Interannual Variation of Seasonal Changes of Precipitation and Moisture Transport in the Western North Pacific

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Abstract

Interannual variation of seasonal changes of precipitation and moisture transport in the western North Pacific from June to August is studied using global monthly precipitation data, and NCEP-NCAR (National Center for Environmental Prediction-National Center for Atmospheric Research) reanalysis for 20 years from 1979 to 1998.

According to the meridional shift of the intense precipitation area and precipitation amounts in June and August to the east of the Philippines, the seasonal changes of precipitation are categorized into Types A and B. Type A is characterized by the northward shift of intense precipitation area and the increase of precipitation from June to August. Type A is further classified into two: Sub-Types A1 and A2. The former is characterized by the gradual increase of precipitation and the northward shift of the intense precipitation area from 6°N to 16°N. The latter is characterized by a relatively intense precipitation in June, decrease of precipitation in July, significant increase of precipitation with a maximum in August, and the northward shift from 13°N to 22°N. Type B is characterized by a seasonal change, with almost no precipitation increase nor northward shift from June to August.

Difference in the precipitation amount between Types A and B corresponds to the westerly moisture flux originating from the Indian Ocean, and the southerly moisture flux which comes across the equator at the lower level. It is found that the westerly and southerly moisture flux in Type B are much smaller than those in Type A, especially in August. The westerly moisture flux in Sub-Type A2 is larger than that in Sub-Type A1. The seasonal changes of westerly moisture flux show gradual increase in Sub-Type A1, and significant increase in June and August and decrease in July in Sub-Type A2. They are corresponding to those of the precipitation amount, respectively.

The large westerly moisture flux and the strong moisture convergence to the east of the Philippines in August in Type A, are associated with the eastward extension of the trough from the Eurasian continent. The northward shift of the intense precipitation area corresponds to the intensification of the eastward extended trough.

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1. Introduction

In the western North Pacific, precipitation and associated moisture transport are intense during the summer monsoon season. These are the most important characteristics of the atmospheric water circulation in the region. In particular, precipitation is most intense around the Philippines during summer in long-term average. Seasonal variation of the precipitation pattern is very diverse and significantly varies year to year. This indicates a large interannual variation of the water circulation pattern in the western North Pacific. However, characteristics of the year-to-year precipitation variation have not been clarified.

Rainfall activity over the western North Pacific in summer is associated with large circulation systems of the subtropical Pacific high, the Tibetan high, the Australian high and the Indian monsoon (e.g., Ninomiya and Kobayashi 1998). Ninomiya and Kobayashi (1998) showed that the precipitation over East Asia is significantly affected by the clockwise circulation over the tropical Indian Ocean, the cross-equatorial flow from the Australian high, and the circulation of the western North Pacific anticyclone. Moisture transports toward Southeast Asia and the Baiu front around China and Japan, are mainly caused by these three circulation systems (Ninomiya and Kobayashi 1999). The tropical western Pacific is a moisture sink region with confluence/convergence between these circulations. Previous studies (Ninomiya and Kobayashi 1998; Ninomiya and Kobayashi 1999) showed that the distribution of precipitation over the tropical western Pacific corresponds to changes of water transport from the Bay of Bengal and the eastern Indian Ocean, and of water transport to eastern China, the South China Sea and Japan. The tropical western Pacific is a key region to characterize the water circulation of the western Pacific and East Asia. However, the year-to-year variations of seasonal changes of precipitation and moisture transport over the western Pacific have not been revealed because of the significant diversity of seasonal change patterns and a lack of precipitation data over the ocean.

Nitta (1986) and Nitta (1987) found that the convective activity over the tropical western Pacific during boreal summer has a north-south oscillation between the subtropical western Pacific near 20°N and the middle latitudes around Japan, which is referred to as the "PJ pattern". Ueda et al. (1995) and Ueda and Yasunari (1996) showed an abrupt northward shift of convection around 20°N, 150°E in late July, which is called "the convection jump". These studies revealed that the northward shift of the convective activity is a characteristic of the seasonal changes over the tropical western Pacific, and is related to the climate of the mid-latitude region during the summer season.

Wang and Ho (2002) showed characteristics and stepwise phases of the Asian-Pacific summer monsoon rainy season using global precipitation data. For the summer monsoon over the western North Pacific, Wu and Wang (2001) and Wu (2002) revealed the stepwise onset, its interaction with the induced SST change in the western Pacific, and the effect of the seasonal SST change on the northeastward movement of monsoon trough. However, precipitation over the western North Pacific has not been studied sufficiently to characterize water circulation in East Asia. The intense precipitation area to the east of the Philippines is extremely large, thus the northward shift of the large precipitation area in the western North Pacific could be concerned with the seasonal variation of the water circulation pattern in East and Southeast Asia.

Interannual variation of the seasonal changes of precipitation is diverse and complicated. In the present study, the largest precipitation area to the east of the Philippines is examined to clarify the interannual variation of precipitation distribution. The purpose of the present study is to find the characteristics of the interannual variation of seasonal changes of precipitation patterns and associated moisture circulation in the western North Pacific region. Mainly, we focus on the distribution pattern of the precipitation to the east of the Philippines, and its relationship to the moisture flux field.

2. Data

The data utilized in the present study are the global monthly precipitation data from the Climate Prediction Center Merged Analysis of Precipitation (CMAP), and the monthly means of the National Centers for Environmental Prediction-National Center for Atmospheric

Research (NCEP-NCAR) reanalysis, for the 20 years from 1979 to 1998.

The CMAP data is comprised of seven precipitation data sources: rain gauge observations, satellite observations including infrared (IR), Outgoing Long-wave Radiation (OLR), the Microwave Sounding Unit (MSU), and microwave scattering and emission from Special Sensor Microwave/Imager (SSM/I), and precipitation forecasted by numerical models (Xie and Arkin 1996; Xie and Arkin 1997). The spatial resolution is 2.5° in latitude and longitude. The precipitation pattern was mainly determined by a combination of satellite estimates and model outputs, and their intensity was determined mainly by gauge observations. In the present study, the term "precipitation" will refer to the monthly averaged precipitation amount per day.

The monthly averaged NCEP-NCAR reanalysis data (Kalnay et al. 1996) were utilized to estimate moisture flux at 925 hPa, which represents lower level of the troposphere. The spatial resolution is 2.5° in both latitude and longitude. The monthly averaged meridional moisture flux can be expressed as:

$$\overline{\boldsymbol{v}q^*} = \bar{\boldsymbol{v}}\overline{q^*} + \overline{\boldsymbol{v}'q^{*\prime}}, \tag{1}$$

where $q^* = \rho q$ and $\boldsymbol{v}$, ρ, q are horizontal velocity, air density and the water vapor mixing ratio, respectively. The overline represents a monthly average and the prime denotes deviations from the monthly mean. The term $\overline{\boldsymbol{v}'q^{*\prime}}$ in (1) is negligibly small in the tropical and subtropical regions. Thus, $\overline{\boldsymbol{v}q^*} \simeq \bar{\boldsymbol{v}}\overline{q^*}$, which was verified by comparing monthly averaged moisture flux calculated from monthly mean variables with those calculated from every 6-hour data.

3. Long-term averaged precipitation pattern in the western North Pacific

In this section, the monthly mean field of precipitation averaged over 20 years is shown as the climatological seasonal changes of precipitation distribution. Figure 1 shows the distributions of monthly 20-year averaged precipitation in unit of mm day^{-1} in East Asia and the western Pacific (10°S–40°N, 100°E–180°E) from April to September. Two major precipitation areas are found; one is located in the subtropical western North Pacific, and the other in the mid-latitude region around Japan and China.

In the western North Pacific, the main precipitation area is located near the equator from April to May. In June, the precipitation intensifies suddenly to the east and west of the Philippines. The largest precipitation area to the east of the Philippines shifts northward from about 6°N in June to 11°N in July, and to 14°N in August. The intensity of the precipitation decreases in July and then increases significantly, to reach a maximum in August. In contrast, to the west of the Philippines, the intense precipitation area is stationary at about 14°N from June to August, with a slight increase in intensity. In September, the precipitation in the western North Pacific decreases suddenly and the largest precipitation area shifts southward gradually from September to December (not shown).

These precipitation areas to the east and west of the Philippines are corresponding to the convection area of the western North Pacific summer monsoon (WNPM), in Murakami and Matsumoto (1994). Although the monthly precipitation data is used in the present study, the seasonal change of the precipitation distribution is similar to their result by the pentad mean OLR. Murakami and Matsumoto (1994) indicated that WNPM is a part of the systematic seasonal variation of the ITCZ, and the onset of WNPM is the formation of the northern hemisphere ITCZ. In particular, the meridional movement of the precipitation area is significant to the east of the Philippines. In the present study, we focus on the intense precipitation areas to the east of the Philippines. To examine the seasonal changes of their meridional distribution and precipitation intensity, the time-latitude cross-section of monthly precipitation averaged between 125°E and 150°E for 20 years is shown in Fig. 2.

The averaged precipitation peak shows a significant northward shift from near the equator to ~14°N, during the period from May to August. Its peak value increases from about 8 mm day^{-1} to 13 mm day^{-1}. The northward shift of precipitation to the east of the Philippines from 6°N in June to 14°N in August is not gradual. The precipitation maximum suddenly reaches 12 mm day^{-1} at 5°N in June. It correspond to the onset of WNPM. The precipitation

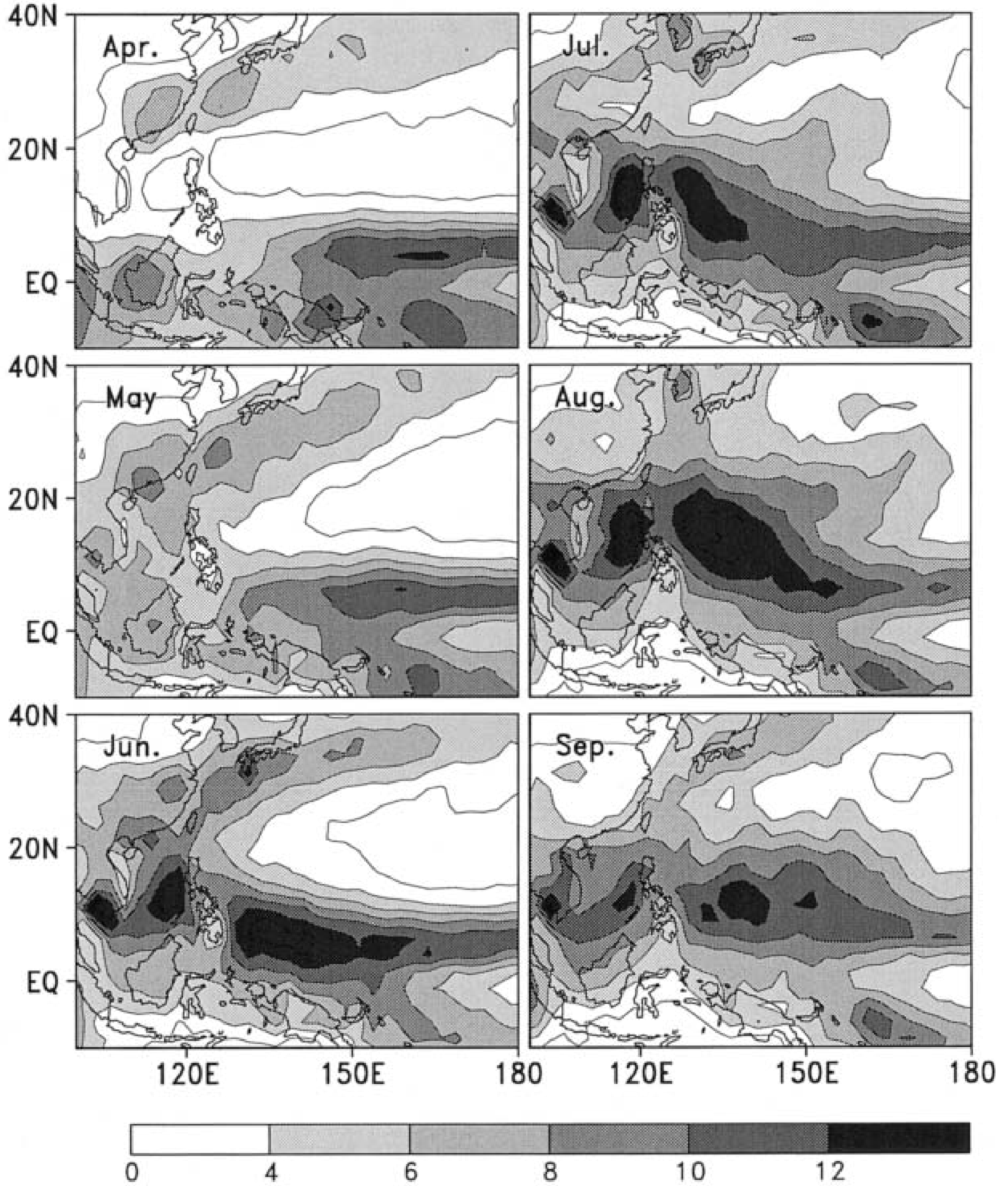

Fig. 1. Distributions of the 20-year (1979–1998) monthly averaged precipitation in East Asia and the western Pacific (10°S–40°N, 100°E–180°E) from April to September. The gray levels are shown at the bottom of the figures, and the unit is mm day^{-1}. Contour interval is 2 mm day^{-1}.

peak over 12 mm day^{-1} disappears in July, and then appears again in August, and the maximum reaches 13 mm day^{-1}. The peak shifts southward after August. Figure 2 show the main precipitation in WNPM and ITCZ averaged between 125°E and 150°E. On the other hand, the "convection jump" is detected by the convective activity, between 150°E and 160°E. It is also found that the climatological precipitation of ITCZ in the western north Pacific in summer increases suddenly in June, weakens once in July, and reaches the maximum in August.

4. Classification of seasonal change

As described in the previous section, the most significant characteristic of the seasonal change of precipitation in the western North Pacific is the northward shift of the intense precipitation area from June to August. Detailed character-

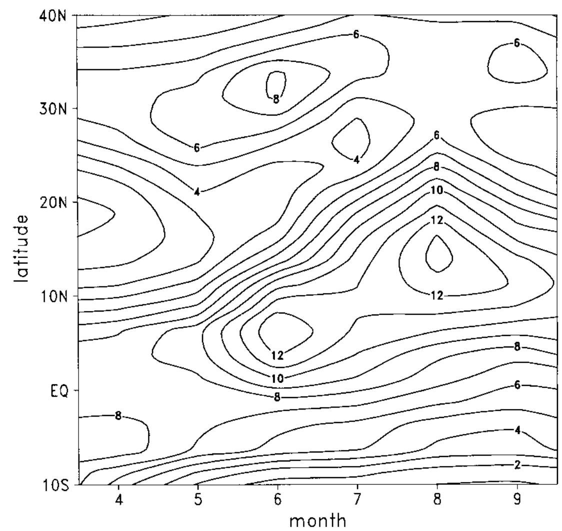

Fig. 2. Time-latitude cross section of monthly precipitation from April to September, averaged between 125°E and 150°E for 20 years. The unit is mm day^{-1}. Contour interval is 1 mm day^{-1}.

istics of the seasonal change of precipitation, such as peak values, their latitudes, month of the largest value, and so on, are significantly different from year to year, and the pattern of seasonal change is diverse.

In the present study, we focus on the seasonal variation of the intense precipitation area from June to August. To examine the year-to-year variation of the northward shift, we define a parameter to characterize how north the intense precipitation area reaches. The parameter is the latitude of the northernmost edge of the precipitation area with rainfall of 16 mm day^{-1} between 125°E and 140°E. The value of 16 mm day^{-1} is chosen because it characterizes the intense precipitation to the east of the Philippines, and is large enough to distinguish it from the precipitation area around Japan.

In the years that the peak value is less than 16 mm day^{-1} between 125°E and 140°E (June of 1983, 1986, 1991, 1995, 1996, 1997 and 1998), the latitude of maximum precipitation is used instead. On the basis of a subjective analysis of the precipitation patterns, we consider that the latitude of maximum precipitation is the second best to measure the northward shift of intense precipitation area if the maximum of the precipitation is smaller than 16 mm day^{-1}. If weak precipitation areas (less than 16 mm day^{-1}) are widely spread or scattered (June of 1989 and August of 1982, 1988, 1996 and 1998), the latitude of maximum zonal mean precipitation between 125°E and 160°E is used to detect the wide precipitating area, which corresponds to WNPM (Murakami and Matsumoto 1994).

The latitudes of the northern edge of intense precipitation in June are compared with those in August for individual years in Fig. 3. This diagram shows that the seasonal changes of intense precipitation from June to August are categorized into two types: Types A and B. Type A shows an obvious northward shift, and is further classified into two sub-types based on the latitude of the intense precipitation; Sub-Type A1 (1983, 1986, 1987, 1989, 1991, 1993, 1994 and 1995), which shows northward shift from about 6°N to 16°N, and Sub-Type A2 (1979, 1981, 1984, 1985, 1990, 1992 and 1997), which shows the northward shift from about 13°N to 22°N. On the other hand, Type B (1980, 1982, 1988, 1996 and 1998) shows almost no northward shift.

Similarly, the precipitation amounts for June and August for 20 years were examined. Figure 4 shows precipitation amounts averaged within 0°–25°N, and 125°E–160°E in June and August for individual years. Type B shows little or no increase, while Sub-Types A1 and A2 show ~3.5 mm day^{-1} increases from June to August. Generally, precipitation for Sub-Type A2 is larger than that for Sub-Type A1 both in June and August, except in 1992 and 1997. Precipitation increases from ~6.5 mm day^{-1} in June to 10 mm day^{-1} in August for Sub-Type A1, and increases from ~8.5 mm day^{-1} in June to 12 mm day^{-1} in August for Sub-Type A2, except in 1992 and 1997 (open rectangles). Hence, 1992 and 1997 are excluded from Sub-Type A2 as exceptions, and hereafter, years 1979, 1981, 1984, 1985 and 1990 are examined as years of Sub-Type A2.

Previous studies indicated a relationship between the convective activity over the western North Pacific and El Niño events (Nitta 1986; Nitta 1987; Ueda et al. 1995; Ueda and Yasunari 1996). In the present study, however, there is no clear relationship between the classification and El Niño events (not shown).

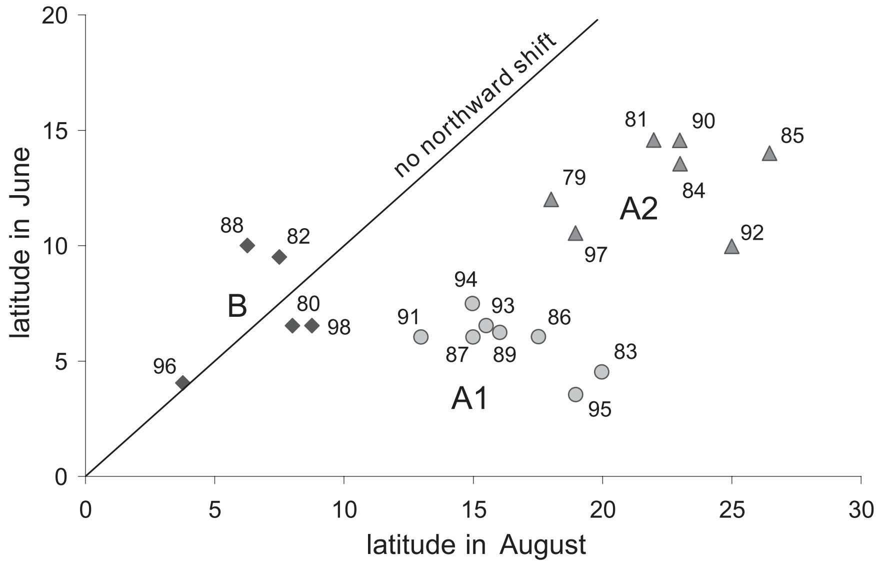

Fig. 3. Scatter diagram of seasonal change of precipitation maximum areas from June to August. Each mark indicates the northernmost latitude of precipitation area of 16 mm day^{-1} from 1979 to 1998. If the maximum value is less than 16 mm day^{-1}, the latitude of the peak value is used instead. The circles, rectangles and squares indicate groups of Sub-Types A1, A2 and Type B, respectively.

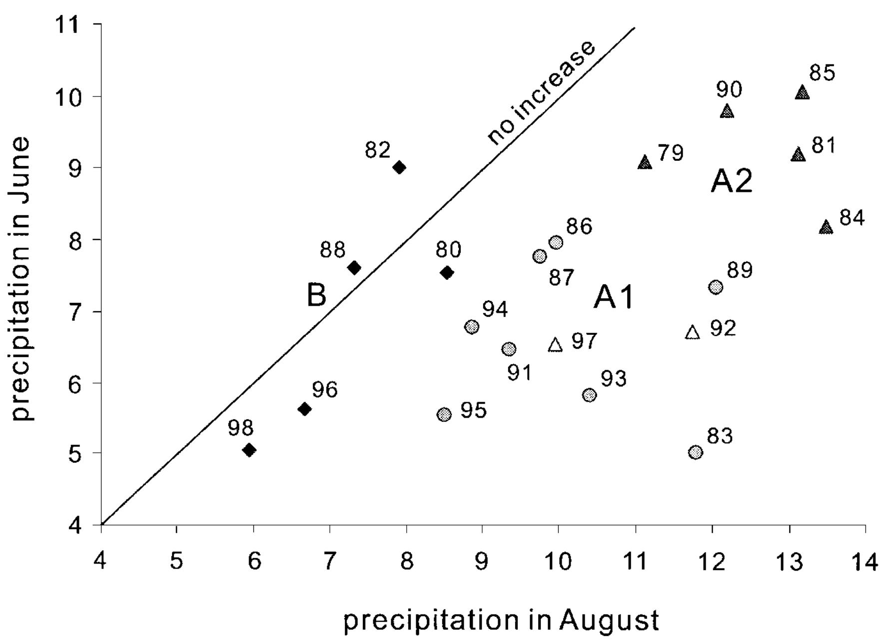

Fig. 4. As in Fig. 3, but for precipitation amount averaged in 0°–25°N, 125°E–160°E. The open rectangles indicate exceptional years of Sub-Type A2, and are excluded from the group of Type A2.

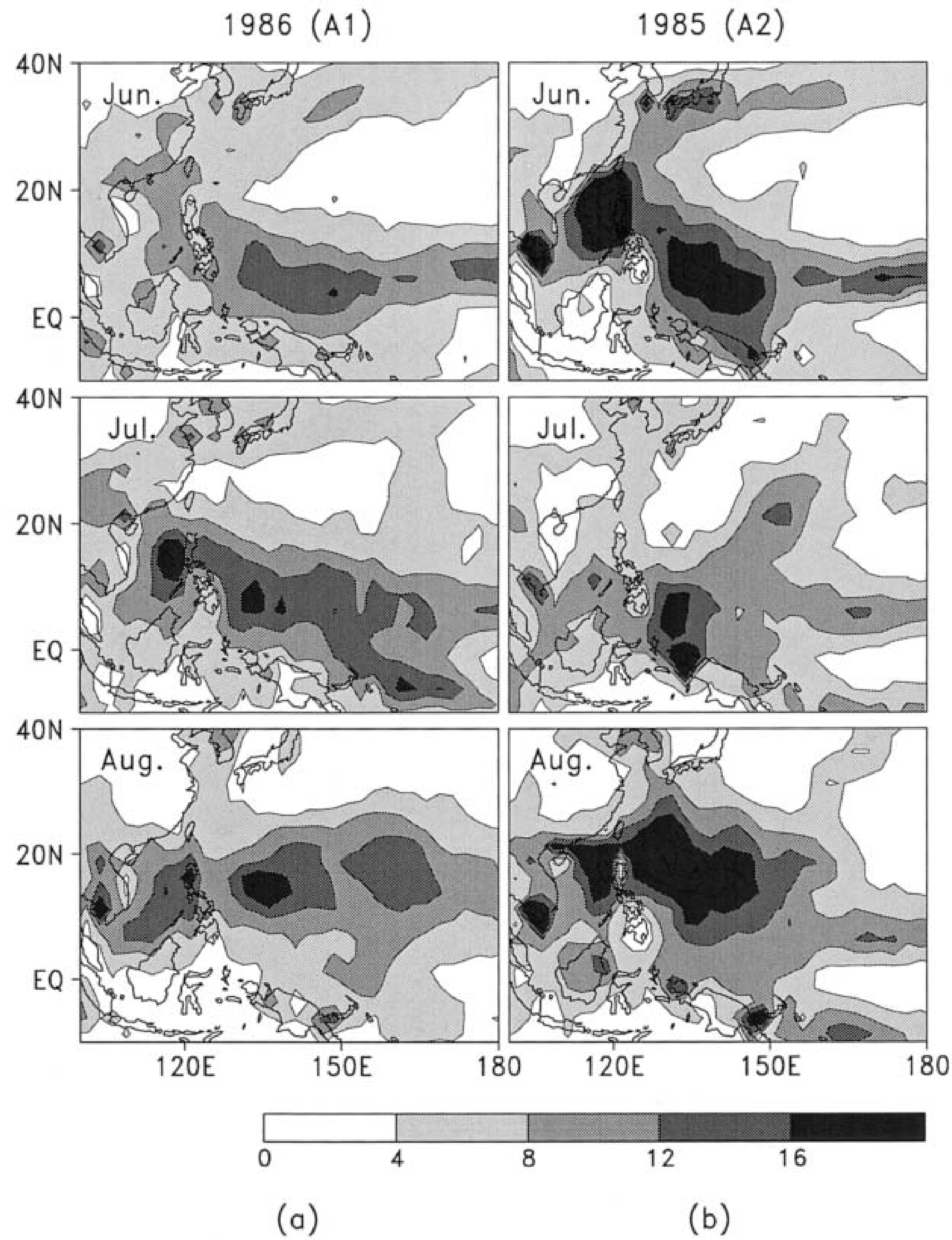

Fig. 5. Seasonal changes of typical monthly precipitation distribution from June to August in (a) 1986 of Sub-Type A1; and, (b) 1985 of Sub-Type A2. The unit is mm day^{-1}. Contour interval is 4 mm day^{-1}.

5. Characteristics of Sub-Types A1 and A2

5.1 Seasonal changes of precipitation and moisture transport

Precipitation distributions from June to August in 1986 and 1985 are shown in Fig. 5, as typical examples of Sub-Types A1 and A2, respectively. In 1986 (Sub-Type A1), the precipitation to the east of the Philippines intensified around 5°N in June. In July, the precipitation area with a maximum value of 16 mm day^{-1} spread, and its peak shifted northwestward to

10°N to the east of the Philippines. In August, the peak to the east of the Philippines shifted northward and its northernmost edge reached around 20°N. The precipitation area spread and the intensity of the precipitation increased.

In 1985 (Sub-Type A2), precipitation to the east of the Philippines intensified around 10°N, 135°E in June, and the area of precipitation over 16 mm day^{-1} spread widely from the northwest to southeast. It weakened substantially and the precipitation area showed almost no northward shift to the east of the Philippines in July. In August, the precipitation to the east of the Philippines intensified again, and its center shifted northward to 20°N. The northern edge of the intense precipitation nearly reached southern Japan in August.

A relative intense precipitation zone was found around Japan in June. It weakened in July and disappeared in August. In July, moreover, another intense precipitation area appeared around 20°N, 150°E. Ueda and Yasunari (1996) refer to the area as the "key region", in which the convection jump occurs. It affects the withdrawal of the Baiu front around Japan.

The characteristic northward shift of the intense precipitation area, and the increase of precipitation amount in 1986 and 1985, are common to other years of Sub-Types A1 and A2, respectively. The averaged fields for each sub-type, therefore, show the characteristics of Sub-Types A1 and A2.

Precipitation is closely related to moisture transport as a part of water circulation, and the relationship between the precipitation and moisture transport at the lower level from June to August is also examined. Figures 6 and 7 show the averaged distributions of precipitation from June to August, and those of moisture flux and moisture flux divergence in Sub-Types A1 and A2, respectively. These averages clearly show the common characteristics of the individual years of each sub-type. On the basis of Figs. 5, 6 and 7, the characteristics of the precipitation distribution and moisture flux convergence for each sub-type are summarized as follows:

Sub-Type A1: Precipitation to the east of the Philippines increases gradually and the peak shifts northward from 6°N to 16°N from June to August. Moisture flux convergence to the east of the Philippines also increases gradually, and shifts northward gradually from ~5°N in June to ~15°N in August.

Sub-Type A2: Precipitation to the east of the Philippines is relatively intense and the area over 16 mm day^{-1} spreads in June. The averaged precipitation weakens to below 16 mm day^{-1} in July, and intensifies significantly to reach the maximum in August. While the precipitation amount to the east of the Philippines decreases in July, relatively intense precipitation appears around 20°N, 150°E. Moisture flux convergence also intensifies significantly from June to August, although it weakens once in July. The northward shifts of precipitation and moisture flux convergence are notable from ~13°N in June to ~22°N in August.

The moisture flux represented by the arrows indicates that the seasonal change of the moisture fluxes closely resembles that of horizontal wind velocity in both Sub-Types A1 and A2 (figures are not shown). There are three major moisture fluxes that transport a large amount of moisture toward the western North Pacific in both Sub-Types A1 and A2. The first is the westerly moisture flux originating from the Indian monsoon westerly. It extends from the northern Indian Ocean to the western North Pacific, between 5°N and 20°N. The second is the southerly moisture flux, originating from the southeasterly to the north of Australia and crossing the equator. These two moisture fluxes meet to the west of the Philippines and continue as the southwesterly moisture flux toward the Philippines. The third is the easterly moisture flux, originating from the easterly of the Pacific high.

In Sub-Type A1 (Fig. 6b), the westerly moisture flux intensifies gradually from June to August and reaches to the east of the Philippines in August. The southerly moisture flux also intensifies gradually from June to August. On the other hand, the easterly moisture flux weakens from June to August.

In Sub-Type A2 (Fig. 7b), the westerly moisture flux intensifies in June, weakens in July, and intensifies significantly in August. It reaches to the northeast of the Philippines in August. It is much more intense than that of

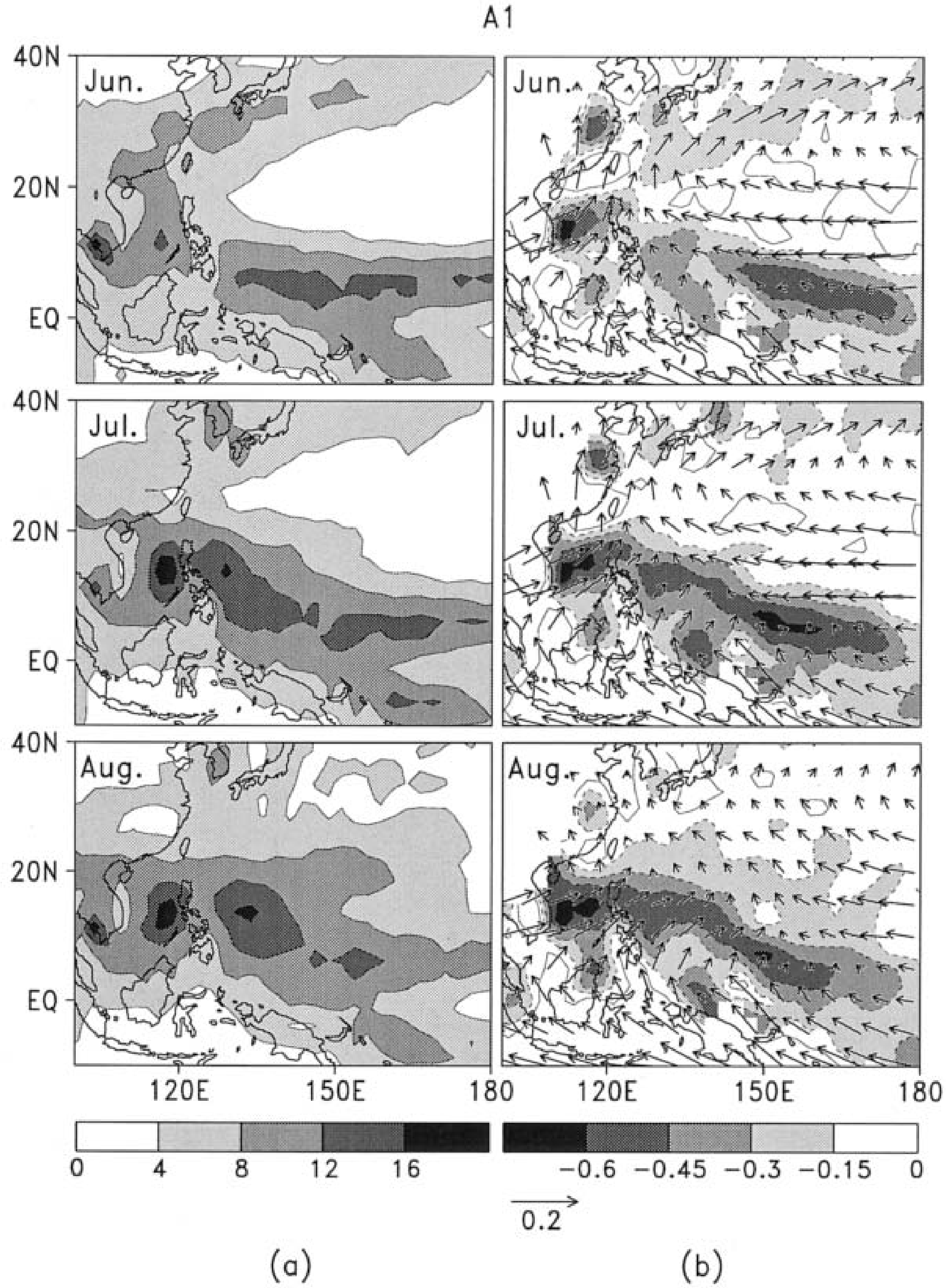

Fig. 6. Distributions of (a) the monthly precipitation (mm day^{-1}) indicated by gray scale and contour (interval is 4 mm day^{-1}); and, (b) the moisture flux (kg $m^{-2}s^{-1}$) indicated by arrows and moisture flux divergence (10^{-7} kg $m^{-3}s^{-1}$) indicated by gray scale and contour (interval is 0.15×10^{-7} kg $m^{-3}s^{-1}$) at 925 hPa from June to August, averaged in Sub-Type A1.

Sub-Type A1. The southerly moisture flux intensifies gradually from June to August. The seasonal change of the southerly moisture flux is similar to that of Sub-Type A1. The easterly moisture flux is similar to that of Sub-Type A1 in June. It weakens to the northeast of the Philippines in July and intensifies again to the east of the Philippines in August. The easterly

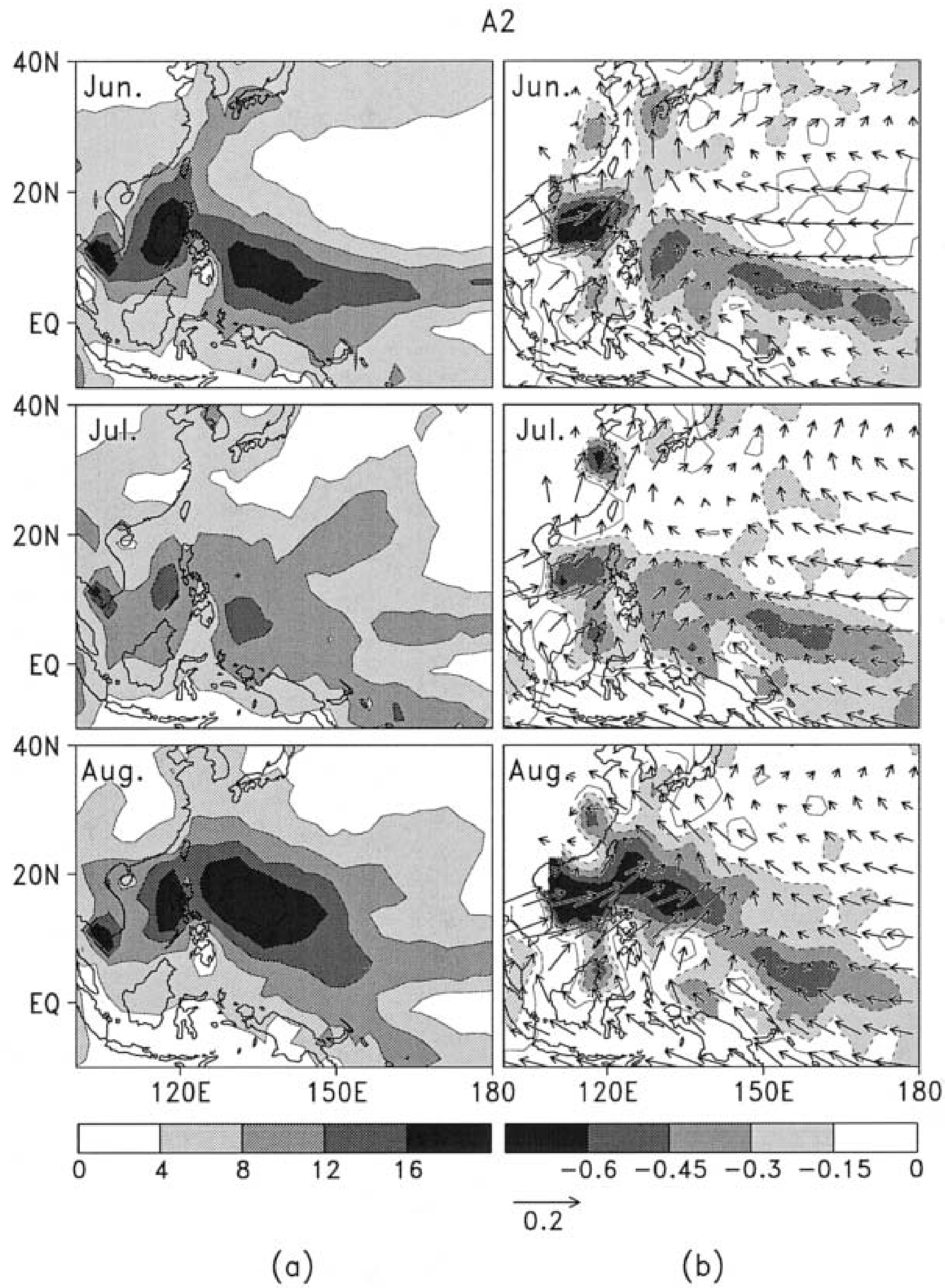

Fig. 7. As in Fig. 6, but for the group of Sub-Type A2.

moisture flux connects to the southeasterly moisture flux toward the south of Japan, and forms a confluence with the westerly moisture flux originating from the Indian monsoon westerly. In Sub-Type A2, the westerly moisture flux coming from the Indian Ocean is the strongest and reaches 150°E in August.

To investigate a correspondence between the moisture fluxes and the seasonal change pattern of precipitation, the westerly and southerly moisture fluxes, which are dominant around the Philippines are examined. The westerly moisture flux along 110°E between 5°N and 20°N, and the southerly moisture flux along the equator between 120°E and 150°E, are compared between June and August for each year (Fig. 8). There is almost no difference in the seasonal change of the southerly moisture flux between Sub-Types A1 and A2 (Fig. 8a). On the other hand, the westerly moisture fluxes toward the Philippines are different between Sub-Types A1 and A2 (Fig. 8b). The westerly moisture flux in Sub-Type A2 is larger than that in Sub-Type A1 in both June and August, except in 1979.

The difference in the amount of moisture flux convergence to the east of the Philippines between Sub-Types A1 and A2 corresponds more closely to the difference in the westerly moisture fluxes than to that of the southerly moisture flux. We infer that the difference of seasonal change of precipitation from June to August between Sub-Types A1 and A2, mainly corresponds to the difference of the westerly moisture flux.

5.2 Box analysis of moisture flux

For the quantitative estimation of the moisture flux around the Philippines in Sub-Types A1 and A2, we use two boxes on the east and west sides of the Philippines. Zonal and meridional moisture fluxes from June to August are examined. The west box will be referred to as Box W, the east box as Box E and the moisture fluxes passing through the north, south, east, and west boundaries as Flux N, Flux S, Flux E and Flux W, respectively. Box W is located from 110°E to 120°E and from 5°N to 20°N, and Box E from 120°E to 140°E and from 5°N to 20°N (Fig. 9). Standard deviation of moisture fluxes within each Sub-Type, defined as s in the following equation (2), is also shown in Fig. 9.

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2}, \tag{2}$$

where X and n are the moisture flux averaged along each boundary line and the number of years in each sub-type, respectively. The overline represents the average of monthly moisture flux for each sub-type.

In both Sub-Types A1 and A2, Flux W of Box W is the largest flux among the moisture fluxes around the Philippines from June to August, and its standard deviation is relatively small. This indicates that the westerly moisture flux from the Indian Ocean is dominant around the Philippines, and seasonal change of the westerly moisture flux from June to August is similar within each sub-type. Moreover, Flux W of both boxes and Flux S of Box W show strong agreement with the change of precipitation to the east of the Philippines. The moisture fluxes for Sub-Type A1 increase gradually from June to August. For Sub-Type A2, these moisture fluxes are large in June, decrease in July and increase significantly in August. Although standard deviations of these moisture fluxes are not so small, the differences in the moisture fluxes between Sub-Types A1 and A2 are recognized clearly.

Another large moisture inflow around the Philippines is the southerly moisture flux from the southern hemisphere, which is indicated by Flux S of Box E. It increases gradually from June to August in both Sub-Types A1 and A2. In addition to the fact that there is no clear difference in mean value between the sub-types, the small standard deviations indicate that the seasonal change of the southerly moisture flux is common to all the years in both Sub-Types A1 and A2.

Flux E of Box E changes from the easterly to the westerly between June and August in both Sub-Types A1 and A2. In August, Flux E of Box E is westerly and its intensity in Sub-Type A2 is larger than that in Sub-Type A1.

Flux N of both boxes in Sub-Type A1, and that of Box W in Sub-Type A2, decreases from June to August. The decrease of the northward moisture flux corresponds to the increase of the moisture flux convergence and the increase of precipitation to the east of the Philippines from June to August. In Sub-Type A2, the increase of Flux N of Box E in August corresponds to the northward shift of the intense precipitation area beyond the northern edge of Box E.

It is found that the seasonal change of Flux W corresponds well to that of precipitation amount to the east of the Philippines. This result is consistent with the result of Murakami et al. (1999), in the point that the westerly moisture flux increases with the evolution of WNPM, and it becomes an important moisture source at the peak of WNPM. In the present study, we focus on the seasonal change of the monthly moisture flux from June to August, and on the year-to-year variation in each sub-Types A1 and A2 (and Type B in Section 6). It

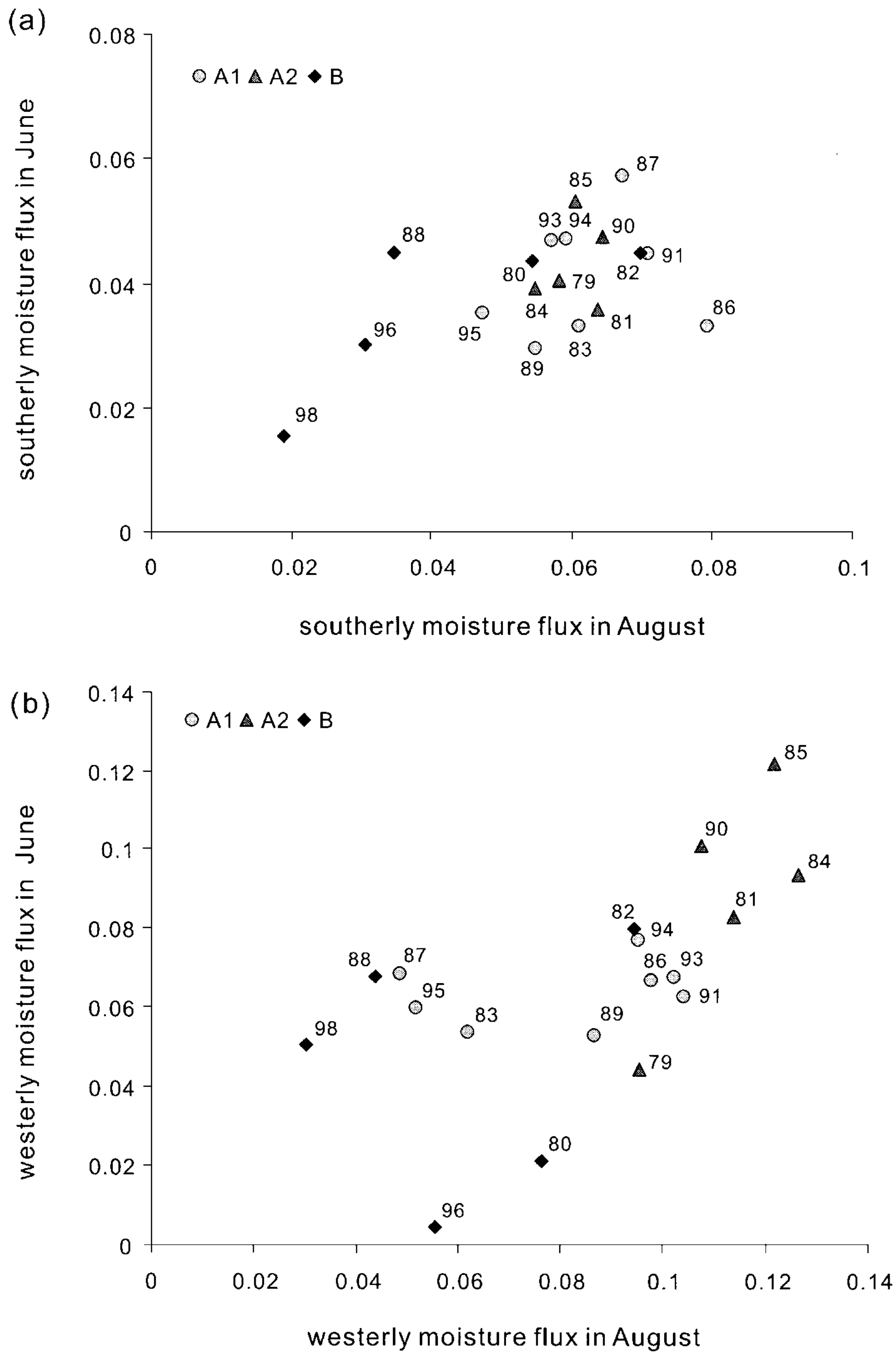

Fig. 8. Scatter diagrams of (a) the southerly moisture fluxes that come across the equator between 120°E and 150°E; and, (b) the westerly moisture fluxes which come across 110°E between 5°N and 20°N, in June and August for individual years. The unit is kg m^{-2}s^{-1}.

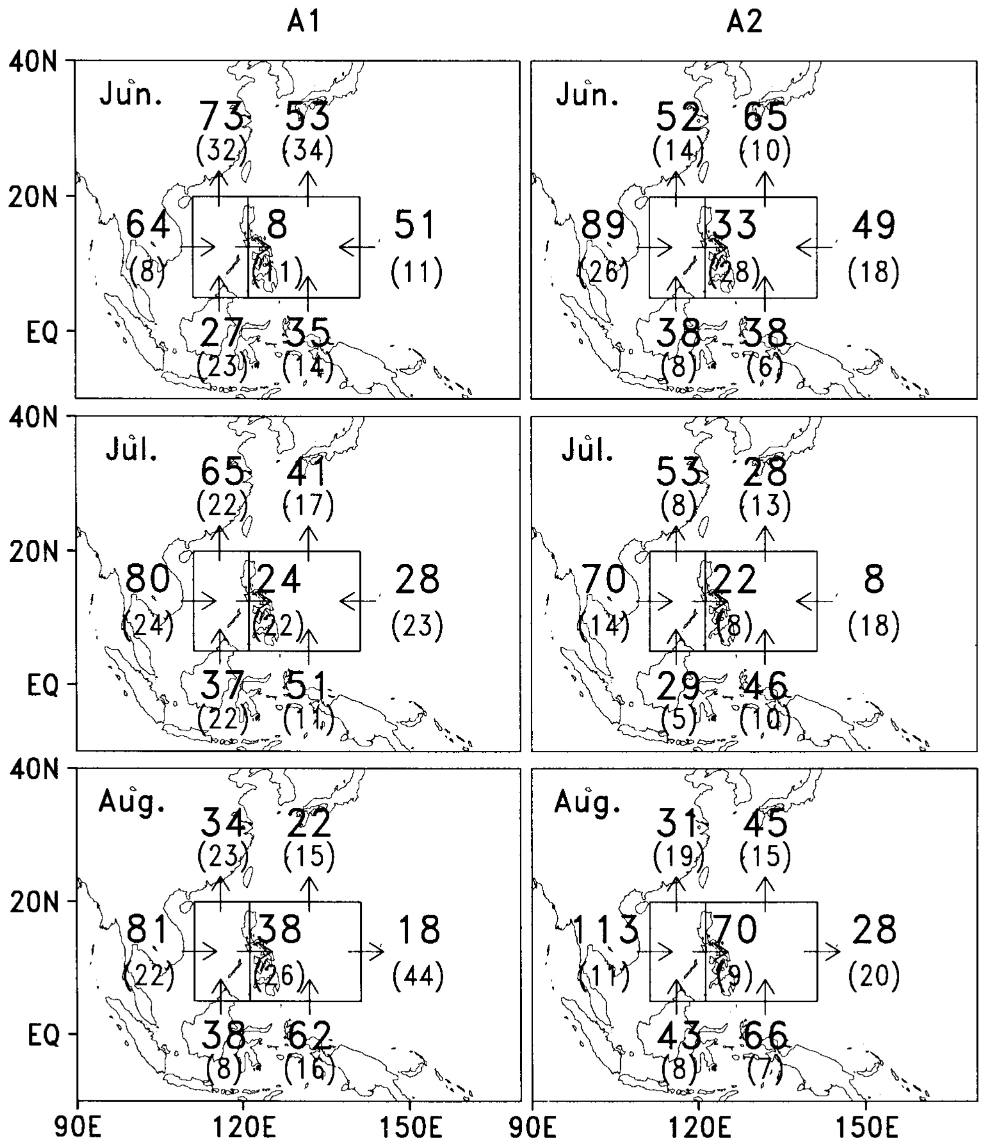

Fig. 9. Monthly mean zonal and meridional moisture fluxes at 925 hPa across boundaries of two boxes in the west and east of the Philippines from June to August. Fluxes are averaged in the groups of Sub-Types A1 and A2, respectively. Arrows indicate the positive direction of flux. The unit is 10^{-3} kg m^{-2}s^{-1}. Standard deviations are indicated in parentheses.

is found that the westerly moisture fluxes in August are quite larger than the easterly moisture fluxes and significantly important in Sub-Types A1 and A2.

6. Characteristics of Type B

6.1 Seasonal changes of precipitation and moisture transport

Type B shows little northward or rather southward shift of the precipitation area from June to August (Fig. 3). Precipitation does not increase or increase little during that period (Fig. 4). The northernmost latitude and amount of precipitation vary within Type B, as shown in Figs. 3 and 4.

In Type B, the distribution of precipitation for each year is diverse, especially in August. In some years of Type B, the precipitation in August is scattered and its amount is very small. In other years of Type B, the precipitation in

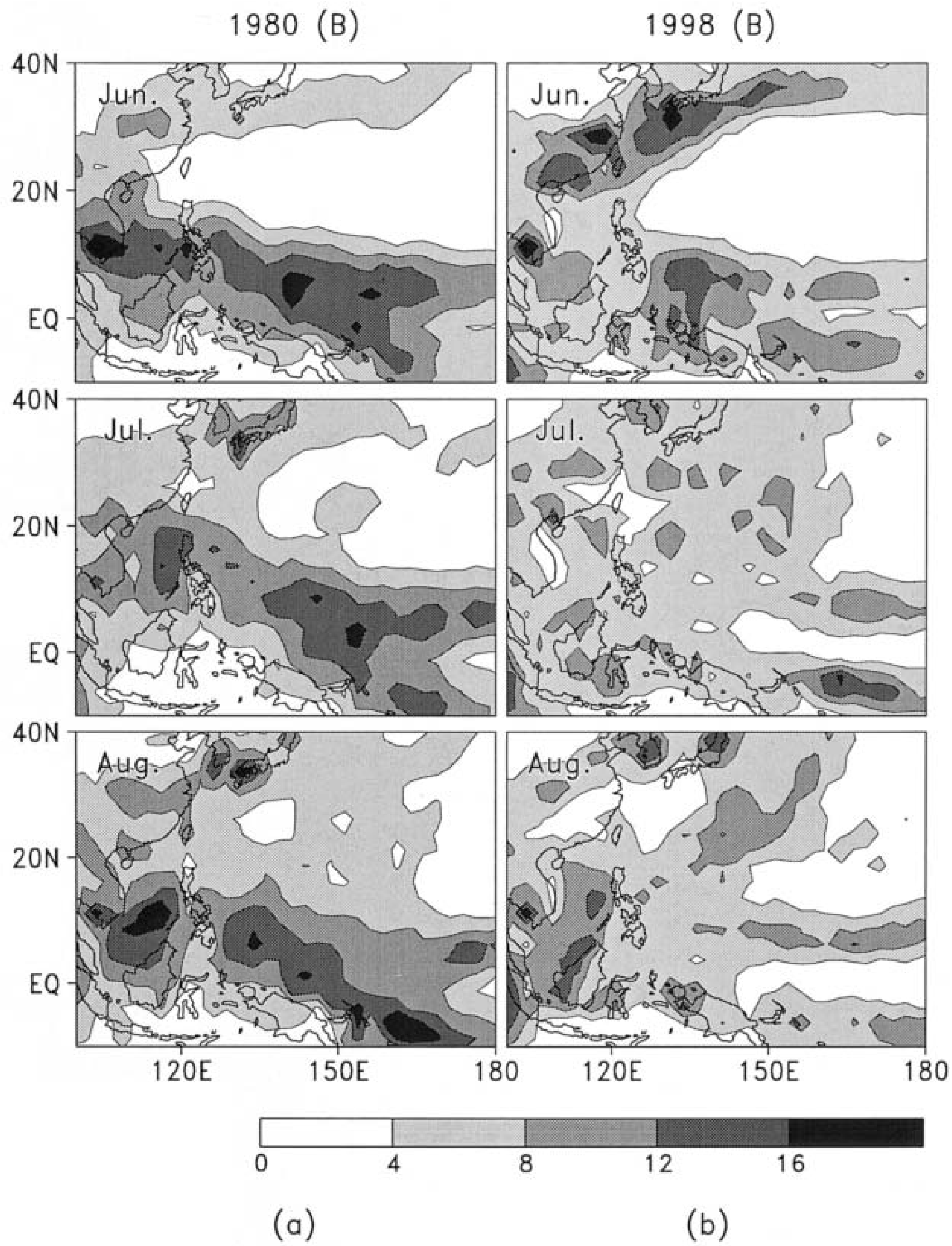

Fig. 10. Seasonal changes of two typical monthly precipitation distributions from June to August in (a) 1980; and, (b) 1998 for Type B. The unit is mm day^{-1}.

August is slightly larger than the former, and it is not scattered to the east of the Philippines.

The year 1998 is an example of the former (Fig. 10b), and 1980 for the latter (Fig. 10a). In 1998, the precipitation weakens clearly from June to August, and the weak precipitation is scattered in August. The climate in the tropical western Pacific in this year is characterized by inactive convective activity. This is corresponding to ENSO, which lasted to the end of summer in 1998. In 1980, on the other hand, the precipitation to the east of the Philippines

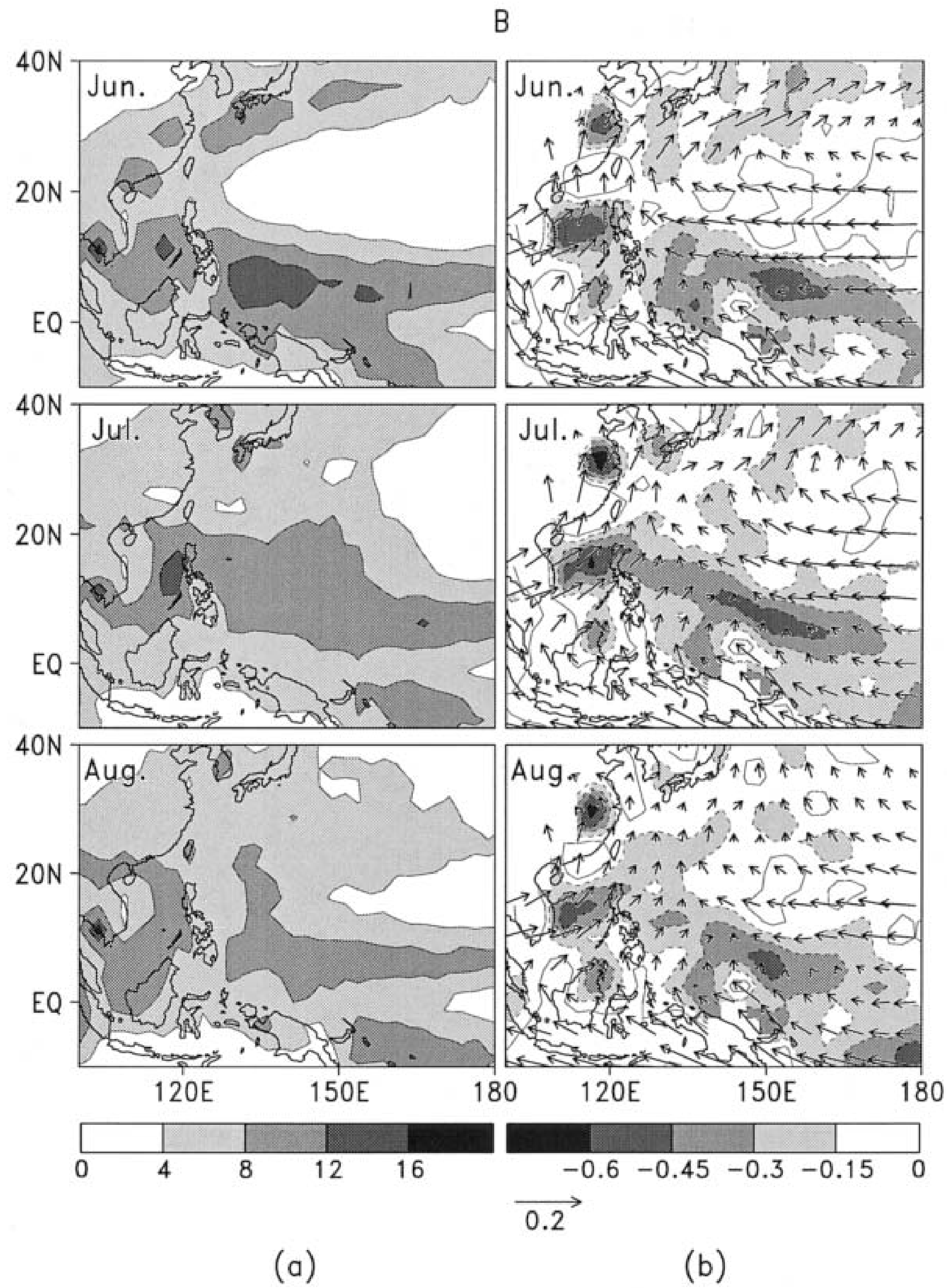

Fig. 11. As in Fig. 6, but for the group of Type B.

shows no increase and shifts slightly southward from June to August, but the precipitation is not scattered in August. In 1980, ENSO is inactive and the tropical climate state is characterized by a kind of normal convective activity and SST in the western Pacific. The characteristics of the seasonal changes of precipitation in 1988 and 1996 are similar to those of 1998, while those of 1982 are similar to 1980.

Precipitation distributions from June to August averaged for Type B are shown in Fig. 11a. In June, relatively intense precipitation is found at ∼5°N to the east of the Philippines. The precipitation weakens gradually from June to

August. A weak precipitation areas spread in July and August. In August, precipitation to the east of the Philippines is much weaker than that in July.

Figure 11b shows the averaged distributions of moisture flux, and their divergence at 925 hPa from June to August for Type B. In Type B, moisture flux convergence is small from June to August to the east of the Philippines.

The moisture flux indicated by arrows in Fig. 11b shows that westerly and southerly moisture fluxes in Type B are weak to the east of the Philippines, especially in August. The seasonal change in Type B is different from that in Type A. In June, the westerly moisture flux is weak, whereas the easterly moisture flux is strong and reaches the Philippines. The southerly moisture flux is also relatively weak. These flows form a confluence to the west of the Philippines. In July, the westerly moisture flux increases slightly, while the southerly flux seems not to change. On the other hand, the easterly moisture flux weakens significantly. In August, the easterly, westerly and southerly moisture fluxes are weak.

Figure 8 indicates that the southerly and westerly moisture fluxes of Type B are relatively small when compared to Sub-Types A1 and A2. In Type B, the westerly moisture flux is small, especially in August. Figure 8 clearly shows that moisture fluxes in Type B are characterized by both relatively small westerly and southerly moisture fluxes in both June and August.

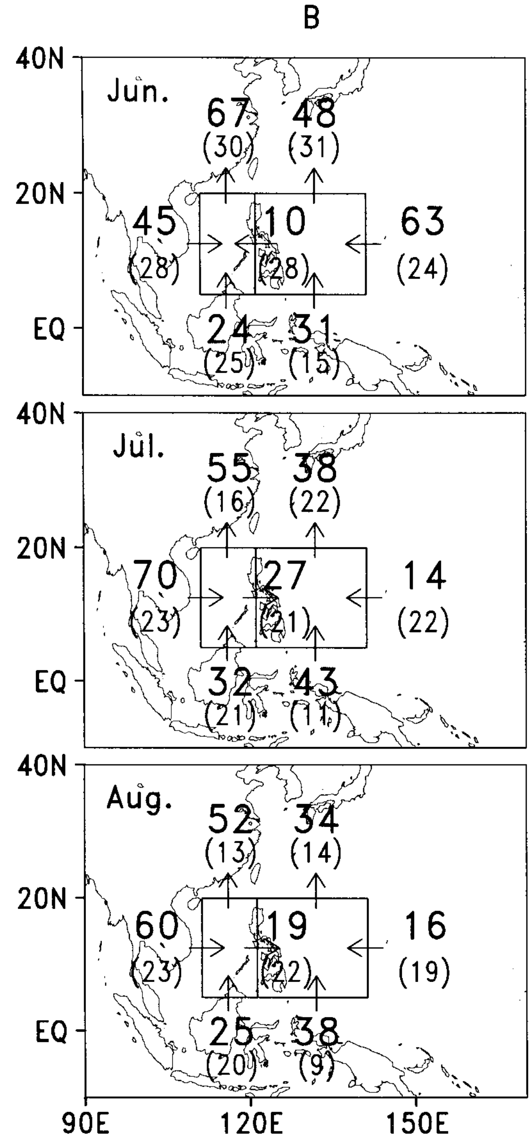

Fig. 12. As in Fig. 9, but for the group of Type B.

6.2 Box analysis of moisture flux

A quantitative estimation of the moisture flux around the Philippines in Type B is performed using the box analysis described in Section 5.2. Figure 12 shows the zonal and meridional moisture fluxes around the Philippines from June to August, averaged among 1980, 1982, 1988, 1996 and 1998.

Flux W and Flux S of both boxes in Type B are small, while Flux E of Box E is large in June. These features are different from Type A. Flux E is, therefore, considered to be the main moisture source in June for Type B. In July, Flux W and Flux S of both boxes increases, but Flux E of Box E decreases significantly. In August, Flux W and Flux S of both boxes slightly decreases, and Flux E of Box E slightly increases. Flux N of both boxes in Type B decreases somewhat from June to August. The decreasing amount in Type B is smaller than that in Type A. Flux E of Box E in June and Fluxes W and S of both boxes in August in Type B show significant differences from those in Type A. The variety of Type B, indicated by the standard deviations, is larger than those in Type A. This indicates that the patterns of the moisture transport corresponding to the precipitation and moisture flux convergence in Type B are more diverse than that in Sub-Types A1 and A2.

7. Discussion

7.1 Characteristics of water circulation in the western North Pacific

Ninomiya and Kobayashi (1998, 1999) found that for the major circulation systems in East Asia, the clockwise circulation over the Indian Ocean, the cross-equatorial flow from the Australian anticyclone and the circulation around the north Pacific subtropical anticyclone, are closely related to variations of moisture transport into the monsoon precipitation areas and a large moisture flux convergence. The year-to-year variation of the moisture transport into the monsoon precipitation area, however, have not been revealed. In Ninomiya and Kobayashi (1998, 1999), the western Pacific is one of the monsoon precipitation area, with large moisture confluence and convergence. In the present study, we found that the seasonal changes of the precipitation in the western North Pacific of the two types correspond to the moisture flux at the low level (Figs. 9 and 12). Differences in the precipitation amount, between Types A and B, correspond to the westerly moisture flux from the Indian Ocean and the southerly moisture flux, which comes across the equator. It is found that the westerly moisture flux from the Indian Ocean in Type B is much smaller than that in Type A, and that the southerly moisture flux crossing the equator in Type B is smaller than that in Type A, especially in August. Difference in the seasonal evolutions of the southerly moisture flux between Types A and B, which have an increasing pattern in Type A and little increasing pattern in Type B, are consistent with the precipitation pattern, respectively. Moreover, the difference in precipitation amounts between Sub-Types A1 and A2 mainly corresponds to the westerly moisture flux from the Indian Ocean. It is found that the westerly moisture flux from the Indian Ocean in Sub-Type A2 is larger than that in Sub-Type A1. In Sub-Type A1, it increases gradually from June to August. In Sub-Type A2, it decreases in July and increases significantly in August.

In order to examine a linkage between the westerly moisture flux and the intensity of the Asian summer monsoon, interannual variation of the westerly moisture fluxes in August, in Fig. 8b, is compared with that of the monsoon index, which has been defined by Kawamura (1998). It is found that the monsoon index in the years of Sub-Type A2 tends to be larger than that of Sub-Type A1, except in 1979 and 1992 in Sub-Type A2. However, there is no clear difference between the monsoon index in the years of Types A and B.

The moisture flux at lower levels is largely controlled by the pressure field. Shon et al. (2001) stated that the northwestward extension of the North Pacific subtropical high in 1995, increases moisture supply over East Asia by the confluence of the Indian summer monsoon westerly, with the easterly coming from the southern flank of the North Pacific subtropical high over the Western Pacific. The monthly mean surface pressure and precipitation averaged, with respect to Sub-Types A1 and A2 and Type B, are shown in Fig. 13. A high pressure area larger than 1011 hPa is found in the North Pacific to the southeast of Japan, and a low pressure area, less than 1008 hPa is found over the Eurasian continent from June to August. The ridge and trough extend, and recede zonally from June to August. The years and characteristics of each Type is summarized in Table 1.

In Sub-Type A1, the ridge of the western part of the north Pacific high extends westward in June and July, and recedes to the east in August. On the other hand, the trough indicated by the isobars of 1008 hPa to the west of the Philippines extends gradually eastward from June to July, and significantly extends to the northeast of the Philippines in August. As a result, surface pressure to the east of the Philippines decreases from June to August.

For Sub-Type A2, the western part of the north Pacific high extends to the south of Japan in June. The ridge recedes to the east in July, and extends westward again in August. The trough extends from the continent toward the northern Philippines in June and July, and extends significantly eastward in August. Consequently, the westerly over the Philippines significantly intensifies.

In Type B, the ridge of the north Pacific high extends westward in June, recedes significantly to the east in July, and slightly extends west-

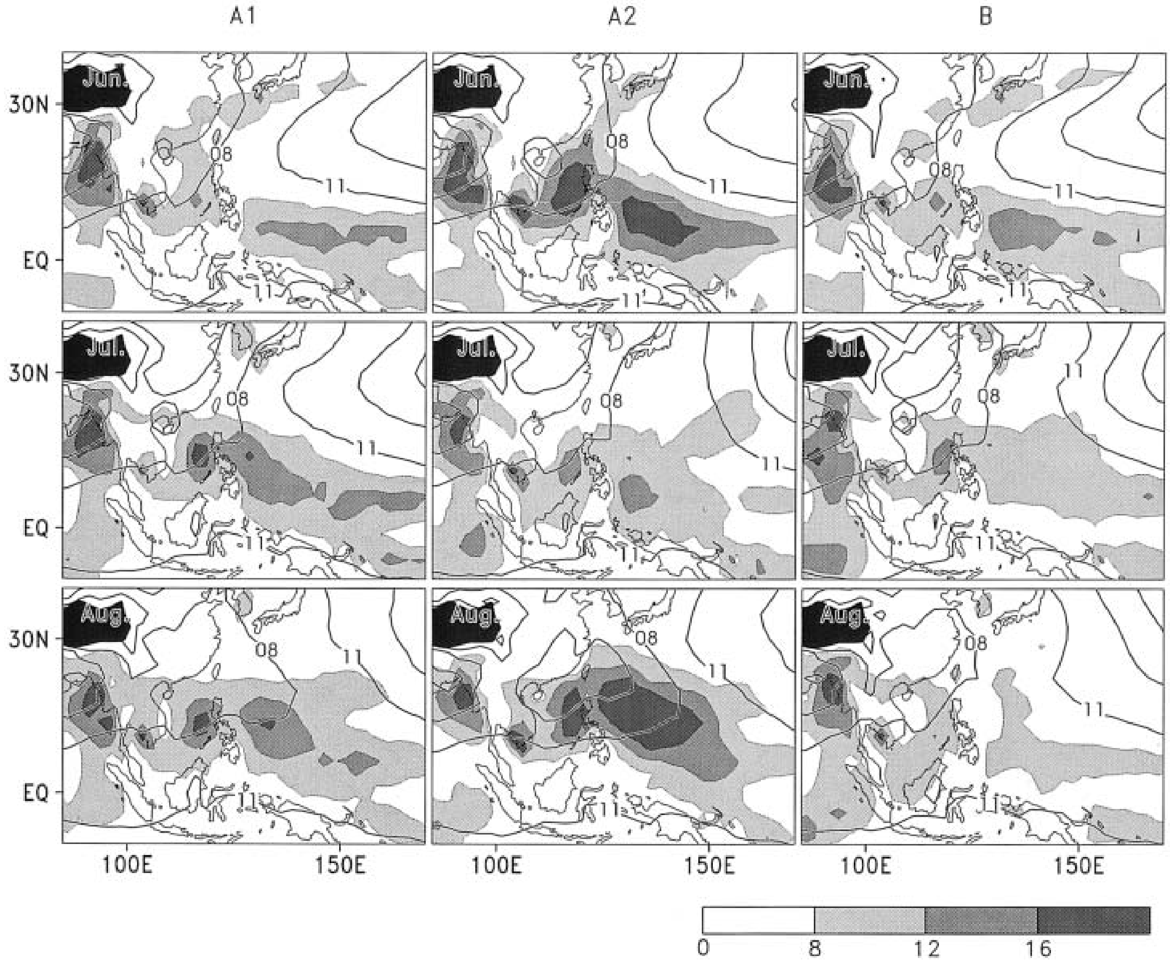

Fig. 13. Monthly mean precipitation indicated by gray scale (mm day^{-1}) and surface pressure indicated by contour lines from June to August with respect to Sub-Types A1, A2 and Type B. Contour interval is 3 hPa. Contour labels are pressure in hPa subtracted from 1000 hPa.

Table 1 List of years, characteristics of seasonal change of rainfall and of pressure fields in the western North Pacific between June and August in each Type and Sub-Type.

Type	years	precipitation	pressure field
A1	1983 1986 1987 1989 1991 1993 1994 1995	Shift from 6°N (Jun.) to 16°N (Aug.) and increase ~ 6.5 (Jun.) to 10 mm day^{-1} (Aug.)	Eastward shift of the north Pacific subtropical anticyclone and the eastward extension of continental trough from June to August.
A2	1979 1981 1984 1985 1990	Shift from 13°N (Jun.) to 22°N (Aug.) and increase ~ 8.5 (Jun.) to 12 mm day^{-1} (Aug.)	The trough extends eastward from June to August and reaches to the east of the Philippines in August, although it shifts to the west in July.
B	1980 1982 1988 1996 1998	Little northward or rather southward shift and little or no increase from June to August.	The trough slightly extends eastward in July, but recedes to the west of the Philippines in August.

ward in August. The trough over the continent slightly extends eastward in July, but it recedes to the west of the Philippines in August.

Further, in August, the decreases in the surface pressure to the north of the Philippines, where the large southerly and westerly moisture fluxes converge significantly, correspond to the northward shift of the moisture flux convergence area in both Sub-Types A1 and A2. The difference of the extension of the trough in Sub-Types A1 and A2, corresponds to the difference of the northward shift patterns of the intense precipitation to the east of the Philippines, between Sub-Types A1 and A2. Eastward extension of the trough corresponds to the increase of moisture flux to the northeast of the Philippines. On the other hand, no extension of the trough over the continent, nor the ridge of the north Pacific high in Type B results in a wide distribution of weak precipitation in July and August.

We infer the relationship between the seasonal change of precipitation pattern to the east of the Philippines, and the surface pressure field as follows. In Sub-Types A1 and A2, the zonal extensions of the northern Pacific high and Eurasian continent trough, correspond to the intensity of the westerly around the Philippines. The eastward extension of the trough, with the westward extension of the north Pacific high, intensifies the westerly around the Philippines. Consequently, the moisture flux convergence at low levels intensifies to the east of the Philippines. The westward retreat of the trough, on the other hand, weakens the westerly and the moisture flux convergence. These seasonal changes of moisture flux convergence correspond to the seasonal change of precipitation to the east of the Philippines. In Type B, the trough does not extend over the Philippines, and the moisture flux around the Philippines is weak. Hence, moisture flux convergence, and precipitation to the east of the Philippines are weak.

7.2 *Relationship between the seasonal change patterns of precipitation in the western North Pacific and in the mid-latitude area*

In addition to the western North Pacific, long-term averaged precipitation (Fig. 1) shows another major precipitation area in the mid-latitude region around Japan and China. The major precipitation around Japan appears twice a year; the Baiu season from May to July, and the autumn rainy season in September (Fig. 2). From May to July, the precipitation extends zonally along the Baiu frontal zone. The characteristics of the seasonal change pattern of precipitation around Japan and East China in the three types are as follows. In Sub-Type A1, intense precipitation appears in June and July, and weakens in August (Fig. 6). In Sub-Type A2, intense precipitation around Japan and East China weakens in July, and disappears in August around northern Japan (Fig. 7). In Type B, a relatively intense precipitation zone extends zonally in June. In July, it weakens and relatively weak precipitation of less than 8 mm day^{-1} spreads widely over Japan and East China until August (Fig. 11). In the mid-latitude area around Japan and East China, the seasonal change pattern of precipitation amount in each type is opposite to that in the western North Pacific.

Nitta (1986, 1987) found the north-south oscillation of convective activity between the subtropical western Pacific near 20°N and middle latitudes around Japan, using monthly averaged high-cloud amount data. The oscillation is named the PJ (Pacific-Japan) pattern. When SST is warmer than normal in the regions to the east of 150°E between 10°N and 25°N (1978, 1981, 1984), the positive PJ cloud anomaly pattern appears. On the contrary, when SST is colder than normal (1980, 1982, 1983), the negative PJ pattern appears. The northward shift of the large cloud amount area corresponds to the movement of the precipitation area of the Baiu front, as described by Nitta. In the present study, although precipitation in 1978 was not studied, the other two years of the positive PJ pattern (1981, 1984) are classified into Sub-Type A2. In 1981 and 1984 for Sub-Type A2, the precipitation to the east of the Philippines is significantly more intense, and it shifts northward from June to August at the higher latitude.

During these years, the intense precipitation corresponds to the large cloud amount near 20°N, which is found in the positive PJ pattern. It is found that the years of the positive PJ pattern are classified as Type A, and they show two types of seasonal change pattern corresponding to sub-Types A1 and A2. On the other hand, the two years of the negative PJ pattern (1980, 1982) are classified into Type B. Precipitation to the east of the Philippines is small, especially in August for Type B, and the cloud amount near 20°N would be decreased. Another negative PJ pattern in 1983 is, however, classified into Sub-Type A1.

8. Summary

In the present study, three patterns of seasonal changes in precipitation in the western North Pacific, from June to August are identified according to the location of the intense precipitation area and precipitation amount. In association with these patterns, moisture fluxes and pressure fields also have characteristic features. Characteristic features of the seasonal change pattern in Sub-Types A1 and A2 are summarized as follows:

Sub-Type A1: The basic feature is the gradual increase of precipitation amount from June to August, and the northward shift of the large precipitation area from 6°N to 16°N to the east of the Philippines. The westerly moisture flux increases gradually from June to August. This seasonal change corresponds to the eastward shift of the north Pacific subtropical anticyclone and the eastward extension of continental trough from June to August. The eastward extension of the trough is associated with the northward shift of the intense precipitation area.

Sub-Type A2: A large precipitation amount is found in June. It weakens in July and intensifies again to reach the maximum in August. The large precipitation area shifts northward from 13°N to 22°N. The westerly moisture flux is larger than that in Sub-Type A1. It increases rapidly from June to August, while it decreases in July. The trough over the continent extends eastward from June to August, and reaches to the east of the Philippines in August, although it shifts to the west in July. Compared with Sub-Type A1, the surface pressure anomaly to the northeast of the Philippines is large.

The precipitation amount to the east of the Philippines in Sub-Type A2 is larger than in Sub-Type A1, and the intense precipitation area appears in more northerly latitudes than in Sub-Type A1. The seasonal evolutions of the westerly moisture flux from the Indian Ocean in Sub-Types A1 and A2 correspond to those of the precipitation amount, respectively. In August, the decrease in the surface pressure to the north of the area corresponds to the northward shift of the moisture flux convergence area in Sub-Types A1 and A2.

The seasonal change of the precipitation pattern in Type B is clearly different from that in Type A.

Type B: The precipitation amount to the east of the Philippines from June to August is small, especially in August. There is no remarkable northward shift of the intense precipitation area, and no remarkable increase of the precipitation amount. Both the westerly moisture flux, which originates from the Indian monsoon westerly, and the southerly, which comes across the equator, are also small. In contrast, the easterly moisture flux is large in June, although it weakens in August. The trough over the continent slightly extends eastward in July, but recedes to the west of the Philippines in August.

Type B is clearly different from Sub-Types A1 and A2, especially in the temporal evolution pattern. Difference of the seasonal evolution of the southerly moisture flux between Types A and B is consistent with the precipitation pattern, respectively. Whereas the gradual eastward extension of the continental trough is found in Sub-Types A1 and A2, its retreat is found in Type B. Through the strengthening (weakening) of pressure to the northeast of the Philippines, the westerly moisture fluxes increase (decrease), and the moisture flux convergence create intense (weak) precipitation in Sub-Types A1 and A2 (B). The northward shift of the intense precipitation area corresponds to the eastward extension and intensification of the trough.

In the mid-latitude area around Japan, the seasonal change pattern of precipitation amount in each type (intense in Type B, weakening from June to August in Sub-Type A1, and relatively weak in Sub-Type A2) is opposite to that in the western North Pacific (relatively weak in Type B, increasing from June to August in Sub-Type A1, and intense in Sub-Type A2). It seems to be consistent to the PJ pattern.

Moreover, two types of seasonal change patterns of precipitation (corresponding to sub-Types A1 and A2) are shown within the years of same positive PJ pattern (corresponding to Type A).

In the present study, the year-to-year variation of the three types of seasonal change patterns for a 20-year period are shown. However, the mechanisms, which explain these differences in seasonal change patterns remain to be clarified in a future study.

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