Diurnal Variations of Precipitation Grouped into Cloud Categories around the Japanese Archipelago in the Warm Season

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Abstract

Diurnal variations of precipitation from 1988 to 1993 are investigated using the radar echo composite chart covering the Japanese archipelago and adjacent seas at intervals of one or three hours. We focus on studying expansive areas on land and sea connected by eighteen digitized radars, and determining variations of precipitation due to the following cloud categories based on a horizontal scale and maximum precipitation intensity: large-scale precipitation clouds originating in quasi-horizontal circulation and cumulus-scale precipitation clouds originating in convection.

The cumulus-scale precipitation cloud, defined as small precipitation clouds with strong intensity, predominates in afternoon peaks over four major islands of Japan excluding some points, the south Korean Peninsula, and Okinawa at about 26N. This is attributed to boundary layer heating by solar radiation during the daytime. Other precipitation clouds mainly composed of the large-scale precipitation cloud exhibit a diurnal cycle peaking in the morning, regardless of land-sea circulation.

Westerly wind fields over Japan have two effects on diurnal variations. Westerly winds over northeastern Japan maximize the cumulus-scale precipitation cloud over the east; and cause an evening peak over the eastern inshore by driving clouds east. Large-scale precipitation cloud driven by westerly wind often pass through the Nansei Islands from the northwest in the afternoon between May and July, and are responsible for afternoon peak precipitation in these islands.

1. Introduction

Diurnal variations of precipitation have been discussed widely for nearly a century (Hann, 1901). Their global structure and mechanism remain to be clarified mainly due to a lack of over water data, and a dearth of ways to categorize precipitation and related meteorological conditions. Accurate understanding of diurnal variation is essential to estimating global climatology of cloudiness and rainfall via polar-orbiting satellites.

Wallace (1975) and Gray and Jacobson (1977) reviewed studies on diurnal variation using rain gauges. Albright *et al.* (1985) and Meisner and Arkin (1987) reviewed results on diurnal variation in convection over land and water using satellite data as well as rain gauges. We summarize results on diurnal variation in middle and low latitudes as follows:

a) Middle latitudes

The simplest and predominant diurnal variation of precipitation originates in cumulus convection due to daytime boundary layer heating, peaking in afternoon over inland areas during warm seasons, especially over mountains, and nocturnally over basins or plains to the lee of mountains. Early morning enhancement exists over inland and coastal areas all year around. An early morning maximum is also observed over the ocean.

b) Low latitudes

Inland areas exhibit deep cumulus convection in the afternoon with no increase in the morning. Coastal regions show maximum precipitation in early morning, depending on the direction of the prevailing wind. An afternoon maximum over larger islands, superimposed on a diurnal cycle peaking in the morning over all sized islands, is reported in the western North Pacific Ocean. Afternoon peaks occur over waters in GATE and ITCZ regions.

No generally accepted process has been substituted for morning maxima in either latitude, although many processes have been proposed, such as the semidiurnal component of atmospheric tides,

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some induced by thermally driven local circulation and others related to cloud top cooling at night.

Fujibe (1988) and Tagami (1990) made detailed studies of diurnal variations of precipitation in Japan using more than 1,400 rain gauges of the Automated Meteorological Data Acquisition System (AMeDAS) operated by the Japan Meteorological Agency (JMA). They used two weather categories, which Fujibe (1988) defined based on the percentage of stations recording precipitation in 24 hours in each of four regions in Japan, and which Tagami (1990) defined based on a macro-scale air-flow pattern around Japan. Their main findings in warm seasons are as follows: (1) When no large-scale disturbance is present, maximum precipitation in Japan's four major islands occurs in the afternoon, but occurs in the morning at seaside areas and nearby small islands. (2) In a large-scale disturbance, a morning maximum occurs at most gauges. (3) Precipitation in the Nansei Islands peaks about noon. Fujibe (1988) also pointed out east-west diurnal asymmetry corresponding to the prevailing westerly wind and a mountain-valley phase difference. Tagami (1990) finds a morning maximum in the winter monsoon, and considers that double maxima in the average day reported by others (Hann, 1901; *etc.*) are a superposition of diurnal variations under different weather conditions. In conclusion, they hold that morning maxima are not responsible for local forcing such as convergence of land breezes. It seems, however, that diurnal variations over waters surrounding Japan must also be considered for a fruitful discussion.

Weather radar is assumed to be the best equipment for observing precipitation over water, especially in middle latitudes where precipitation estimation using satellite IR measurement is less reliable than in low latitudes. Few studies report diurnal variations of echoes over water in limited periods, *e.g.*, Wexler (1983) for the GATE region and Frank *et al.* (1967) for the Florida Peninsula, because few radars watching precipitation over water regularly operate.

The digitized JMA radar network continuously observes precipitation over the Japanese archipelago and surrounding seas (Sakota, 1990). The radar echo composite chart (RECC) from this network provides precipitation intensity in $5\text{ km} \times 5\text{ km}$ grids throughout the observable domain at intervals of one or three hours. The RECC is less accurate than AMeDAS, but is sufficient to estimate relative diurnal variation for an average at each grid. The RECC provides data over water, making it possible to grasp precipitation structure and size and to group precipitation clouds into categories.

This paper describes diurnal variations of precipitation in the RECC mostly in the warm season (May–September). Diurnal harmonics of precipita-

tion in the RECC are presented. We studied sixteen regions with distinctive diurnal patterns. Diurnal harmonics of precipitation due to cloud categories are summarized. We also discuss basic processes controlling diurnal precipitation variation in the Japanese archipelago.

2. Data and methods

2.1 RECC

The RECC is a composite of radar echo intensity of $5\text{ km} \times 5\text{ km}$ grids at an altitude of approximately 2,000 meters obtained by the digitized JMA radar network each hour. RECC coverage and radar locations are shown in Fig. 1. The Japanese archipelago consists of four major islands; Hokkaido, Honshu, Shikoku, and Kyushu, with an area of over $10,000\text{ km}^2$; and small islands scattered around the major islands, and the Nansei Islands extending southwest with an area of about $1,000\text{ km}^2$ or less. The RECC echo intensity is expressed in fifteen levels (Sakota, 1990), rearranged into five classes shown in Fig. 2.

a) Period of available data

We analyze the RECC from April 1988 to October 1993. Since the network has expanded, the number of analyzed warm seasons is distributed from six around Honshu to three around the Nansei Islands (Fig. 1).

b) Data interval

Digitized radars obtain echo intensity automatically every three hours (mode 1), called the basic hour. The RECC at the basic hour almost always covers the area shown in Fig. 1. Since digitized radars operate normally under subjective decisions of operators to trace precipitation detected at the last observation by obtaining the echo intensity six or eight times an hour (mode 3), the RECC at other hours, called the auxiliary hour, record most precipitation.

c) Normalized amplitude

Although large errors in precipitation intensity induced from echo intensity depending on the location are seen in RECC (Makihara, 1995), such bias error is removed using a normalized parameter as a measure of diurnal variation. We use the precipitation intensity at each hour in a period divided by the mean of precipitation intensity for all basic hours in the period as normalized precipitation, after Wallace (1975) and Fujibe (1988). The root mean square of the used precipitation intensity at each hour is used to measure the significance of diurnal variation.

d) Comparison with other data

The RECC is used with the Radar AMeDAS composite chart to watch Japan's precipitation. The Radar AMeDAS composite chart is a composite of

Fig. 1. Enlargement of RECC coverage. That since April 1988 is enclosed by thick solid lines, since April 1989 by thick broken lines, since April 1990 by broken lines, and since April 1991 by dotted lines; dates are written on lines. Coastlines and contours with an altitude of 200 m in the Japanese archipelago are shown by thin solid lines and thin dotted lines. Areas with an altitude of more than 500 m are dotted with density by altitude. Numbers of two digits and three digits on the edge of the figure indicate the east longitude and the north latitude, respectively. Each longitude-latitude intersection is shown by a dot. Radar sites are shown by circled letters: a) Sapporo; b) Kushiro; c) Hakodate; d) Sendai; e) Akita; f) Kashiwa; g) Mt. Fuji; h) Mt. Yahiko; i) Tojinbo; j) Nagoya; k) Mt. Takayasu; l) Mt. Misaka; m) Mt. Haigamine; n) Muroto; o) Mt. Seburi; p) Nakatanega; q) Honcha; and r) Itokazu.

hourly precipitation of 5 km × 5 km grids calculated from integrated echo intensity in one hour caught by digitized radars in mode 3 through calibration using AMeDAS rain gauges (Makihara, 1995). Although the estimated precipitation in Radar AMeDAS composite charts is more accurate than RECC, the recording rate of precipitation in Radar AMeDAS composite charts is no more than RECC at the auxiliary hour, which is worse than at the basic hour (Figs. 8 and 12). Therefore, we use RECC.

2.2 Precipitation clouds

Each isolated echo in RECC is regarded as a precipitation cloud in this study. These are automatically picked up under a simple and objective definition making it possible to enlarge the area and extend the period from those in previous studies (Lopez, 1976; Lopez, 1977; Houze and Cheng, 1977), which defined the echo manually. We introduce original parameters for categorizing precipitation clouds.

a) Definition

A precipitation cloud is defined as a cluster of meshes in RECC with precipitation intensity greater than zero contacting one another at one or more points.

b) Parameters

The following two parameters are introduced: Horizontal scale: $(12S^2 + 25)^{1/2}$, where S^2 is the

maximum dispersion of positions of all meshes composing a precipitation cloud among those along all axes around it. The constant and coefficient make the horizontal scale of the oblong shape cloud equal to the actual length; horizontal scales of ellipse (dumbbell)-like clouds are shorter (longer) than their actual length.

Activity level: the maximum echo intensity in a precipitation cloud.

Note that the rate of ill-categorized clouds increases closer to the outer boundary of RECC or as the horizontal scale of cloud increases, because the horizontal scale of the cloud extending outside RECC is underestimated.

c) Category

Using these two parameters, we divide precipitation clouds into 35 groups (Fig. 2). It is expected that large-scale precipitation clouds (Fig. 2) correspond to precipitation clouds in tropical and extra-tropical cyclones and Baiu fronts, while small-scale precipitation clouds with strong activity (Fig. 2) involve precipitation clouds due to deep cumulus convection dissolving vertical instability. Empirically, isolated one-mesh echoes in RECC, *i.e.*, clouds with minimum horizontal scale, include some echoes independent of precipitation such as ground and sea clutter (Makihara, 1995).

Fig. 2. Definition of precipitation cloud category. Letters and subscripts indicate categories and subcategories. The ordinate is the horizontal scale, and the abscissa is the activity level, the precipitation intensity class, and range of precipitation intensity per hour in conformity with the Z-R relation (Marshall and Palmer, 1948).

3. Diurnal cycles of precipitation over the Japanese archipelago

The harmonic dial of the diurnal cycle calculated using precipitation in each 50 km $\times$ 50 km square averaged from original grids in RECC at basic hours in the warm season (May–September), is shown in Fig. 3. Two typical diurnal cycles in middle latitudes (Introduction) are shown in Fig. 3.

Inland: the afternoon maximum covers inland areas, centered in eastern Hokkaido, central and western Honshu, and central Kyushu.

Sea: the morning maximum appears widely over seas. The amplitude of the cycle is significant over the Pacific Ocean south of Honshu and east of the Sea of Japan.

There are three diurnal cycles around coasts.

Windward seaside: a morning maximum is observed over most seaside areas such as western Kyushu, the Sea of Japan coast, and the Pacific coast of

southwestern and central Japan.

Leeward seaside: an afternoon maximum for the inland extends to coastal areas such as the Pacific coast of northeastern Japan and the Inland Sea of Japan coast.

Leeward inshore: an evening maximum is found inshore over northeastern Japan adjacent to the leeward seaside.

Names of these types are empirically based on precipitation clouds toward the sea, overwhelming the majority at the coast bordering the leeward seaside and leeward inshore, while those toward the land are often observed over the windward seaside.

An atypical diurnal cycle over the sea occurs around the Nansei Islands.

Southwestern area: the phase of precipitation over the sea around the Nansei Islands is distributed about noon.

4. Sixteen regions with distinctive diurnal variation

We select sixteen regions (Fig. 4) from RECC representing diurnal cycles.

4.1 Inland

As inland examples, we examine four inland regions involving the centers of the afternoon maximum: A in eastern Hokkaido; B in central Honshu, C in western Honshu and Shikoku; and D in Kyushu. A significant afternoon peak in precipitation is the primary feature common to the four regions, see the first row of Fig. 5, which is the origin of the afternoon maximum of the diurnal cycle (Fig. 3). In addition to the afternoon peak, there is an enhancement of precipitation in the morning over these regions.

To study these two in detail, precipitation over B, exhibiting the largest amplitude of the afternoon maximum (Fig. 3), is divided into 35 groups (Fig. 2). Figure 6 shows diurnal variations of precipitation due to each group, with fixed size independent of the maximum indicated by logarithmically sized digits. The afternoon peak is caused by smaller precipitation clouds with strong activity, except for the smallest clouds including non-precipitation echoes. The small morning enhancement originates in the largest precipitation clouds. Small and strong precipitation clouds rarely appear in the morning and have steeper and earlier peaks than larger or weaker precipitation clouds; for example, 15 JST peak of the VS precipitation cloud less than 30 km, and about 18 JST peaks of the VS precipitation cloud between 180 km and 450 km and of the W precipitation cloud less than 30 km. This delay is explained by smaller strong precipitation clouds suddenly developing in the afternoon, and gradually expanding

Fig. 3. (a) Harmonic diagram of diurnal components of normalized precipitation in $50 \text{ km} \times 50 \text{ km}$ grid calculated from the $5 \text{ km} \times 5 \text{ km}$ grids in RECC in the warm season using precipitation at basic hours, an interval of three hours, on the same map as Fig. 1. Grids where total estimated precipitation is more than 0.4 % of the maximum in this figure are shown enclosed by a solid line. Normalized amplitude is shown by arrow length; and phase is indicated by arrow orientation; an arrow pointing upward indicates a 0000 JST maximum and one pointing to the right indicates a 0600 JST maximum. Maxima before noon are indicated by arrows with circles; circle's diameter equals half of the maximum amplitude in the figure, which is 0.265 by normalized precipitation. (b) Distribution of amplitude shown in (a). Areas where amplitude is more than 0.75, 0.5, or 0.25 of the maximum amplitude are shown by contours and dots in order of thickness and density.

into larger clouds or decaying into weaker ones.

After the same study for A, C, and D (not shown), we define three categories of precipitation cloud, C, I, and L, defined as follows: C is a set of cloud groups exhibiting a significant afternoon peak over the four regions; L is a set of cloud groups with a horizontal scale longer than 450 km not exhibiting the afternoon peak over any of the regions; and, I is a set of cloud groups not falling in C or L but exhibiting a morning maximum and/or an afternoon maximum over one or more regions. Groups categorized in C, L, and I are shown in Fig. 2 as C_1 , C_2 , and C_3 ; L ; and I_1 , I_2 , and I_3 . To confirm these definitions, diurnal variations due to C, I_1 , I_2 , L, and I_3 -clouds are shown in Fig. 5. Nondiurnal components of precipitation are omitted up to the sixth row of Fig. 5, though it is more than 80 % of total precipitation (the top-right graph of Fig. 6).

The second row of Fig. 5 shows the afternoon peak associated with an explosive increase of C-cloud beginning about noon from the very low level in the morning to about 5 % of the mean over all regions. The last row of Fig. 5 shows ratios of precipitation of each intensity class (Fig. 2) to the total precipitation at each basic hour. The afternoon peak has an increase of S and VS precipitation equal to or more than 16 mm/h in the Z-R relation (Marshall and Palmer, 1948). Figure 7 shows diurnal variations due to C-clouds over region B each month. The afternoon peak occurs only in the warm season, especially in July and August, and C-clouds are inactive during other months.

Diurnal variations of precipitation due to L-clouds in the fifth row shows a trapezoid pattern with the minimum in the evening over three regions, excluding region A. Compared to the first row, the mag-

Fig. 4. Sixteen regions indicated by letters A to P. The thick line shows RECC coverage since April 1991. X-Y indicates the center of the island line in Fig. 14.

nitude of the morning enhancement is mostly attributed to this L-cloud variation over the three regions. Region A is an exception, because it is close to the northeastern edge of RECC and the RECC extent around it is much smaller than other regions. Thus, the variation of I_3 -clouds, which has a sharp early morning maximum agreeing with that in total precipitation in the first row and a trapezoid in the afternoon, is larger than that of L-clouds.

Diurnal variations due to I_1 and I_2 -clouds over these regions have three patterns excluding I_2 -clouds over region A: the same as the C-cloud, *i.e.*, I_1 -clouds over region B; the same as the L-cloud, *i.e.*, I_2 -clouds over region D; and a pattern with double maxima, *i.e.*, I_2 -clouds over region B. The range of these variations indicates that the C-cloud pattern appears where the non-diurnal component is small, and the L-cloud pattern appears where the non-diurnal component is large. The I-cloud is thus not composed of clouds having an independent diurnal variation, but of clouds with the diurnal variation of C and L types, whose ratio depends on the region.

4.2 Sea

As examples of the sea type, diurnal variations of precipitation over two regions are examined: E in the Pacific Ocean, and F in the east of the Sea of Japan (Fig. 8). The first row of Fig. 8 shows a diurnal variation of precipitation with a maximum in the morning (6–9 JST) and a minimum in the early evening (18–21 JST), more significant over E than F (Fig. 3).

Diurnal variations due to the L-cloud in the fifth row of Fig. 8 account for major parts of the wave-like pattern in the first row over both regions. The I_2 -cloud over E also takes part in the diurnal variation,

but not over F. The large regional dependence of I-cloud variation is common to the inland region. Figure 9, the same as Fig. 7 but for precipitation due to L- and I_2 -clouds (L, I_2 -cloud) over E, shows that the morning maximum is significant from June through September; no significant diurnal variation is found in other months, although precipitation due to L, I_2 -cloud is a similar amount. The bottom row of Fig. 8 shows that the wave-like pattern is mainly controlled by the variation of the cloud element weaker than S precipitation, instead of stronger than S precipitation for the inland afternoon peak. The second row of Fig. 8 shows that the C-cloud takes little part in precipitation over two regions, and has the same phase as the L-cloud.

4.3 Coastal areas

To determine diurnal variations around coasts, we divide northeastern Honshu, where windward-leeward asymmetry is predominant (Fig. 3), into six regions (Fig. 4): G, the sea; H, the windward seaside; I, the inland; J, the leeward seaside; K, the leeward inshore; and L, the lee of K where both morning and afternoon maxima are distributed in Fig. 3. Two new facts not seen in Fig. 3 are found in the first row of Fig. 10: the morning enhancement over inland regions (Fig. 5) also exists over I, but is obscure over J and K; and the afternoon peak exists over H, exhibiting the morning phase in Fig. 3, earlier than that of leeward regions. The sixth row of Fig. 10 shows that the morning enhancement over I results from the same wave-like variation of the L-cloud as the sea type, and no wave-like variation results in no morning enhancement over J and K. The second row of Fig. 10 shows that the afternoon peak over H results from the afternoon peak of C_1 and C_2 -clouds ($C_{1,2}$ -cloud), common to the three

Fig. 5. Diurnal variations of normalized precipitation, in the first row; the same but due to each cloud (sub-) category at left, from the second to the sixth rows; and ratios of precipitation by precipitation intensity class to total precipitation at each basic hour, in the last row; in the warm season over inland regions shown at bottom. The description of graphs except for the last row is as follows: the abscissa is JST and the ordinate is normalized precipitation drawn on the same scale; values at the basic hour are connected by a thick solid line and those at every hour by a thin solid line; and vertical bars at 6 and 18 o'clock, and at the maximum indicate the root mean square error at the hour. The range of each graph is indicated on the top of each graph except the first row, the top of which is mean of precipitation intensity by mm/h, the unit of normalized precipitation. The ordinate and letters on lines in the last row indicate the ratio and the precipitation intensity class defined in Fig. 2.

Fig. 6. Diurnal variation of normalized precipitation (top-right) and those due to 35 precipitation cloud groups divided by the horizontal scale at left in km and the activity level at bottom (Fig. 2) over region B. Graphs are the same as in Fig. 5, but the vertical size is fixed independent of the maximum of normalized precipitation, indicated at the top by logarithmically sized digits according to value.

regions over land.

Graphs between the second and fifth rows in Fig. 10 show that predominant afternoon peaks from $C_{1,2}$ -cloud to I_2 -cloud move eastward according to the horizontal scale of clouds and are delayed east-

ward. Eventual peaks of the I_2 -cloud occur at night over K and L, without the peak of the $C_{1,2}$ -cloud. This pattern is clearly confirmed in Fig. 11, in which the magnitude and hour of afternoon peaks of sub-categories in C and I-clouds are shown. Assuming

Fig. 7. Diurnal variations of normalized precipitation due to C-Cloud drawn on the same scale for each month over region B. Descriptions are the same as in Fig. 5, but the month is indicated at top instead of the range.

that deep cumulus convection is usually driven by westerly winds, predominant at all levels in the troposphere over these regions, the tilting in Fig. 11 is as follows: isolated deep convective clouds, *i.e.*, $C_{1,2}$ -cloud, are initiated by solar heating on the land, especially in mountains; the most significant is found over I. Clusters of convectively driven clouds such as C_3 -cloud, result from mergers or extension of $C_{1,2}$ -cloud from windward of the driving wind; so the number of C_3 -, I_1 - and I_2 clouds increases over J more than over H. Mature clusters of convectively driven clouds such as I_1 - and I_2 -clouds having longer lifetimes and generating forced convection by their own outflow penetrate over the leeward sea where solar heating on the surface is not enough to initialize free deep convection clouds; these clusters result in the precipitation peak due to I_1 - and I_2 -clouds in the evening. Mature clusters decay into peaks of I_3 or L-clouds precipitation at 21 JST over L (bottom right graphs, Fig. 10).

4.4 Southwestern area and islands

The area around the Nansei Islands where a non-typical diurnal cycle appears in Fig. 3 is divided into four regions: M, the northwestern side; N, the adjoining sea where the non-typical diurnal cycle predominates; O, islands; and P, the southeastern side. Diurnal variations of precipitation in the first row of Fig. 12 exhibit broad enhancement around noon over M and in early afternoon over N, an early after-

noon peak over O, and two maxima, in the morning and in the evening, over P.

The fifth row of Fig. 12 shows that the enhancement is equivalent to that of L, I_2 -cloud. This variation of L, I_2 -cloud is quite different from that over the rest of RECC: Figure 13 shows that this afternoon maximum is limited to May, June, and July, when most precipitation comes from precipitation clouds in the Baiu front. The inner structure of precipitation cloud in the bottom row of Fig. 12 exhibits no variation over M and N, but it has a clear variation over E (Fig. 8). L, I_2 -cloud is not active in the afternoon, but the number appearing in the region is larger in the afternoon than in the morning. Since Fig. 12 shows that the peak time of L, I_2 -cloud is delayed southeastward, the area around the Nansei Islands is divided into 10 strips 40 km wide parallel to the line of the islands plotted as X-Y in Fig. 4, and diurnal variations of precipitation frequency due to L, I_2 -cloud over these strips in the three months are shown in Fig. 14. The sharp peak at 15 JST over 180 km northwest of the islands becomes wider and later southeastward, and finally terminates about 140 km southeast of the islands. This suggests that large precipitation clouds often come from the northwest at about 15 JST, and pass through the region southeast at various speeds.

Superimposed on the maximum due to L, I_2 -cloud, precipitation due to $C_{1,2}$ -cloud in the second row of Fig. 12 peaks in the afternoon over O. This peak is

Fig. 8. Same as in Fig. 5, but for sea regions shown at bottom. Notches by thin solid lines suggest that data at the auxiliary hour are not reliable.

the same as that over H where solar daytime heating causes deep cumulus convection clouds without incoming C-cloud. Figure 15 shows the harmonic dial of the diurnal cycle of precipitation due to $C_{1,2}$ -cloud in each $25 \text{ km} \times 25 \text{ km}$ square averaged from the original grids of RECC between southern Kyushu and Okinawa. There is a predominant afternoon maximum over Okinawa in the left bottom of Fig. 15. These suggest that deep convective clouds due to solar heating on the land develop over Okinawa with an area of $1,200 \text{ km}^2$. No clear afternoon peak of C_1 -cloud or C_2 -cloud is found over any islands smaller than Okinawa in Fig. 15 or in the rest of RECC (not shown).

5. Diurnal cycles of precipitation due to three cloud categories

We confirm the validity of the characters in the sixteen regions by studying diurnal cycles of precipitation due to three categories, C, L, and I, and $I_{1,2}$ ($I_{1,2}$), throughout RECC. Diurnal harmonics of these categories are shown in Figs. 16, 17, and 18. The major characters found in these figures are listed below:

C-cloud (Fig. 16)

- (1) The afternoon maximum of C-cloud precipitation covers the major Japanese islands including windward seaside except for some points such as southern Kyushu (Fig. 15), and south of the Korean Peninsula (not contoured but located north of 35°N and west of 130°E).
- (1') Its amplitude, which is the maximum in these three figures, is predominant over the inland in the southwest and the center of Japan, but larger leeward than windward in northeast Japan.
- (2) The afternoon maximum of C-cloud precipitation also exists over Okinawa with an area of $1,200 \text{ km}^2$, but is not significant over other islands with an area less than $1,000 \text{ km}^2$.
- (3) No distinctive diurnal cycle of C-cloud precipitation occurs on or near coasts.
- (4) The diurnal cycle of C-cloud over seas is not significant, but generally exhibits a morning maximum.

L-cloud (Fig. 17)

- (5) The morning maximum of L-cloud precipitation covers most of the area north of 30°N . Two ridges of amplitude are over seas along the major islands, and a trough over the inland and east of the mountains in central Honshu.

Fig. 9. Same as in Fig. 7, but due to $L_{1,2}$ -cloud over region E.

- (6) The afternoon maximum of L-cloud precipitation occurs south of 30N.
 $I_{1,2}$ -cloud (Fig. 18)
- (7) The afternoon maximum of $I_{1,2}$ -cloud precipitation appears over central and northeastern Honshu.
- (8) The afternoon maximum of $I_{1,2}$ -cloud precipitation with predominant amplitude is also seen over the eastern seas of northeastern Japan and Korean Peninsula.
- (9) $I_{1,2}$ -cloud precipitation shows a morning maximum over the Pacific Ocean south of Honshu and around Kyushu.
- (10) The late morning maximum of $I_{1,2}$ -cloud precipitation is over the area about 28N.

6. Discussion

6.1 Cloud category

We define two new categories of precipitation cloud in terms of horizontal scale and maximum precipitation intensity according to the average diurnal variation pattern around the Japanese archipelago as follows:

Cumulus-scale precipitation cloud, composed of C-cloud and part of I-cloud involving primarily clouds originated by mergers or extension of C-cloud, is expected to be mainly clouds developed and maintained by dissolving vertical instability (Emanuel, 1986), and causes small-scale short precipitation with strong intensity. This involves both the meso γ scale and the meso β scale phenomena in Orlanski (1975), such as isolated cumulus convection clouds and a cluster of convectively driven clouds involving cumulonimbus and severe convective storms.

Large-scale precipitation cloud, composed of L-cloud and I-cloud excluded from cumulus-scale precipitation clouds, accompanies atmospheric disturbances originating in quasi-horizontal circulation of moist air, such as tropical and extratropical cyclones and Baiu fronts. This is considered to involve both synoptic scale and meso α scale phenomena (Orlanski, 1975).

6.2 Cumulus-scale precipitation cloud

a) Vertical instability

As summarized in the Introduction, solar radiation heating the boundary layer over land should cause convective instability generating a sharp precipitation maximum of cumulus-scale precipitation

Fig. 10. Same as in Fig. 5 without the last row, but for different cloud (sub-) categories at left and for regions crossing northeast Honshu at bottom.

Fig. 11. Amplitude and phase of cloud subcategories shown at left over the same regions as Fig. 10 shown at top. Thick solid lines show contours of range of normalized precipitation of each subcategory. Digits show phase delay of each subcategory from 15 JST over each region, and thin broken lines are contours. Honshu (land) is shaded at bottom.

clouds in the afternoon, noted in (1), (2), and (7) in Section 5. Daytime boundary layer heating is enough to generate deep cumulus convection clouds over the coastal area of the major islands, where Fujibe (1988) and Tagami (1990) do not find such a phenomenon, but not enough over islands with an area of less than 1,000 km² around them. As noted in (2), the afternoon maximum is found over Okinawa with an area of 1,200 km² in the Nansei Islands at the southwest edge of RECC. Fujibe (1988) found maximum of the local precipitation around noon on the island, and considers the maximum caused by the island at 26N usually situated in the tropical air mass, potentially more unstable than the extra-tropical air mass. This is consistent with Gray and Jacobson (1977), who find predominant afternoon maximum in precipitation over four larger islands with an area of about 100 km² among islands in the tropical air mass around 10N south of Japan. However, we cannot conclude whether the difference of Okinawa from other islands is due to its area or po-

sition, before precipitation over some islands at the southwestern end of the Japanese archipelago out of RECC is examined.

As noted in (4), the cumulus scale precipitation cloud scarcely develops over the seas around the Japanese archipelago. Thus, increased cumulus convection during the night responding to a steepened lapse rate due to cooling in the clear upper troposphere in the warm season, is excluded from processes related to diurnal variations of precipitation around the Japanese archipelago.

b) Horizontal flow

There is clear evidence that cumulonimbi due to land breezes develop during the night along the north coast of Borneo (Houze *et al.*, 1981) and the northeast coast of Brazil (Kousky, 1980) at low latitudes. At middle latitudes, Wallace (1975) attributes the nocturnal or the morning maxima of precipitation along the gulf coast of the United States to convective precipitation due to convergence of the land breeze. Our result shows no

Fig. 12. Same as in Fig. 5, but for different cloud (sub-) categories at left and for regions crossing the Nansei Islands shown at bottom.

Fig. 13. Same as in Fig. 9, but over regions M and N.

special activity of the cumulus-scale precipitation cloud over any sides of the coastline as noted in (3). Therefore, the generation of cumulus convection triggered by the land breeze is excluded from processes controlling diurnal variations in the warm season around the Japanese archipelago.

Fujibe (1988) finds east-west asymmetry north-east of Japan and attributes it to the prevailing westerly wind (Neiuwolt, 1977). We show in Subsection 4.3 that the east-west asymmetry results from eastward movement of cumulus-scale precipitation clouds raised over the central mountains. This movement over land involves simple advection and propagation by creating new convection cells at the lee side due to down loading of upper air momentum in old convection cells under a convectively unstable condition (Cotton and Anthes, 1989). Since northeast Japan is narrow west to east, the propagation terminates soon at the coast and then only huge cumulus-scale precipitation clouds intrude a few hundred kilometers over the Pacific Ocean as noted in (8). However, if the unstable convective

area extends widely to the lee of mountains, long-distance propagation should occur; as an example, Karr and Wooten (1976) find eastward propagation of the maximum echo frequency over Colorado during the afternoon of fine days, responsible for the eastward delay of precipitation maximum over the lee of the Rocky Mountains (Wallace, 1975; Riley *et al.*, 1987).

The land-sea contrast and uniform distortion by the wind on diurnal variations of the cumulus-scale precipitation cloud is striking in Fig. 16, because the scale of topography in Japan is much smaller than that of land-water distribution. We also see, however, small fluctuations of phase and amplitude in Fig. 16 responsible for topography such as mountain-valley as suggested by Fujibe (1988).

6.3 Large-scale precipitation cloud and others

a) Extent of variation

The diurnal variation of precipitation over the sea north of 30°N exhibits a significant diurnal cycle with the morning maximum mainly due to large-scale precipitation clouds as noted in (4) and (7) in

Fig. 14. Diurnal variations of frequency ($\times 10$) of precipitation due to L_{12} -cloud over 10 strips 40 km wide centered on the island line of the Nansei Islands plotted as X-Y in Fig. 4. The distance from the island line is indicated in km above or below. Each graph is the same as graphs in Fig. 5, but the ordinate is tenfold frequency and the maximum indicated at top.

Fig. 15. Harmonic diagram of diurnal components of normalized precipitation in $25 \text{ km} \times 25 \text{ km}$ grids between southern Kyushu and Okinawa in RECC in the season using precipitation at basic hours. Arrows are the same as Fig. 3a. Broken lines show contours of 0.75, 0.5, and 0.25 of maximum amplitude in the figure, 0.12 by normalized precipitation, in order of thickness.

Fig. 16. Same as in Fig. 3, but for precipitation due to C-cloud. The maximum amplitude is 0.18 by normalized precipitation.

Section 5. Diurnal variations over the sea south of 30°N , noted in (6) and (10), are masked by the afternoon maximum due to repeated intrusion of large-scale precipitation clouds from the northwest, discussed in the last third of this section. However, some signs of the morning maximum are found, such as diurnal variations due to I_1 and C_3 -clouds over regions M and P in Fig. 12, and those due to L, I_2 -cloud in August and September in Fig. 13; Gray and Jacobson (1977) find a relative morning maximum of precipitation over all islands in the western North-Pacific south of Japan, from which tropical cyclones advance.

The weaker morning maximum due to large-scale precipitation clouds is also distributed over the major islands as noted in (5), and is the source of the early morning secondary precipitation maximum. Similar early morning secondary maxima are reported by Riley *et al.* (1987) in the central United States and shown in Figs. 16–24 of Landin and Bosart (1985) in the northeast; both are more than thousands of kilometers away from the windward sea. Thus, (5) suggests the existence of the morning maximum over the land slightly disturbed by the strong topographic effect on precipitation over mountainous Japan.

The facts above indicate that the morning maximum precipitation is a general character common to clouds in the warm season except for cumulus-scale precipitation clouds. In winter, Fig. 9 does not exhibit the same sense, though other studies (Tagami, 1990; Wallace, 1975; Landin and Bosart, 1985; Riley *et al.*, 1987) report morning maxima in winter. This suggests that the six seasons examined in this study are too short to detect the diurnal variation in winter, found to have smaller amplitude than that in summer by other studies with longer periods from 11 (Tagami, 1990) to 35 years (Riley *et al.*, 1987). Therefore, we do not discuss diurnal variations of precipitation in the winter.

b) Candidate mechanisms

Processes related to land-sea circulation suggested by Wallace (1975) are excluded from origin of the morning maximum, because the maximum appears all over RECC. Speculation that attributes the morning maximum to the semidiurnal solar atmospheric tide (Brier and Simpson, 1969) also does not hold for Japan, because the morning maximum is independent of the afternoon maximum. We also doubt that the predominance of the semidiurnal component of precipitation on the average day over other regions (Brier and Simpson, 1969; *etc.*) only

Fig. 17. Same as Fig. 16, but for L-cloud. The maximum amplitude is 0.14 by normalized precipitation.

indicates two diurnal variations due to cumulus-scale and large-scale precipitation clouds (Tagami, 1990).

There remains a convenient candidate for explaining the morning maximum, that is, the diurnal cycles of radiative balance on cloud tops. The following two mechanisms connecting radiative balance and the morning maximum without observational and theoretical evidence are proposed: circulation in clouds dependent on lapse rates (Hobgood, 1986), and convergence due to differential radiational structures between cloud and cloud-free areas (Gray and Jacobson, 1977; McBride and Gray, 1980). Precipitation weaker than or equal to class M accounts for more than 75 % of the diurnal variation over region E or 95 % over region F (not shown); such intensity in large-scale precipitation clouds has usually been observed under clouds with a bright band, namely strong stratiform cloud with embedded convection, in Japan. Since embedded convection is a phenomenon likely to be affected by radiative processes around cloud tops, diurnal cycles of radiative balance on cloud tops seem a convincing candidate for origin of the morning maximum.

c) Movement

The afternoon maximum due to L_2 -cloud around the Nansei Islands between May and July in the three years from 1991 to 1993, is less significant than other diurnal variations discussed in this study. The existence of the afternoon maximum over the area is supported by Fujibe (1988), who found a similar weak tendency of wide spread precipitation on the Nansei Islands in warm seasons from 1978 to 1986. McGarry and Reed (1978) report a similar diurnal variation over the GATE region. They suggest that the afternoon maximum of precipitation is related to passages of easterly wave troughs originating at the coast of Africa about 500 km east of the GATE region. Instead of Africa for the GATE region, the lower reaches of the Yangtze in China are located about 500 km west-northwest of the Nansei Islands; strong large-scale precipitation clouds are often observed to organize in the Baiu front between May and July over the reaches, and to propagate east toward the Nansei Islands as westerly wave troughs. The timing of their organization over China and their movement over the East China Sea are interesting topics to examine in the future.

Fig. 18. Same as on Fig. 16, but for $I_{1,2}$ -cloud. The maximum amplitude is 0.14 by normalized precipitation.

7. Concluding remarks

This study clarifies three essential factors controlling diurnal variations of precipitation around the Japanese archipelago in the warm season by categorizing precipitation clouds into the cumulus-scale precipitation cloud and large-scale precipitation cloud based on horizontal scale and maximum precipitation intensity. Details are summarized as follows:

- 1) Vertical instability due to solar daytime heating on the boundary layer makes cumulus-scale precipitation clouds develop in the afternoon. The cumulus-scale precipitation cloud, defined as small precipitation clouds with intense precipitation, is expected to correspond to isolated clouds or clusters of clouds developed and maintained by free convection. This development is found over the four major islands of Japan with an area of more than 10,000 km² except some points, that is, both inland and coastal areas; and south of the Korean Peninsula. The development also occurs over Okinawa with an area of 1,200 km², the largest of the small islands of the Japanese archipelago except the major islands and located at the southern edge of the studied area. There is no significant develop-

ment of cumulus-scale precipitation clouds in the morning.

- 2) Unknown processes in precipitation clouds make their precipitation a diurnal cycle with a morning maximum. This cycle is significant in the large-scale precipitation cloud due to quasi-horizontal atmospheric disturbances such as tropical and extratropical cyclones and Baiu fronts. This cycle is found over most of the Japanese archipelago, especially over the sea. These processes are independent of land-sea circulation and the semidiurnal solar atmospheric tide, but are probably induced by a diurnal cycle of radiative balance on cloud tops.
- 3) Westerly wind fields over Japan modify diurnal variations above by two ways: controlling propagation of precipitation clouds and advecting precipitation clouds themselves or systems organizing them. Diurnal variations modified are as follows: cumulus-scale precipitation clouds over northeastern Japan usually propagate or are advected east due to westerly wind over the region. This results in the predominant but delayed afternoon maximum of cumulus-scale precipitation clouds east of the region, and the evening maximum of well-developed cumulus-

scale precipitation clouds over the eastern in-shore where few convective clouds can develop. Large-scale precipitation clouds in Baiu fronts driven by westerly winds often pass through the Nansei Islands in the afternoon between May and July; they probably originate in the lower reaches of the Chinese Yangtze River. As a result of the passage, the afternoon maximum of precipitation appears from large-scale precipitation clouds around the islands.

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降水雲型別に見た日本列島付近の降水日変化 (暖候期)

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1988年から93年のレーダーエコー合成図を解析して日本列島付近の降水の日変化を調べた。この解析は、18のデジタル化レーダーを合成した陸海両方を含む広い領域上で、降水雲の水平規模及び最大降水強度によって、準水平循環によると考えられる大規模降水雲及び対流によると考えられる積雲規模降水雲に分類して日変化を調べた点に特徴がある。

小規模で降水強度の強い雲で定義される積雲規模降水雲は、一部の岬を除く日本の4大島の全域・朝鮮半島南部及び沖縄本島で、午後に卓越的な降水最大を持つ。これは疑いなく日射の境界層加熱による。主に大規模降水雲で占められるその他の降水雲はほぼ合成図全域で朝に最大値を持つ日周期を示す。この変動は海陸循環には関係しない。

日本上空の西風はこれらの日変化に以下のように影響を与える。東北日本上空の西風は積雲規模降水雲の活動を領域東側で最大にし、さらにそれらの雲を東側近海に運び降水極大を引き起こす。琉球列島周辺では、西風に運ばれる大規模降水雲が5月から7月の間しばしば午後に北東から通過するために、降水量の極大が午後に現れる。