Precipitation and Moisture Balance of the Asian Summer Monsoon in 1991

Part I: Precipitation and Major Circulation Systems

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Abstract

The large-scale features of the moisture transport and the water balance of the Asian summer monsoon in 1991 were studied by utilizing the 24-hour prediction by a T106 spectral global model. In part I of the present study, we will describe the seasonal change of the precipitation in relation to the change of the major circulation systems over the Asian monsoon region.

The most remarkable change in the onset period of the Asian summer rainy season over the Indian Ocean and the 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 in the onset phase of the rainy season over East Asia is the formation of a precipitation belt, which corresponds to the Meiyu and Baiu frontal zone.

In order to realize the relation between the variations of the precipitation with the those of the low-level circulation, several major circulation systems (CSs) in the lower troposphere are defined. Among them, the variations of the clockwise circulation centered over the Indian Ocean (CS-3) and a cyclonic circulation over the northern part of the Indian subcontinent (CS-6) are closely related with variations of the Indian monsoon rainfalls, while the cross-equatorial flow from the Australia anticyclone (CS-4) and the circulation around the North Pacific subtropical anticyclone (CS-5) are the major systems related with the East Asia rainfalls.

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

1. Introduction

The Asian summer monsoon (hereafter abbreviated as monsoon) is a complicated global-scale circulation system and has significant influence on the weather and climate over the Asia. Although extensive studies have been made on the monsoon from various viewpoints, the variations of the precipita-

tion over the whole monsoon region has not been fully studied yet. We need more synthesizing studies to fully understand complicated features of the monsoon precipitation for various years. As the first step for such studies, we will study, in Part I of the present paper, seasonal and intraseasonal variations of the precipitation, mixing ratio of water vapor and vertical stability associated with the changes of the large-scale monsoon circulation systems for May, June and July (MJJ) in 1991.

A brief summary of several previous studies on the Asian summer monsoon related to the subject

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of Part I is given first.

Pearce (1992) stated the following features of the 1990 monsoon: At lower levels, an extensive cyclonic circulation around a convergent region over the northern India and an anticyclonic divergent circulation in the southern Indian Ocean are linked by a pronounced southerly cross-equatorial flow with its maximum along the east coast of Africa (Somalia low-level jet stream). A zone of strong latent heat release with strong rainfall and prominent ascending motion extends from northern India to south China, while the pronounced decent motions are over the south Indian Ocean-Australia anticyclone belt, the north Pacific anticyclone and the Mediterranean-Arabian Sea region. The monsoon westerly over the Arabian Sea intensifies rapidly in June. The low-level flow over the southern Indian Ocean obtains substantial moisture from the underlying sea surface and carries the moisture through the east African low-level jet, and becomes westerly after crossing the equator picking up more moisture over the Arabian Sea. In addition, the monsoon depressions over the Bay of Bengal and the Indian subcontinent bring large precipitation (*e.g.*, Das, 1987).

Luo and Yanai (1984), He *et al.* (1987) and Yanai *et al.* (1992) studied the heating of the Tibetan Plateau and its effects on the evolution of the monsoon. They stated that low-level inflow toward the plateau is a pronounced feature. The monsoon exhibits two distinct periods of abrupt changes that result in the successive commencements of summer rains over Southeastern Asia and the west coast of India. The major warming occurs first in May over the areas from the eastern Tibetan Plateau to south China, which results in reversal of the meridional temperature gradient south of the eastern plateau and the commencement of the low-level southwesterly over areas from the Bay of Bengal to the south China Sea, then the onset of the Indian monsoon occurs over the Arabian Sea and the Indian subcontinent in June with the increase of temperature over the area from Saudi Arabia to the western Tibetan Plateau. The ascending motion over the southern portion of the Plateau becomes a part of intense monsoon vertical circulation.

Tao and Chen (1987) and Ding (1991) discussed the relation between the cross-equatorial flow in 90–110°E and 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. The strong southwesterly occurs over the South China Sea when the Indian monsoon and the cross-equatorial flow converge.

Lau *et al.* (1988) studied the climatology of station rain data over China and compared it with satellite OLR (outgoing long-wave radiation) and large-scale circulation. They identified two major

monsoon rainfall onsets over China. The first one, Meiyu, occurs over the central China around early-mid June, and the second one over the northern China during late July. The multiple onset occurs as the major rain zone makes a rapid transition between three somewhat stationary positions over the south China (pre-monsoon rainfall), central China (Meiyu) and the northern China (polar front). The abrupt change of the major rain zone is related to the phase-locking between the intraseasonal and the seasonal variations. A similar seasonal transition of the East Asia monsoon rainfall zone over China and the Japan Islands has been reported by several authors (*e.g.*, Ding, 1992; Ninomiya, 1989; Ninomiya and Muraki, 1986; Matsumoto, 1992). Some authors (*e.g.*, Kato, 1985 and 1989; Hirasawa *et al.*, 1995; Ueda and Yasunari, 1998) showed a close relation between the abrupt change of the regional monsoon circulation and the variations of regional ocean-land thermal contrast over the Bay of Bengal, the South China Sea and southern China.

One of the outstanding features of the East Asia monsoon is the formation of a quasi-stationary long rain zone (Baiu/Meiyu front) extending from the eastern foot of the Tibetan Plateau to the western North Pacific via the Japan Islands. Many authors (*e.g.*, Akiyama, 1973 and 1990; Matsumoto *et al.*, 1971; Ninomiya, 1984 and 1989; Ninomiya and Akiyama, 1992; Ninomiya and Murakami, 1987; Ninomiya and Muraki, 1986) pointed out that the low-level southwesterly flow along the western periphery of the Pacific subtropical anticyclone transports the large amount of moisture into the rain zone and generates the convective instability through the process of differential advection. It is also inferred that a quasi-stationary cold trough (Baiu trough), extending from the Bering Sea to the Japan Sea and further to the Yellow Sea, works to keep the rain zone along $\sim 30^\circ\text{N}$.

Murakami and Matsumoto (1994) stated that the seasonal change in OLR does not necessary accompany the wind reversal. They identified SEAM (Southeast Asia monsoon), WNPM (western North Pacific monsoon; south of the Pacific subtropical high belt) and BAIU (Baiu zone) as the major monsoon areas, based on the seasonal change of OLR. The WNPM is related with the west-east circulation while the SEAM is associated with the strong meridional circulation derived by the heating of the Tibetan Plateau.

Lau (1992) discussed the relation between the India and the East Asia monsoon by applying EOF to 5-day mean OLR. The EOF-1 shows an eastward-oriented dipole structure with centers over the Indian Ocean (positive) and the tropical western North Pacific (negative) accompanied by a weaker dipole of opposite polarity on the north side. In EOF-2, the east-west oriented dipole are displaced

northward to 15°N over the India subcontinent (positive) and the Pacific just east of Philippines (negative). Two distinct bands of positive anomaly, one along ITCZ and another from central China to Japan (Baiu/Meiyu rain zone), form an elongated horseshoe pattern surrounding the negative center around 15°N and 140°E .

Many authors related the abrupt seasonal transition of the monsoon to the intraseasonal oscillation of 30–50 days. Nakazawa (1992) pointed out that the first eastward extension of the monsoon westerly occurs in early June over the Indian Ocean, which then propagates to the western Pacific in mid June. The second enhancement of the monsoon occurs with the eastward propagation of the monsoon westerly from the Arabian Sea and the tropical Indian Ocean in mid July. This westerly extends further to the western Pacific up to 150°E in late July, which results in the enhancement of cyclonic circulation over the subtropical western Pacific and the northward shift of the Pacific subtropical anticyclone toward the Japan islands. He also noted that the seasonal northward propagating speed of the convective area is ~ 1 latitude degree/day. Ueda *et al.* (1995 and 1996) also pointed out the simultaneous occurrence of abrupt northward transition of the active convective area over the western Pacific and the northernward shift of the Pacific subtropical anticyclone.

Although aforementioned studies have clarified many important features of the Asian summer monsoon, the following problems have not been fully explained yet;

- (1) The spatial and temporal variations of the Asian monsoon precipitation.
- (2) The variations of the precipitation in relation to the variations of major monsoon circulation systems.
- (3) The variations of the vertical motion, mixing ratio of the water vapor and the vertical stability associated with the variations of precipitation.

We thus intend to study the large-scale features of the 1991 monsoon precipitation with special attention to the aforementioned problems. The moisture transport and moisture balance of the monsoon will be discussed in Part II of the present study.

2. Data and outline of the analyses

The data of 24-hour numerical prediction (NP) obtained for 00 and 12 UTC by a global spectral model (GSM) of Numerical Prediction Division, JMA, which is stored in 2.5° latitude and longitude grid system, are utilized for the present study.

Since many of the previous analyses were based on the objective analysis (OA) data, the difference between the OA data and the NP data should be stated here. Over data sparse areas, the OA data are nothing but the NP data, in fact, because the objective analysis is made in the successive analyses-prediction cycle utilizing the NP data as the first guess field.

In the analysis with the OA data, precipitation over the data sparse area is usually estimated as the residual term in moisture balance equation after the evaluation of the moisture flux convergence and the moisture supply from the underlying surface. It is the significant advantage of NP data that the every meteorological quantity, including the precipitation, the moisture supply from the underlying surface, the vertical velocity and the moisture flux convergence, are consistent with each other, because they are adjusted in the process of time integration according the physics included in governing equations of the model. Huffman *et al.* (1995) reported good agreement of the precipitation estimated by the “satellite-gauge-model” and that by the ECMWF T106 model. This will support the validity of using the precipitation obtained by the numerical model for the present study.

From this reason, we use the NP data obtained by the GSM for the present analysis. In quantitative discussion, we use the time-averaged value of wind velocity to eliminate some unrealistic gravitational wave noise, which may appear at each time step.

As the detailed description of the GSM was reported by NPD, JMA (1993), a very brief explanation is given here. The GSM has 106 triangular truncation wave numbers and the corresponding truncation grids are spaced by 110 km. In vertical, it has 21 levels up to 10 hPa with the sigma-pressure hybrid coordinate system. The physical processes are long and short wave radiative processes with parametrized cloud fractions, moist convection with the modified Kuo scheme, large-scale condensation, shallow convective vertical diffusion, surface fluxes, planetary boundary process with a level-2 closure scheme, gravity wave drag, and a land-surface process with a SiB scheme.

Considering the time-scale of the variations in the monsoon, we studied the 10-day averaged field for nine 10-day subperiods in MJJ as shown in Table 1. The features of the monsoon in these subperiod known from the present study are noted in Table 1.

Here, we should note the meaning of such a simple descriptive study against the analysis of the anomaly fields and analysis by various objective methods such as EOF. The anomaly analysis has the advantage of demonstrating the deviation from a certain basic field, and the EOF analysis has, certainly, the advantage of expressing mathematically the predominant component in space and time variations of

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

several quantities correlated with each other. However, the implication of the anomaly fields and of results from EOF are not realized without the understanding of actual precipitation systems and circulation systems in the atmosphere. Thus, the description of the monsoon basing on the simple 10-day mean maps has the significant meaning.

3. Overview of the Asian summer monsoon precipitation

We here characterize the monsoon precipitation from the global-scale view point. Fig. 1 presents the 10-day mean maps of the precipitation and the 850 hPa geopotential height for 1–10 June 1991, which corresponds to the onset period of the Indian monsoon of 1991.

The distribution of the precipitation and the 850-hPa height in the western hemisphere exhibits a north-south symmetric pattern, with the symmetric axis on the equator. In the western hemisphere, large precipitation concentrates within areas with a diameter of ~ 500 km aligned in the ITCZ. Zones of the secondary maximum of precipitation exist in the middle latitude polar frontal zone along $\sim 40^\circ\text{N}$ and $\sim 30^\circ\text{S}$. In the height field, an east-west oriented zone of minimum height elongates over the equator. Two predominant subtropical anticyclone belts are seen over $\sim 30^\circ\text{N}$ and $\sim 20^\circ\text{S}$, while large cyclones are located over $\sim 50^\circ\text{N}$ and $60\text{--}70^\circ\text{S}$.

The aforementioned axis symmetric patterns in the height and precipitation field are distorted in the Asia monsoon region ($30\text{--}150^\circ\text{E}$). A large area of low-height covers the southern Asia. The monsoon trough, which elongates from the Indochina Peninsula to the Philippines, is one of the characteristic features of the summer monsoon. In the Southern Hemisphere, the subtropical anticyclone belts are seen over the western Indian Ocean and Australia. The zone of maximum monsoon rainfall elongates along the monsoon trough and extends further to southeastern foot of the Himalayan Mountains. Another prominent maximum of precipitation is seen around the western coast of India. A pre-

cipitation zone extending from the southern part of China to the Japan Islands, which corresponds to the Baiu/Meiyu frontal zone, is also a notable feature.

The features of the sea surface 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 MJJ of 1991.

We here examine features of the precipitation in detail for the area bounded by 60°N , 20°S , 0°E and 180°E . Figure 2 shows maps of 10-day averaged precipitation for May-II, June-I, June-II, July-I and July-II. The variations of 10-day mean precipitation, averaged over each of 15 subdivided regions with the dimension of 10° lat. $\times$ 30° long., are presented in Fig. 3. From these figures, the following features are pointed out: The basic feature of the seasonal change of precipitation in MJJ over $50\text{--}110^\circ\text{E}$ is the shift of the maximum precipitation areas from the equatorial zone toward the vicinity of the southern foot of the Tibetan Plateau, while that over $110\text{--}150^\circ\text{E}$ is the increase of the precipitation within the monsoon trough region and the formation of the precipitation zone (Baiu/Meiyu frontal zone) along the northwestern rim of the North Pacific subtropical anticyclone.

4. Major circulation systems in and around the Asian summer monsoon region

In the following sections we will describe the variations of the precipitation in relation to those of the circulation in the lower troposphere. Figure 4 shows maps of 10-day averaged 850 hPa wind velocity for May-II, June-I, June-II, July-I and July-II.

As already pointed out in many papers (see introduction), the whole monsoon circulation consists of several major circulation systems. We intend to relate the variations of the precipitation on respective regions with the variations of relevant major circulation systems. For this, we should first define the major circulation systems of the monsoon. By inspecting the maps in Fig. 4, we are able to de-

Fig. 1. A: The global distribution of the precipitation averaged in June-I, 1991. The isohyet is given at 5 mm/day interval. B: The global distribution of the geopotential height at 850 hPa averaged in June-I. The blackened area indicates the Tibetan Plateau higher than 1500 m. The height contour is given at 60 gpm interval. The area of the geopotential height more than 1500 gpm are indicated by hatch marks.

fine subjectively eight major circulation systems in and around the monsoon region. The features of the major circulation systems in June are schematically illustrated in Fig. 5. It should be noted that the location, extension and intensity of these major circulation systems vary significantly with time.

The circulation systems labeled by CS-1 (CS is abbreviation of circulation system) and CS-2 are the trade wind easterly in the southern and northern hemisphere, respectively. While CS-1 predominates over the Indian Ocean and the South Pacific throughout the monsoon season, CS-2 appears only over the North Pacific east of $\sim 150^\circ\text{E}$ on the average.

Within the tropical-subtropical latitude of the monsoon region, three predominant clockwise circulations align from west to east. They are CS-3 over the Indian Ocean, CS-4 over $80\text{--}130^\circ\text{E}$, and CS-5 over the western North Pacific, respectively.

The easterly in the upstream part of CS-3 (CS-3-E) flows from the cold Mascarene high over the southern Indian Ocean. It turns to the southerly along the east coast of Africa, and crosses the equator in $40\text{--}60^\circ\text{E}$ as the Somalia low-level jet (CS-3-S). It turns to southwesterly over the northern Indian Ocean and further to the Indian monsoon westerly (CS-3-W).

The easterly of the upstream part of CS-4 (CS-

Fig. 2. The 10-day mean maps of the precipitation for May-II, June-I, June-II, July-I and July-II of 1991. The isohyet is given at 5 mm/day interval. Areas of precipitation larger than 10 mm/day are indicated by hatch marks.

4-E) originates from the cool anticyclone over Australia and the adjacent sea area. It turns to the southerly (CS-4-S) and crosses the equator in 80–120°E, and changes to the East Asia southwesterly monsoon (CS-4-W). The cross equatorial flow of CS-4 is significantly weaker than that of CS-3 and indicates large temporal variations.

The circulation of CS-5 is accompanied by the

North Pacific subtropical anticyclone. The easterly flow, the southerly flow and the westerly flow along the southern, western and northern periphery of the subtropical anticyclone are hereafter signified by CS-5-E, CS-5-S, and CS-5-W, respectively.

A large cyclonic circulation centered over the Tibetan Plateau is identified as CS-6. Local enhancement of southerly wind along the east side of the

Fig. 2. (Continued)

Indian subcontinent (*i.e.*, over the Bay of Bengal), the Indochina Peninsula (over the South China Sea) and the Tibetan Plateau (over the southwestern part of China) are seen within the basic flow of CS-6.

Two major circulation systems are identified around the monsoon region. CS-7 is the circulation associated with the subtropical anticyclone centered over the Mediterranean-northern Africa. CS-8 is the westerly in the mid-latitude north to the monsoon region. Within the basic flow of CS-8, the blocking anticyclone (CS-8-AC) tends to predominant in 30–80°E, while the cut-off low (CS-8-C) tends to developed in 110–170°E during the monsoon season.

These circulation systems interact with each other and yield complicated spatial and temporal variations of the monsoon precipitation. In addition, synoptic-scale disturbances, such as the monsoon depression, tropical disturbances and mid-latitude frontal depressions bring intense precipitation.

5. Variations of the major circulation systems and precipitation

In this section, variations of the precipitation associated with those of the low-level circulation will

be studied by inspecting the 10-day mean maps of the precipitation (Fig. 2) and 850 hPa wind (Fig. 4) for May-II, June-I, June-II, July-I and July-II.

5.1 Features before the onset of Indian monsoon (May-I–May-II)

Features before the onset of Indian monsoon are seen Fig. 2A and Fig. 4A. In May-I and II, significant precipitation does not yet occur over India, and precipitation dominates, in general, over the tropical latitudes. A few intense precipitation areas are seen over the tropical Indian Ocean.

The cyclonic circulation of CS-6 has not fully developed yet, while the anticyclonic circulation of CS-7 extends southeastward over the Arabian Sea. The northerly wind of CS-7 prevails around the west coast of the Indian subcontinent and the easterly of CS-7 extends southward to ~5°N. Suppressed by CS-7, the westerly branch of CS-3 is confined only in the narrow area of 0–5°N and 45–60°E, although the easterly wind of CS-2 over the tropical Indian Ocean is gradually replaced by the westerly of CS-3.

The cross equatorial flow of CS-4 is already identifiable around 80°E. The formation of an anticyclonic circulation is seen over the Bay of Bengal,

Fig. 3. The temporal changes of the 10-day mean precipitation averaged over each of the 15 subdivided region with a dimension of 10° latitude $\times$ 30° longitude.

which forms a west-east elongated anticyclone belt merging with the western tip of the North Pacific subtropical anticyclone. The confluence of southeasterly of CS-4 and the southwesterly of the anticyclonic circulation yields a strong southerly wind over the Bay of Bengal, which flows further into the Indochina Peninsula, merging with the southwesterly flow of CS-6 to produce significant precipitation. The intense rainfalls over the northern part of Myanmar in May-I (map is not shown) occurs within the southwesterly flow. The increase of the rainfall over the Indonesia and the Indochina Peninsula precedes the onset of the western Indian monsoon rainfall by 10–20 days.

The Pacific subtropical anticyclone dominates in this period. Its western tip protrudes westward to 100°E . The strong southwesterly of the CS-5 covers the southern part of China. Formation of a precipitation zone extending from the southern China to the southern coast of Japan along the northern periphery of the Pacific subtropical anticyclone is already seen in May-II. This precedes the onset of the rainfall over the west coast of India by 10 days.

In this period, the easterly wind of CS-1 and CS-2 predominate over the western Pacific, the South China Sea and Indonesia. Precipitation systems with diameters of ~ 500 km are aligned in the equatorial belt. The satellite cloud images (not shown) indicate that these precipitation systems are accompanied by tropical cyclones and tropical cloud clus-

ters in the ITCZ. The intense rainfall around the Philippines in May-II is associated with a typhoon.

5.2 Onset of Indian monsoon (May-III–June-I)

Significant changes occur in the field of the precipitation and CSs over the whole Asian monsoon region during May-III and June-I (see Fig. 2B and Fig. 4B).

While the area of westerly wind of CS-7 shrinks westward from the Arabian Sea in late May with the northwestward shift of the Mediterranean anticyclone, the southwesterly flow of CS-6 increases considerably. Simultaneously, the clockwise circulation of CS-3 intensifies rapidly over the southern tropical Indian Ocean ($\sim 6^\circ\text{S}$, $\sim 65^\circ\text{E}$), and the westerly zone of CS-3 expands abruptly to northward to $\sim 15^\circ\text{N}$. The cross equatorial flow and the westerly (~ 15 m/s) of CS-3 attains its maximum intensity in the early June. In association with the changes in CSs, the area of maximum rainfall over the equatorial Indian Ocean shifts eastward first from $\sim 55^\circ\text{E}$ to $\sim 65^\circ\text{E}$ and then moves northeastward to the west coast of India. These features are recognized as the first onset of the Indian monsoon.

The westerly zone extends eastward to $\sim 110^\circ\text{E}$ as the monsoon westerly burst extends. The formation of a strong southwesterly over the Bay of Bengal is accompanied by the confluence of CS-3-W with CS-4-S and the development of monsoon depression over the central part of India. The intense precipitation is

Fig. 4. The 10-day mean maps of wind velocity at 850 hPa for May-II, June-I, June-II, July-I and July-II of 1991. A wind barb indicates wind speed of 10 m/s. The blackened areas indicate the high-lands higher than 1500 m above sea level.

brought out over the areas around the Bay of Bengal by the intensified southwesterly flow.

Other notable changes are seen over the Indonesia and the south China Sea regions. The confluence of the eastward-intruding westerly (CS-3-W and CS-4-W) with the southeasterly of CS-5 around the western rim of the anticyclone yields well developed monsoon trough over the South China Sea

and the southerly flows over the South China Sea. This southerly flow changes to west-southwesterly flow (CS-5-W) along the northern periphery of the anticyclone. Concurrently with the changes in wind field, the zone of maximum rainfall shifts from the equatorial belt to the monsoon trough, and the Baiu/Meiyu rainfall zone forms along the northern periphery of the anticyclone in this period.

Fig. 4. (Continued)

Fig. 5. Schematic illustration of the major circulation systems (CSs) at 850 hPa in June. Arrows indicate the direction of flows. The location, extension and intensity of CSs vary significantly with time, although the basic features of CSs remain throughout MJJ.

Significant changes are also found in the mid-latitude westerly zone (CS-8). A blocking ridge (CS-8-AC) forms over Kazakhstan-Uzbekistan area ($\sim 40^\circ\text{N}$ and 60°E) in this period. The northerly winds along the eastern rim of the ridge causes dry advection in $40\text{--}25^\circ\text{N}/55\text{--}70^\circ\text{E}$. Almost simultaneously, a cut-off low appeared over the Okhotsk Sea.

The cold air advection to the west of the cyclone blocks the poleward intrusion of the air-mass of the tropical and subtropical origin.

5.3 Break of Indian monsoon (June-II-June-III)

Shortly after the peak period of the Indian monsoon westerly, the circulation of CS-3 weakens re-

markably in mid June (Fig. 4C). The 850 hPa wind speed over the southeastern Arabian Sea ($\sim 10^{\circ}\text{N}$, 75°E) decreased to ~ 10 m/s from their maximum value of ~ 15 m/s seen in June-I. With the rapid weakening of the monsoon depression, the southwesterly winds over the Bay of Bengal in the onset period changes into zonal flow of ~ 10 m/s in the break period. At the same time, the rainfall over the western coast of India decreases rapidly in June-II and the precipitation area disappears from the northern Indian Ocean and the Arabian Sea (Fig. 2C). The maximum precipitation in this period is found over the western coast of the Indochina Peninsula. This abrupt decrease of westerly wind and precipitation over the western coast of India is recognized as the break of Indian monsoon.

5.4 Eastward intrusion and westward retreat of the monsoon westerly (June-II–July-I)

The eastward extension of the Indian monsoon, which began in the onset period, still continues in middle June, in spite of the break of Indian monsoon. In the northern tropical belt between the equator and $\sim 15^{\circ}\text{N}$, the eastern tip of the westerly flow reaches to $\sim 110^{\circ}\text{E}$ in early June and forms the distinct monsoon trough over the South China Sea between the monsoon westerly and the southerly flow of CS-5 (Fig. 4B). The westerly flow further intrudes to the western Pacific around 140°E in middle June, and induces the development of a tropical cyclone over $\sim 15^{\circ}\text{N}$ and 140°E (Fig. 4C). Owing to the intrusion of the westerly and the development of the tropical storm, the North Pacific subtropical anticyclone shifts eastward.

The westerly burst causes significant variations in the precipitation field (Fig. 2B and Fig. 2C). The intense rainfalls are brought out by the tropical disturbance generated ahead the intruding westerly flow ($\sim 15^{\circ}\text{N}$, 150°E) and by the intensified monsoon trough over the South China Sea near the Philippines ($\sim 15^{\circ}\text{N}$, 120°E). With the eastward shift of the North Pacific anticyclone, the area of maximum precipitation in the Baiu/Meiyu frontal zone appears over the southwestern part of Japan ($\sim 32^{\circ}\text{N}$, 130°E) in June-II.

In late June and early July, the monsoon westerly withdraws westward, and the North Pacific subtropical anticyclone begins to extend westward to $\sim 120^{\circ}\text{E}$. The monsoon trough is remarkably intensified around the Philippine and the South China Sea on the western rim of the westward expanding anticyclone (Fig. 4D). In this period, southerly winds over the South China Sea and the southern China are enhanced along the west-northwestern periphery of the anticyclone.

The large amount of precipitation occurs over the south-central part of China simultaneously with the intensification of the southerly winds. The long pre-

cipitation zone develops fully along the north side of the anticyclone. It indicates the largest extension from the eastern foot of the Tibetan Plateau to the northwestern Pacific via the central part of China and the Japan islands (Fig. 2D). The precipitation is also large in the intensified monsoon trough. Thus, the east-west elongated horseshoe pattern of precipitation around the clear area is accomplished in the peak period of the east Asia rain season.

5.5 The second onset of the Indian monsoon and associated change of the North Pacific subtropical anticyclone (July-II–July-III)

After the break period of the Indian summer monsoon in middle June, the circulation of CS-3 re-enhances gradually and then rapidly attains the second maximum in middle July (Fig. 4E). Concurrent with the second peak of the monsoon westerly over the Arabian Sea, the second peak of the rainfall occurs over the western coast of India and around the Bay of Bengal in July-II and III. This second maximum of the monsoon westerly associated with the second maximum of precipitation (Fig. 2E) is signified as the second onset of the Indian monsoon.

The features of the second onset are significantly different from those of the first onset. The maximum 850 hPa wind velocity over the Arabian Sea during the second onset reaches to ~ 25 m/s, which is considerably stronger than that in the first onset. The circulation center of CS-3 is located at equator in the second onset, while that in the first onset is at $\sim 5^{\circ}\text{S}$. The zone of maximum westerly over the Arabian Sea is at $12.5\text{--}15^{\circ}\text{N}$ in the second onset, while that in the first onset is at $\sim 5^{\circ}\text{N}$. The area of maximum rainfall also appears around 15°N in this period. This indicates the seasonal northerly displacement of the entire Indian monsoon circulation system. The cyclonic circulation of CS-6 exhibits its largest extension from $\sim 45^{\circ}\text{E}$ to $\sim 115^{\circ}\text{E}$ in this period. The southerly component of the wind over the Bay of Bengal and the Indochina Peninsula in the second onset period is, however, obviously smaller than that in the first onset.

Merging with the westerly of CS-4, the westerly of CS-3 protrudes eastward to the tropical North Pacific to $\sim 150^{\circ}\text{E}$ in July II, and forms a deep monsoon trough, which extends from western Pacific ($\sim 5^{\circ}\text{N}$, 145°E) to the South China Sea. The North Pacific subtropical anticyclone and the circulation of CS-5 are pushed northward by the monsoon westerly burst in the tropical zone. Another remarkable feature seen in this period is the disappearance of the quasi-stationary cut-off low around the Bering Sea. In association with the aforementioned variations in the wind field, the horseshoe pattern of precipitation around the Pacific subtropical anticyclone is also distorted. The distinct Baiu/Meiyu precipitation zone also loses its identity in this period,

although intense summer rainfall still remains over northern China and the South China Sea coastal zone.

6. Seasonal changes of thermal and height fields in the lower troposphere

The 10-day mean maps of the 850-hPa temperature and height for May-II, June-I and July-II are shown in Fig. 6 and Fig. 7, respectively. From these figures, the following features are pointed out.

6.1 Thermal contrast between the continent and oceans

The basic features of the 850-hPa thermal field in the monsoon season is the continent-ocean contrast. Since the seasonal rise of temperature over oceanic areas is very gradual, the tropical-subtropical parts of the Pacific and Indian oceans are covered by the almost uniform 850-hPa temperature of 20–16°C, during the monsoon period. Owing to the rapid temperature rise over the tropical and subtropical parts of the Eurasia and the African continent in the spring, these areas are covered by the high 850 hPa temperature of 24–32°C during MJJ. The strong thermal gradient in the lower troposphere is thus sustained in the periphery of the continents.

Around the Mediterranean, the cold air advection by the northerly wind of CS-7 sustains the low temperature over the Mediterranean coast of Egypt ($\sim 20^\circ\text{E}$) and restricts the further westward extension of the high temperature area.

In the polar latitude, The cold pool at 850 hPa remains over the Okhotsk Sea, Bering Sea and the northwestern Pacific north to $\sim 45^\circ\text{N}$ throughout the summer season, although the temperature in the cold pool rises $\sim 10^\circ\text{C}$ during the three months of MJJ. The cold air advection from these cold pools blocks northeastward intrusion of the warm moist air flow beyond $\sim 45^\circ\text{N}$ over the respective sea areas.

The height field in JJ is characterized by a vast low-height area centered over the high temperature area around southern part of the Tibetan Plateau.

6.2 Seasonal changes in thermal and height field

In the pre-monsoon period, a zone of high 850 hPa temperature more than 24°C elongates from the Indian subcontinent to northern Africa. The highest 850 hPa temperature more than 28°C is found over the central part of India (Fig. 6A). Owing to the high temperature over the Indian subcontinent, strong thermal gradient of $\sim 1^\circ\text{C}/(100\text{ km})$ is maintained over the coastal zone of Bay of Bengal in this period (Fig. 6A). The appearance of the southerly wind over the Bay of Bengal in the pre-monsoon period will be owing to the strong regional thermal contrast. In this period, the area lower than 1500 gpm expands gradually over the Indian subcontinent (Fig. 7A).

After the first onset of the Indian monsoon rainfall, the 850-hPa temperature over the southwestern parts of India decreases gradually. With the seasonal march of the monsoon, the temperature over there further falls under 24°C , when the monsoon rainfall is maximized (Fig. 6B). With this cooling, the thermal gradient over the Bay of Bengal decreases rapidly. In this period, the area of the high temperature shifts westward and the zone of high temperature more than 28°C elongates from the Pakistan-Iran area to the Arabian Peninsula and northeastern Africa. The area of highest temperature more than 32°C is found around Pakistan and Iran in early June (Fig. 6B). With the change in the thermal field, significant changes in the height field occurs around June-I (Fig. 7B). In association with the height fall over central India to 1440 gpm, the strong height gradient appears over the northern Arabian Sea, India and the Bay of Bengal. The maximum gradient reaches to $\sim 25\text{ gpm}/(500\text{ km})$ in the Indian monsoon onset period.

The area of maximum temperature shifts to the Arabian Peninsula in middle July (Fig. 6C). With the westward shift of the maximum temperature area from India to Pakistan-Iran area, the zone of maximum thermal gradient moves also from the Bay of Bengal to the northern Arabian Sea, where the thermal gradient reaches to $\sim 1^\circ\text{C}/(100\text{ km})$ in mid July.

Another significant seasonal change at 850-hPa is the warming over east Asia. In the pre-monsoon period, the northern and eastern extension of warm area higher than 24°C is bounded by the southwestern rim of the Tibetan Plateau (Fig. 6A). The warm area protrudes gradually northeastward with the seasonal march. Its northern and eastern boundary reaches to $\sim 45^\circ\text{N}$ and $\sim 115^\circ\text{E}$ in middle July (Fig. 6C), respectively. The disappearance of the Baiu/Meiyu precipitation belt is concurrent with this warming in the mid-latitudes.

The height gradient decreases once in the monsoon break period in mid June (map is not shown) but increases again in the second onset period, when the lowest 850 hPa height of 1410 gpm appears over the Indian subcontinent (Fig. 7C). The area bounded by 1440 gpm height contour attains its largest extension from 40 to 130°E . In this period, the maximum height gradient reaches to $\sim 30\text{ gpm}/(500\text{ km})$.

6.3 Cold air advection in the cross equatorial flow of CS-3

Owing to the cold air advection by the southerly cross-equatorial flow along the east coast of African continent (CS-3-S), the temperature over the southern Indian Ocean decreases gradually with the seasonal march of the southern winter. The 16°C isotherm over the southern Indian Ocean, which was

Fig. 6. The 10-day mean maps of the air temperature at 850 hPa for May-II, June-I and July-II of 1991. The isotherm is given at 4°C interval. The areas with temperature more than 28°C and 24°C are indicated by thick and thin hatch marks, respectively.

located over 15°S in the pre-monsoon period (Fig. 6A), moves slowly northward and reaches the equator in July (Fig. 6C).

7. Seasonal variations in the mid-troposphere

Features of the seasonal change in the mid-troposphere will be described briefly showing the 10-day mean maps of 500 hPa equivalent potential

temperature (θ_e) and height for May-II and July-II in Fig. 8 and Fig. 9, respectively.

In the pre-monsoon period, a zone of high θ_e more than 336 K extends over the equatorial zone from Africa to the central Pacific. From the equatorial high θ_e zone, a narrow area of high θ_e protrudes northward to the Indochina Peninsula and the southern part of China. Except this area, θ_e de-

Fig. 7. The 10-day mean maps of 850 hPa geopotential height for May-II, June-I and July-II of 1991. The contour is given at 30 gpm interval. The areas lower than 1440 gpm is indicated by hatch marks.

creases northward in the northern hemisphere (Fig. 8A). The features of a springtime height field with a subtropical high belt extending over $\sim 15^{\circ}\text{N}$ and a strong height gradient in the middle latitudes are still seen in this period (Fig. 9A).

The northward shift of the area of maximum θ_e from the equatorial zone to the southern foot of the Tibetan Plateau is a notable feature in the monsoon period. While θ_e over the equatorial zone decreases

slightly during May and June, θ_e around the southern foot of the Tibetan Plateau increases rapidly. In July, the area of high θ_e more than 344 K covers a wide area centered over the southern Tibetan Plateau, where the maximum θ_e reaches to 356 K (Fig. 8B), which indicates strong heating and moistening over the area of maximum precipitation.

The height field changes rapidly owing to the strong heating in the middle troposphere over the

Fig. 8. The 10-day mean maps of the equivalent potential temperature (θ_e) at 500 hPa for May-II and July-II of 1991. The isopleth is given at 4 K interval. The areas with θ_e more than 344 K and 336 K are indicated by thick and thin hatch marks, respectively.

Tibetan Plateau. In the monsoon period, the north-south height gradient at 500 hPa vanishes over the Tibetan Plateau, and the subtropical high belt is cut apart into two subtropical anticyclones over northern Africa and the North Pacific (Fig. 9B).

At the upper troposphere (200 hPa), the anticyclone with a strong divergent flow predominates over the northern part of the Indochina Peninsula, where the monsoon rainfall is maximized (map is not presented).

8. Seasonal variation in the moisture and vertical motion in the lower troposphere

The 10-day mean maps of the water vapor mixing ratio at 850 hPa and vertical motion ω at 700 hPa for May-II, June-I and July-II are presented in Fig. 10 and Fig. 11, respectively.

While the areas of high mixing ratio coincide with the areas of the ascent motion over the oceanic areas throughout MJJ, a relatively small mixing ratio is associated with the dominant subsidence that occurs within the North Pacific subtropical anticyclone (CS-5), the Mediterranean anticyclone (CS-7) and

the cross equatorial flows from the southern hemisphere.

In the pre-monsoon period (May-I and May-II), while a moist zone with ascending motion extends along the ITCZ over the Pacific and Indian Ocean, the areas of relatively small mixing ratio cover the higher latitudes and subtropical zone in 10–35°N, except the Indochina Peninsula (Fig. 10A and Fig. 11A).

The moisture field changes rapidly in and after the Indian monsoon onset period. The northward shift of the high-moisture area from the tropical zone toward the Southeast Asia and the decrease of the moisture in the cross equatorial flows are the basic seasonal change in the moisture field.

While the mixing ratio over the southern part of the Tibetan Plateau increase rapidly from 12 g/kg to 18 g/kg in association with the intensification of the ascending motion during one and half months between the middle of May and early July, the mixing ratio over the western Indian Ocean and the southern part of the Arabian Sea decreases gradually from 12 to 10 g/kg, owing to the subsidence

Fig. 9. The 10-day mean maps of 500 hPa geopotential height for May-II and July-II of 1991. The contour is given at 60 gpm interval. The areas higher than 5880 gpm are indicated by hatch marks.

and the horizontal dry advection within the intensified cross-equatorial flow of CS-3 (Fig. 10B and Fig. 11B).

The northward shift of the moist area is also seen around 120°E. The zone of the maximum mixing ratio moves from Indonesia (May-II, Fig. 10A) to the eastern foot of the Tibetan Plateau (July-II, Fig. 10C). The decrease of mixing ratio over the Indonesia area from 12 to 11 g/kg is due to the subsidence (Fig. 11C) and dry advection within the cross-equatorial flow from the Australia anticyclone (CS-4).

The seasonal variation of the moisture is very small over the western Pacific. The wide moist area with the mixing ratio more than 12 g/kg is maintained over the tropical and subtropical zone as well as in the monsoon trough zone.

During the monsoon season, a particularly strong moisture gradient at 850 hPa is maintained over certain areas. In the southern hemisphere, the zone of strong moisture gradient at ~15°S corresponds to the equatorward rim of the subtropical high belt. In the northern hemisphere, the moisture front over northern Africa and the Arabian Peninsula is main-

tained along the southern periphery of the CS-7, while that to the west of the Tibetan Plateau is sustained by the northerly winds of CS-8-AC. The large moisture difference is also found between the south and north side of the Tibetan Plateau, which bounds the tropical and the polar air masses.

Over east Asia, from China to the Japan islands, the moisture front (*i.e.*, the Baiu/Meiyu front) forms along the boundary between CS-5-W and CS-8. The cold and dry advection by the northerly wind of a stationary low over the Okhotsk-Bering Sea area in the north side of the front and the warm and moist advection by CS-5 in the south side maintain the moisture front along ~35°N. In the peak period of Baiu/Meiyu rainfall in July-I and II (Fig. 10C), the typical feature known as the moist tongue, which is the eastward protruding narrow moist zone along the northern periphery of the Pacific subtropical anticyclone, is found over the Baiu/Meiyu front. In late July, with the weakening of the stationary low over the Okhotsk-Bering Sea area, the moisture front shifts northward to ~45°N and the moisture gradient decreases rapidly (figure is not shown).

Superposing the aforementioned seasonal

Fig. 10. The 10-day mean maps of the mixing ratio of water vapor at 850 hPa for May-II, June-I and July-II of 1991. The isopleth is given at 2 g/kg interval. The areas with mixing ratio more than 14 g/kg and 12 g/kg are indicated by thick and thin hatch marks, respectively.

changes, significant west-east oscillation of the moist area is recognized as intraseasonal variation. For example, the variation in the mixing ratio over the western coast of India is seen in association of the aforementioned intraseasonal shift of the moist area. The mixing ratio once decrease to 12 g/kg in the monsoon break (June-II, figure is not shown) from 14 g/kg of the onset period (June-I). However, the

mixing ratio increase again to 14 g/kg with the second onset of the Indian monsoon in July-II.

9. Variations of the equivalent potential temperature and vertical stability

The 10-day mean maps of the equivalent potential temperature θ_e at 850 hPa and maps of $-\partial\theta_e/\partial p$ in 850–500 hPa layer for May-II, June-I and July-II are

Fig. 11. The 10-day mean maps of the vertical-p-velocity at 700 hPa for May-II, June-I, and July-II of 1991. The blackened area indicates the lands 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.

presented in Fig. 12 and Fig. 13, respectively.

During the pre-monsoon period, the area of the high θ_e more than 336 K covers the southern part of the Asian continent, the equatorial zone of Africa and the equatorial oceanic zone, while the area of low θ_e below 316 K covers the middle latitude zone (Fig. 12A). The areas of weak convective instability

(~ -1 K/100 hPa) cover a large part of tropical Indian Ocean and the Pacific, and the area of strong instability is seen over the southeastern part of India. While the stable area in the southern hemisphere spreads along the equator side of the subtropical high belt, the stable areas in the northern hemisphere are seen over the northern Africa and

Fig. 12. The 10-day mean maps of the equivalent potential temperature (θ_e) at 850 hPa for May-II, June-I, and July-II of 1991. The blacked area indicates the lands higher than 1500 m. The isopleth is given at 4 K interval. The areas with θ_e more than 344 K and 336 K are indicated by thick and thin hatch marks, respectively.

the Arabian Peninsula under the anticyclonic circulation of CS-7. The wide areas in the middle latitude westerly zone and the northern portion of the Pacific subtropical anticyclone are also characterized by the stable condition (Fig. 13A).

After the onset of the Indian monsoon, the area of maximum θ_e moves from the equatorial zone to-

ward the Asian continent. The maximum area of θ_e , more than 344 K, covers the Indian subcontinent and the Indochina Peninsula in June-I (Fig. 12B). With the seasonal march, the high θ_e area expands further from the southern rim of the Tibetan Plateau toward China and the highest value of θ_e , more than 356 K, appears over $\sim 30^\circ\text{N}$, $80\text{--}115^\circ\text{E}$.

Fig. 13. The 10-day maps of the vertical stability ($-\partial\theta_e/\partial p$) in the layer between 850 and 500 hPa for May-II, June-I and July-II of 1991. 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.

On the contrary, the θ_e over the Indian Ocean decreases gradually with the northward intrusion of relatively dry cold air flow along the eastern coast of Africa (Fig. 12C).

During the peak period of the east Asia rain season, a tongue-shaped high θ_e area, which corresponds to the moist tongue seen on Fig. 10C,

protrudes from China toward Japan (Fig. 12C), whereas the relatively low θ_e is maintained over the Asian continent north to $\sim 40^\circ\text{N}$, the Okhotsk Sea, the Bering Sea and the adjacent northwestern Pacific. Consequently, the strong gradient of θ_e is maintained along the southern rim of the Tibetan Plateau and the northern periphery of the Pacific

subtropical anticyclone. The gradient of θ_e is largest in early and middle July (Fig. 12C).

Significant changes occur in the field of vertical stability over the subtropical parts of Asia continent, the Indian Ocean and the Arabian Sea with the onset of the Indian monsoon (Fig. 13B). The most unstable area shifts from southeastern India toward the southern rim of the Tibetan Plateau and the value of $-\partial\theta_e/\partial p$ over there reaches to ~ -4 K/100 hPa in July (Fig. 13C). Another remarkable change is the appearance of the stable region over the moisture source region for the Indian monsoon rainfall, *i.e.*, the Indian Ocean along Africa, the northern Indian Ocean and the Arabian Sea. The increase of the vertical stability over these areas is due to the low level dry and cold advection in CS-3 and/or the increase of θ_e at 500 hPa associated with subsidence. On the other hand, the stratification over the north-western Pacific does not change significantly in JJ except the Baiu/Meiyu rainfall zone, where the convective instability is maximized along the northwestern periphery of the Pacific subtropical anticyclone in the peak period of rainfall (Fig. 13B and Fig. 13C).

With the seasonal march to the end of July, the θ_e gradient over the Meiyu/Baiu region begins to decrease as the θ_e in the northern areas increases in late July, while the unstable region over the western North Pacific shifts northward and the area of weak instability begins to spread in the middle latitudes north to the Tibetan Plateau (figure is not shown).

10. Conclusion

In Part I, we describe the temporal variations of precipitation over the whole Asian monsoon region in MJJ of 1991 utilizing 24-hour prediction data obtained by a global numerical prediction model. In order to realize the relations between variations of precipitation and those of monsoon circulation, eight circulation systems (CSs) are identified as the major sub-circulation systems of the monsoon, and the variations of the precipitation are related to the variations of these CSs. Among them, the clockwise circulation over the tropical Indian Ocean (CS-3), the cyclonic circulation over the southern part of the Tibetan Plateau (CS-6) and the circulation of the Mediterranean anticyclone (CS-7) are the most important CSs around the Indian subcontinent, while the cross-equatorial flow from the Australia high (CS-4) and the circulation of the western North Pacific anticyclone (CS-5) are the most predominant CSs over the East Asia monsoon region.

The results of the present study are summarized as follows:

- (1) The basic feature of the seasonal change in MJJ over 50–110°E is the shift of the maximum precipitation areas from the equatorial zone toward the vicinity of the southern foot of the Tibetan Plateau, while that over 110–150°E is the increase of the precipitation within the monsoon trough region and the formation of precipitation zone (Baiu/Meiyu frontal zone) along the northwestern rim of the North Pacific subtropical anticyclone.
- (2) The seasonal changes are also seen in the fields of moisture and vertical stability. The moist area with unstable stratification moves from the ITCZ to the southern rim of the Tibetan Plateau, while the dry area with stable stratification under the subsidence spread in the cross equatorial flows from the southern hemisphere.
- (3) These changes are concurrent with the rapid intensification of the cyclonic circulation over the southern part of the Tibetan Plateau (CS-6) and the clockwise circulation over the tropical Indian Ocean (CS-3). The rapidly intensified westerly of CS-3 appears with the onset of the Indian monsoon rainfalls.
- (4) The Indian monsoon westerly indicates large temporal variations. The westerly and precipitation weaken rapidly in June-II shortly after the first onset in June-I and intensifies again in middle July with the second onset of intense rainfalls. The latitude of the maximum westerly and the rainfall over the western India is $\sim 10^\circ\text{N}$ in the first onset and $\sim 15^\circ\text{N}$ in the second onset.
- (5) The intensified westerly in the first onset propagates eastward and intrudes into the western Pacific to $\sim 140^\circ\text{E}$. The monsoon westerly, however, retreats westward to $\sim 115^\circ\text{E}$ following the break of the Indian monsoon. After the second onset of the monsoon, the second westerly intrudes again into the western Pacific, to $\sim 140^\circ\text{E}$, in middle and late July. With this west-east oscillation of the westerly zone, the Pacific subtropical anticyclone, the monsoon trough and the associated intense precipitation area oscillate in west-east direction, while the Baiu/Meiyu precipitation zone oscillates in a southwest-northeast direction. The Baiu/Meiyu rainfall zone loses its identity in late July after the northward shift, following the second westerly burst.

We shall compare the results of the present study with these of the previous studies for various years cited in the introduction. The overall features of the monsoon circulation in 1991 found in the present paper coincide, except for minor differences, with these obtained for other years by several authors, although they did not clearly identify the major circulation systems.

The features of the regional circulation over the Bay of Bengal and the South China Sea found in the present study coincide with these in the previous studies, although the previous studies were made with special interests on respective areas only.

The features of the intraseasonal variations in 1991 are very similar to other years, as shown in many previous studies. This supports that these variations are the characteristics of monsoon variations seen commonly in many years.

At the end of the discussion, we should note the meaning of the present studies by comparing with the previous studies. In the previous studies, the variations of precipitation are discussed only over the land areas where the dense data are available. In the vast oceanic areas, which are the important moisture source regions for the monsoon rainfalls, variations of precipitation are inferred, based only on the satellite IR data and some indexes obtained from IR data. The significant meaning of this present study is, thus, that temporal variations of precipitation over the whole monsoon region are discussed in relation to the variations of the major circulation systems and associated changes in vertical motion, static stability and the moisture fields.

In the Part II of this paper, the moisture transport and the moisture balance of the Asian monsoon in 1991 will be made in relation to the temporal variations of major circulation systems and precipitation obtained in Part I.

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1991 年アジア夏季モンスーンの降水と水蒸気収支

I: 降水の変動と主要な循環系

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(気象庁気候情報課)

1991 年アジア全域に於ける夏季モンスーンの降水の季節変動を全球予報モデルの 24 時間予報データに基づいて調べた。まず、モンスーン循環を構成する主要な循環系を 850 hPa 10 日平均場によって定義し、それらの変動と降水の季節及び季節内変動との関係を示した。インドモンスーン域の降水と最も密接に関係するのはチベット高原上の低気圧性循環系 (CS-6)、インド洋赤道付近に中心を持つ時計回りの循環系 (CS-3) 及び地中海高気圧の循環系 (CS-7) であり、東アジア域の降水と最も密接に関係するのはインド西風モンスーン (CS-3 の西風)、オーストラリア高気圧から流れ出る赤道を横切る循環系 (CS-4) 及び太平洋亜熱帯高気圧の循環系 (CS-5) である。これらの循環系はそれぞれの変動と相互作用を通じて降雨の変動をもたらす。

春から夏への大きな変化は降雨極大域と対流圏中層の相当温位極大域の赤道からアジア大陸南部への移動である。即ち、6 月初め CS-7 の西方への変位、CS-6 と CS-3 の発達と共に、降水域・湿潤域は赤道域からアジア大陸南部に移動し、インドモンスーン西風と降雨の極大が出現する (1st onset)。それ以後インド洋西部は乾気・寒気移流域及び下降流域となり水蒸気量は減少し成層は安定化する。6 月中旬、インド洋上の西風とインド近辺の降雨は弱まり (monsoon break)、7 月中旬に再び極大となる (2nd onset)。

東アジアの 5 月の降水は CS-4 と CS-5 の南西風によってもたらされ、降水域・湿潤域は赤道からモンスーントラフ～インドネシア・インドシナ半島に移行する。梅雨前線の降水帯は 5 月末～6 月初旬に明瞭となる。インドモンスーン 1st onset の西風は 6 月中旬太平洋の $\sim 140^\circ\text{E}$ に達し擾乱を発生させ、太平洋高気圧の東方への変位をもたらす。この後 (6 月末～7 月初旬) 西風域は西に後退し、同時に太平洋高気圧の西方への変位が起こる。上記の太平洋高気圧の変位は、その南西縁及び北西縁のモンスーントラフ (南シナ海) 及び梅雨前線帯の位置と降水量の変化をもたらす。2nd onset のインドモンスーン西風は 7 月中旬に太平洋に達し擾乱を発生させる。同時に太平洋高気圧と梅雨前線帯は北東へ変位する。