に依ってもたらされる。この南風水蒸気流束は 6 月初旬に急激に増加した。5~7 月を通し、領域-C 内の水蒸気流束収束、及び 降水量と南風水蒸気流束との間には高い相関関係が見られる。

上記の 20°N を横切る南風水蒸気流束の上流域にあたる $0\text{--}20^\circ\text{N}$ 及び $110\text{--}125^\circ\text{E}$ の領域-S (南シナ海を含む) においては、赤道を横切る水蒸気流束の変動は 20°N を横切る水蒸気流束に比べると非常に小さい。又 $95\text{--}110^\circ\text{E}$ における赤道を横切る水蒸気流束の変動も小さい。一方、領域-S での東西方向の水蒸気流束の収束量と 20°N を横切る南風水蒸気流束との間に高い相関関係が見いだされる。この領域-S における東西方向の水蒸気流束の収束は、モンスーン西風風系と太平洋高気圧南側の東風風系との合流収束域であるモンスーン・トラフ域で生じている。即ち領域-S に於ける東西方向の水蒸気流束の収束量と領域-C 内の降水量は強い相関関係を持って変動する。領域-S は水蒸気ソース域ではないけれども、上述の東西方向の水蒸気流束の収束を通して $0\text{--}20^\circ\text{N}$ 域から北向きに水蒸気を輸送し、中国 30°N 帯の降水および $20\text{--}40^\circ\text{N}$ の東向き水蒸気輸送に強い影響を及ぼす。

モンスーン西風の吹き出し、太平洋高気圧の東西変位などの季節内変化は、モンスーン・トラフの変化を通じて中国上の降水に影響を及ぼす。

7 月初旬の 10 日平均場では、揚子江流域で著しい降雨帯が見られた。降雨帯は、上昇域と一致し、その南北両側に下降域が現れていた。降雨帯の南で降雨帯に対して法線方向の水蒸気流束の収束が見られ、降雨帯中心の風下で大きな切線方向の水蒸気輸送が見られた。降雨帯では、成層の不安定性は最大ではなく、引き続き積雲対流による不安定の解消が示唆される。