Time and Spatial Variations of Mesoscale Rainfalls and their Relation to the Large-Scale Field in the Western Tropical Pacific

By Tomoki Ushiyama, Shinsuke Satoh and Kensuke Takeuchi

Institute of Low Temperature Science, Hokkaido University Sapporo, Japan 060

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Abstract

We examine the relationship between mesoscale rainfalls and large-scale atmospheric fields in the western Pacific using data obtained in the TOGA-COARE IOP (Tropical Ocean and Global Atmosphere-Coupled Ocean Atmosphere Research Experiment, Intensive Observation Phase). The data used for our analysis were a two-months period of successive x-band radar data taken at Manus island P.N.G. (2S, 147E), sounding data and GANAL (Global Analysis by Japan Meteorological Agency) data. Radar observation data were converted into rainfall rates as an index of local convective activity, and averaged into two horizontal areas: land area and sea area, and into three vertical layers to evaluate the island effect and the vertical distribution.

The rainfall rates of the land area were dominated by a strong diurnal variation. On the other hand, diurnal variation in the sea area was much weaker than the land area. In the spectrum of rainfall rates in the sea area, 1.5 to 2-days and 3 to 5-days-period peaks were more significant than those of the land area.

Lagged correlation analysis and cross spectral analysis was done to examine the relationship between the local rainfalls and large-scale atmospheric fields. The correlation between the rainfall rates and the CAPE showed that before a rainfall event the CAPE increased for two days, and then decreased after it. The correlation between the rainfall rates and the zonal wind or mixing ratio showed an eastward propagation of the correlation that may correspond to a Madden-Julian oscillation. The phase relation of this correlation was such that, when the lower tropospheric wind changed its direction from easterly to westerly, a rainfall event started. After a rainfall event, the mixing ratio at 500 hPa increased. This relationship between the mixing ratio and the rainfall rates was also found in the sounding data.

1. Introduction

In the western tropical Pacific, the atmosphere has a large thermodynamic energy deduced from the high sea surface temperature ocean that is called the warm water pool, (Graham and Barnett, 1987). Therefore, this is one of the strongest areas of convective activity and thus the atmosphere in this region plays an important rôle in the global climate system. Convective systems in tropical oceans interact with the ocean surface and large-scale atmospheric field, and mesoscale convective systems have their own original maintenance mechanism. It is important to understand these complicated structures of atmospheric convective systems in order to study the global climate system.

In the tropical ocean, various observations have been carried out. However, in the tropical western Pacific, sufficient observations have not been carried out. The biggest experiment in the trop-

ical Pacific was MONEX (Monsoon Experiment) carried out in 1978–1979. In the winter of 1978 (WMONEX), c-band radar and GMS satellite observations were carried out in the area of north Borneo to the south China sea. In this experiment, a distinct diurnal variation over Borneo and the south China sea was closely analyzed, and also an 8-day oscillation was found in the variety of areas covered by cloud or radar echo. This oscillation was greatly affected by the monsoon surge and the Easterly Wave propagation (Houze *et al.* 1981). Further, Ishihara (1985) analyzed the relationship between the Easterly Wave propagation and the variation of echo area or amount in the north west area of New Guinea (2N, 130E). He suggested that the Easterly Wave propagation enhanced the convection in the phase ahead of the trough. Thus, a relationship between mesoscale convective systems and synoptic-scale disturbances was investigated. Nevertheless, these two experiments were restricted to a small region and were located little bit farther west than the warm

water pool.

However, around the tropical Atlantic ocean, big experiments have been carried out, such as GATE (GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment) in 1974 (Houze and Betts, 1981) and COPT-81 (Convection Profonde Tropicale) in 1981. After these experiments, studies of the mesoscale convective systems in this area were greatly advanced. In GATE, the mesoscale convective systems were observed by four ship-borne c-band radars covering a range of a few hundred kilometers (Houze and Cheng, 1977). The characteristics of the squall lines or the cloud clusters in this area were defined by Houze (1977) and by Leary and Houze (1978). Squall lines or cloud clusters are characterized by their kinematic structures, life stages and life time. These characteristics were also found from dual-Doppler radar analysis by COPT-81 (Chong *et al.* 1987). Further, an analysis of the relationship between the environmental field and the mesoscale convective systems was made. The formulations of squall lines are highly affected by the initial atmospheric humidity of the environment (Barnes and Sieckman 1984). Reeves *et al.* (1979) represented the relationship between large-scale motion and convective-scale rainfall. In their study, a tight connection between the Easterly Wave (African wave) and the rainfall was reported, even the strength of connection had some differences with the strength of the Easterly Wave. Convective systems also change their environmental condition (Leary and Houze, 1980). However, almost all these studies were restricted to case studies. There are no studies dealing with the successive datasets.

On the other hand, since the development of satellite data or objectively analyzed data, tropical atmospheric oscillations were analyzed with tropical wave dynamics. For example, El Niño and the southern oscillation, intraseasonal variation (Madden and Julian 1971, 1972), super clusters (Nakazawa 1988, Takayabu and Murakami 1991), westward-propagating cloud clusters (Takayabu and Nitta 1992) or Easterly Waves (Wallace 1971). Nakazawa (1988) reported that these atmospheric oscillations are composed in a hierarchical structure and that they interact with each other. Mesoscale convective systems are also closely connected by these atmospheric oscillations (Takayabu and Nitta 1992). It is also important to describe the effects of the mesoscale or the convective-scale systems that determine the heat and moisture source of the atmosphere, because this process is essential in order to parameterize the effect of convection in global circulation models, an example of which was demonstrated by Arakawa and Schubert (1974).

However, these studies discussing the atmospheric oscillations are mainly done by using satellite or objectively analyzed data. These data are useful for

large-scale atmospheric analysis (Slingo *et al.* 1992), but their resolution is too coarse for the discussion of mesoscale convective systems. Some satellite data have a resolution of less than a few kilometers. However, satellites can only see the cloud tops and cannot evaluate the structure inside of the convective systems. Thus, there have not been sufficient studies about the relationship between large-scale atmospheric fields and convective systems using successive datasets.

Recently, from Nov. 1992 to Feb. 1993, the TOGA-COARE IOP (Tropical Ocean and Global Atmosphere-Coupled Ocean Atmosphere Response Experiment, Intensive Observation Phase), which is a component of the WCRP (World Climate Research Program), was carried out. In this period, various observations were made over the western tropical Pacific around the warm water pool. In this experiment, Doppler radar observation was carried out at Manus island in Papua New Guinea (2 S, 147 E). The outline of this observation has been presented by Uyeda *et al.* (1995).

In the TOGA-COARE IOP, we obtained two successive months of radar observation data. This was the first time such a long period of successive radar data had been gathered in a tropical ocean. By utilizing these data, we can analyze the statistical characteristics of the three-dimensional radar echo. Further, we also used an omegasonde and objectively-analyzed data as the index of environmental variables to study the relationship between the variation of radar echo and the environmental fields. During the analysis, we converted the radar echo into rainfall rates by using a Z-R relationship. This was only for a better understanding of variations, and doesn't claim to be an accurate estimation of rainfall. This analysis can permit discussion of the three-dimensional structure of the radar echo, and not only the upper-cloud areas covered by the satellite data. And to evaluate the islands effects, cloud physical effects and height of convection, we defined two horizontal areas and three vertical layers as representative of each three-dimensional domain. We have performed an analysis of the local rainfall and the relationship between local rainfalls and large-scale fields with these successive datasets.

In Section 2, we will discuss the data. In Section 3, we present the method of producing the time series dataset of the rainfall rates. In Section 4, we will show the characteristics of the time series of rainfall rates. In Section 5, we will make lagged correlation analyses between the time series of rainfall rates and the environmental atmospheric field variables. In Sections 6 and 7, we will discuss and summarize the results.

Fig. 1. Map of the observation area. The large circle indicates the radar observation range. The land area and the sea area defined for analysis are indicated in the circle. The radar range is 64 km. The radar was set at Momote airport on the east side of Manus Island, P.N.G. at 2°S, 147°E. Four rain gauges were set in the island, at Bowat, Nabu, Kitchapon and Momote.

2. Data

We used mainly data obtained by x-band radar, omegasonde, rain gauges on Manus island and GANAL data (Global Objective Analysis produced by Japan Meteorological Agency) around Manus island from Nov. 1992 to Jan. 1993 (while TOGA COARE IOP).

The x-band radar was set at Momote airport, located on the east side of Manus island, Papua New Guinea (2°S, 147°E, shown in Fig. 1). The characteristics of the radar are represented in Table 1 of Uyeda *et al.* (1995) as the ILTS (Institute of Low Temperature Science) radar. The range of ILTS radar is 64 km. Observation by this radar was made from 17 Nov. 1992 to 21 Jan. 1993. The minimum interval of three-dimensional scanning is 15 minutes, but the observation stopped many times for several hours when, for example, there was no echo in the radar range, when doing maintenance on the generator, or because of radar troubles. The ILTS radar has almost no shadow area for all azimuth angles when the elevation angle is higher than 3 degrees.

The omegasondes were launched at Momote airport (same as the radar site) four times a day. However, humidity data from 1 Dec. 1992 to 24 Dec. 1992 on Manus island was not obtained due to humidity sensor trouble. We also used omegasonde data of

other observation sites which were some hundreds of kilometers away from Manus island (not shown in this paper).

GANAL data over the area of 125°E to 168°E and 13°S and 13°N were used to define some environmental variables. The horizontal resolution of the GANAL data is 1.875 degrees in latitude and longitude covering the entire globe; vertically, it has 16 layers from 1000 hPa to 10 hPa (including the surface). From 1000 hPa to 100 hPa, there are 10 levels. The time interval is 12 hours.

3. The method of calculating time series of rainfall rates

Firstly, we made up the time series datasets of the rainfall rates converted by the Z-R relationship from the radar reflectivity factor. The Z-R relationship is represented as follows:

$$Z = BR^\beta,$$

where Z is the radar reflectivity factor, R the rainfall rate, and B and β are the constants that are defined by the size distribution of precipitation particles. In this study, the coefficients of $B = 200$ and $\beta = 1.6$ proposed by Marshall and Palmer (1948) were used.

For this data conversion, the rainfall rates were considered to be the amounts of precipitation particles such as rain droplets or snow flakes or hail *etc.*

Fig. 2. The time series of the rainfall rate in the middle layer obtained from radar. (a) the rainfall rate in the sea area (b) the rainfall rate in the land area Small shaded rectangles on the x axis indicate the periods that the radar observation had not been made for more than two hours.

These amounts are considered to be the consequents of convection; however, there can be a time lag between the development of convection and an increase of these particles. When evaluating the amounts of precipitation particles, there are many problems to take into account. The precipitation particles include the liquid and ice phases and the coefficients of the Z-R relationship equation vary with the particle's phase. It is very difficult to distinguish between the phases of particles, and the coefficients of the Z-R relationship vary with the prevailing cloud type or rain pattern. Through this data conversion, the same coefficients of the Z-R relationship are used. In this study, the rainfall rates are treated as a variable that is consistent with the local convective activity. Thus, the absolute value of the particle amounts will not be discussed, but the variation in time is considered.

When calculating the rainfall rates, the radar scanning volumes are divided into two areas horizontally to evaluate the island effect, and into three layers vertically to evaluate the cloud physical effect or the intensity of convection, and averages are taken in each domain. Horizontally, the sea area and the land area are defined as the area over the sea about 10 kilometers away from the islands and the area over the island, respectively (shown in Fig. 1). Vertically, the lower, the middle and the upper layers are defined. These three layers' heights

are 0.25 km–3.5 km, 4.5 km–11.0 km and 11.5 km–20.0 km, respectively. The 4-km height layer, which corresponds to the bright band, is excluded to avoid overestimating rainfall rates. In our radar observations, the number of raw data points was varying with respect to the scanning mode of the radar antenna, which varied with the echo patterns. When the number of antenna scans was small, areas with sparse data points were poorly sampled, especially at the higher altitudes. The upper layer (upper troposphere) was separated from other layers so that the other layers are free from the sampling inequality. Further, we divided the lower layer into two layers. With respect to the dividing height of the middle and the upper layers, it was decided from our case studies (not shown). Our case studies showed that the distributions of precipitation particles were usually restricted to below 11 km, with respect to both convective and stratiform echo (not shown). Thus, the upper layer was defined as above 11 km in height. In this way, a time series of the rainfall rates during 66 days from Nov. 17 1992 to Jan. 21 1993 was derived, with 15 minutes to several hours interval.

4. Characteristics of time series of the rainfall rates

Time series of the rainfall rates calculated from radar observation from 17 Nov. 1992 to 21 Jan. 1993

Fig. 3. The diurnal variation of the rainfall rate. (a), (b) The diurnal variation of the rainfall rate from the radar data about three layers. Solid line, broken line and dash-dot line indicates the lower layer, the middle layer and the upper layer defined with radar scanning volume, respectively. (a) the sea area. (b) the land area. Each value is averaged for an hour with local standard time. (c) The diurnal variation of the rainfall rate observed by raingauges at Manus Island. Solid line, long broken line, short broken line and dash-dot line indicates the rainfall rates at Nabu, Kitchapon, Bowat and Momote, respectively.

are shown in Fig. 2. In this figure, the variations of the middle layer are shown. As in Fig. 2a and Fig. 2b, the rainfall rate in the sea area seemed to vary with a time scale of a few days to a week. On the other hand, with respect to the land area, the daily variation dominated, as shown by the many spiky peaks. In these figures, many no-data periods are included, as mentioned in Section 2. Small shaded rectangles on the x axis indicate the periods that the radar observation had not been made for more than two hours.

In Fig. 3a, 3b, which show the mean diurnal variations of the rainfall rates of each layer as per the radar data, a clear diurnal variation is seen in the

Fig. 4. Spectrum of the rainfall rates. Spectrum of the rainfall rate of (a) the sea and (b) the land area. Solid line and dash-dot line indicates spectral density of the lower and the middle layer, respectively. This spectrum is calculated from auto correlation functions.

land area whose peak is at mid day. On the other hand, in the sea area, diurnal variation is much weaker. In Fig. 3c, we also get diurnal variations of rainfall rates calculated from a raingauge data from several sites on Manus island (observation sites are shown in Fig. 1). In Fig. 3c, the variation at Bowat (shown by a short dashed line) has a distinct peak at 13–14 h LST that agrees well with the peak of the land area by radar. However, there is a one-hour time lag between them, which is possibly due to the difference of maximum time for rain droplets in the atmosphere and the same at the ground. The variations of the raingauge data at other sites is rather confusing. The diurnal variations of the lower and the middle layers almost agree with each other; however, the variation of the upper layer is a much weaker than for the lower two layers, and has a rather different kind of variation.

Figure 4 shows the power spectrum of the rainfall

rates of the lower and the middle layers in each area. The spectrum of the rainfall rates in the land area has a dominant peak at a period of 1-day. That is consistent with the strong diurnal variation found in Fig. 2 and Fig. 3. A half-day period peak is also clear. On the other hand, in the spectrum of the sea area, some peaks are seen with periods of about a half day, 1-day and 1.5-days to 1.8-days. The 1-day-period peak is lower than that of the land area, while the peaks at 1.5-2 days are higher than that of the land area.

Concerning differences found between the layers, in the sea area, peaks of the middle layer (dash-dot line) are higher than those of the lower layer (solid line) at around 2-days and longer than 15-days. In the land area, the peaks of the middle layer are higher than those of the lower layer for nearly all the periods. These results suggest that the variations in the middle layer are strongly affected by the atmospheric variations whose period is longer than 1 day. In the land area, this pattern is more distinct than in the sea area.

In the following sections, we mainly focus on the variation in the sea area, especially of the middle layer, because it is seemed to be less affected by the island than variations in land area.

5. Relationship between the rainfall rates and large-scale field

In this section, we will examine the relationships between the rainfall rates calculated from the radar data in the sea area and several indexes of atmospheric conditions. The indexes are, CAPE and the mixing ratio calculated from the sounding data, divergence, vertical shear, wind and the mixing ratios calculated from GANAL data. To evaluate these relationships, we utilized a lagged correlation analysis. Further, we calculate a cross spectrum to examine the variation periods of each relationship.

Significance levels of lagged correlation coefficients for 95 percent confidences are 0.19, except the sounding data, which is 0.19–0.23 depending on lags.

5.1 Relationship between the rainfall rates and CAPE or mixing ratio by sounding data

At first, we will show the lagged correlation between the rainfall rates and the environmental variables deduced from the sounding data at Manus island, CAPE, and the mixing ratio.

CAPE (Convective Available Potential Energy) is a suitable parameter to evaluate atmospheric instability. In Holton (1992), CAPE is represented by the following equation:

$$CAPE = \frac{w_{\max}^2}{2} = \int_{Z_{LFC}}^{Z_{LNB}} \left(\frac{T_{\text{parcel}} - T_{\text{env}}}{T_{\text{env}}} \right) dz,$$

where $w_{\max}$ is the maximum vertical velocity caused by atmospheric potential energy, Z_{LFC} the height of the Lifting Condensation Level, Z_{LNB} the height of Level of Neutral Buoyancy, T_{parcel} , T_{env} the temperature of a rising parcel and the environmental air, respectively. This equation shows that CAPE is the maximum kinetic energy per unit mass that a buoyant parcel could obtain by ascending from a state of a rest at Z_{LFC} to Z_{LNB} . So CAPE is considered as the parameter of the strength of the atmospheric instability. However, there is a problem when one calculates CAPE. The sounding data are much disturbed near the ground. Thus, if one calculates the lifting condensation level or level of free convection (Z_{LFC}), these levels are much lower than the cloud bottoms observed visually around the observation sites. To avoid this inconsistency, we excluded the sounding data that were lower than 300 m in height when calculating the CAPE. In this way, the lifting condensation levels are about 1000m in almost all the cases, which is consistent with the true cloud bottoms. From the sounding data, we also get the mean mixing ratio in three layers, that is ground to 900 hPa (correspond to the mixing layer, 0 to 1 km height), 700 hPa to 500 hPa (3 to 6 km height) and 400 hPa to 200 hPa (7.5 to 12.5 km height).

Figure 5 shows the lagged correlation between the variation of the rainfall rates and the CAPE at Manus. The correlation coefficients are relatively high for a lag time of minus 2 to 0 days, especially for the rainfall rates of the middle layer, whose coefficients exceed the significant level for 95 percent confidence. The coefficients drop sharply and become negative for a lag 0 to plus 2 days. This shows that the CAPE at Manus tends to be high for 2 days before a rainfall event and then drops sharply after it. It is consistent with the natural expectation that a higher value of the CAPE is a favorable condition for the generation of convection. In addition, a peak at –5 days in the middle layer is also significant. It can be seen that the correlation varies periodically with a period of 4 to 5 days in left portion of the figure. We also calculated the lagged correlation between the CAPE of the other sites, for example Kavieng (not shown), and the rainfall rates of Manus radar, but no such variations as in Fig. 5 were found. This result shows that such variations of CAPE (atmospheric instability) are restricted locally.

Figure 6 shows the cross spectrum between the rainfall rates and the CAPE. This figure shows some significant peaks in the periods at 1 to 1.3 days, 4 days and 8 to 10 days. It would be considered that these periods were important to the variation of CAPE or the recovery time of atmospheric instability.

We have also calculated a lagged correlation between the rainfall rates and the mean mixing ratio

Fig. 5. Lagged correlations between CAPE and the rainfall rates in the sea area. Solid line, dash-dot line and broken line indicates the correlations with the rainfall rate at the lower, the middle and the upper level, respectively. Near the 0.2 and -0.2 correlations, level horizontal broken lines indicate the significant level at 95 percent confidence. Correlations in the middle layer increased before rainfall events (lag at -2 to 0 -days), and then dropped sharply there after.

Fig. 6. Cross spectrum between the rainfall rate in the sea area and CAPE. Solid line, long broken line and short broken line indicates the low layer, the mid layer and the upper layer of the rainfall rate, respectively. A 4-day period and an 8- to 10-day period are significant.

of the three layers (ground to 900 hPa level, 700 to 500 hPa level, 400 to 200 hPa level) calculated from the sounding data, which is shown in Fig. 7a-7c. In these figures, only correlations with the rainfall rate of the middle layers are shown. The correlation between the mean mixing ratio in the ground to 900 hPa level and the rainfall rates (Fig. 7a) shows a similar shape with the lagged correlation between the CAPE and the rainfall rates (Fig. 5), in its increase of correlation before a rainfall event. This result possibly shows that the CAPE depends pre-

dominantly on vapor distribution in the atmospheric mixing layer.

Further, Fig. 7b and Fig. 7c show a lagged correlation between the mean mixing ratio in the 700 hPa to 500 hPa layer and the 400 hPa to 200 hPa layer, respectively. These figures clearly show that the mixing ratios of these layers sharply increase after the rainfall events, and keep their large value for a few days. This increase of the mixing ratio is considered to be a consequence of convection. Compared to the mixing ratio in middle or upper layers of the troposphere, the mixing ratio in the atmospheric mixing layer is quite different. However, these middle and upper tropospheric mixing ratios varied in quite similar ways. In Fig. 7c, a cyclic pattern of a week was seen. That is an 8-day-period oscillation that is found in a cross spectrum between the rainfall rates in the sea area and the upper tropospheric mixing ratio (not shown). That 8-day cycle is also found in the cross spectrum with the middle tropospheric mixing ratio, though its spectrum density is lower than that of the upper tropospheric mixing ratio.

5.2 Relationship between the rainfall rates and large-scale fields from GANAL data

In this subsection, the longitude-lag time section diagrams were used to describe the lagged correlation coefficients. Also, the rainfall rate in the middle layer was used to calculate the lagged correlation. A negative lag indicates that the GANAL data precedes the rainfall rates.

Figure 8 shows a lagged correlation between the rainfall rates and the wind divergence at two levels along the latitude of 1.875°S , near Manus Island. Correlation coefficients in Fig. 8 are almost under the significant level. Lower and upper tropospheric divergence is considered as having some

Fig. 7. Lagged correlation between the mixing ratio from the sounding data at Manus and the rainfall rate in the middle layer. (a) the lagged correlation of the mixing ratio in the ground to 900 hPa layer (0 to 1 km height) with the rainfall rate. (b) Same as (a), except for the mixing ratio in the 700 hPa to 500 hPa layer (3 to 6 km height). (c) Same as (a), except for the mixing ratio in the 400 hPa to 200 hPa layer (7.5 to 12.5 km height). Solid line, long broken line and short broken line indicates the low layer, the middle layer and the upper layer of the rainfall rate, respectively. Near the 0.2 and -0.2 correlations level, horizontal dashed lines indicate the significant level at 95 percent confidence. The middle and the upper tropospheric mixing ratio (b), (c) increase after rainfall events, and keep their large value for a few days.

relationship with convection; however, no significant correlation was found. This non-significance might be due to the resolution of the GANAL data. We also calculated the lagged correlation between divergence in low latitudes of northern hemisphere and the rainfall rates (not shown). In this time-longitude diagram, the correlation was propagating westward, and is considered as a signal of westward-propagating cloud clusters. But these values were also below the significant level. Also, in Fig. 8b, a very weak westward-propagating signal might be found.

Figure 9 shows a lagged correlation between the zonal wind at 850 hPa or 200 hPa and the rainfall rates. In this figure, the negative and positive coef-

ficients propagate eastward at a speed of 2.6 m/s (2 degrees per day) and have a cycle of about 40 days. Those propagation speeds and cycles correspond to that of the Madden-Julian oscillation (Madden and Julian, 1971, 1972). The maximum absolute values of both in positive and negative coefficients lags, are well over the significant level. The phase relation shows that, when the lower tropospheric zonal wind change its direction from easterly to westerly, a rainfall event occurs.

A similar propagating feature is also found in the lagged correlation between the mixing ratio at 500 hPa height and the rainfall rates (Fig. 10b). Maximum positive correlation was found just after a rainfall event, which indicates that the increase

Fig. 8. Lagged correlation between the divergence from GANAL and the rainfall rate. (a) Lagged correlation with the divergence at 850 hPa. (b) Lagged correlation with the divergence at 200 hPa. Contour and shading or hatches indicate the lagged correlation coefficients with a contour interval of 0.1, and shade pattern is divided as 0.0 ± 0.25 , ± 0.45 . Solid contours and hatches indicate a positive correlation, and broken contours and shadings indicate a negative correlation. The contour line at 0 is removed. A negative sign of ordinate indicates a lag time before rainfall events for GANAL data. The abscissa indicates longitude. Level and latitude of a variable from GANAL are indicated in right upper corner of each figure.

of the mixing ratio is a consequence of a rainfall event and not the cause of it. This is consistent with the result obtained from the sounding data (Fig. 7). However, the propagating feature is not found in the lower layer, as shown in Fig. 10a.

6. Discussion

In the previous section, we have shown the characteristics of the time series of rainfall rates and the relationships between the rainfall rate by radar and large-scale fields. In this section we will discuss these relationships and their periods.

Firstly we have shown diurnal variations of the rainfall rates. The diurnal variation by radar in the sea area is significantly weaker than that in the land area. This result does not agree with Gray and Jacobson (1977).

Diurnal variation of precipitation over islands calculated from a 13-year average in the western trop-

ical Pacific was discussed by Gray and Jacobson (1977). They showed that diurnal cycle of precipitation in 'small islands', defined as more than 10 times smaller than Manus island, has a maximum in early morning. In 'large islands', being a few times smaller than Manus island, there is a maximum peak in the afternoon (14 h LST). Our results are not consistent with Gray and Jacobson's results, in that an early morning peak as in their diurnal cycle of 'small islands' is not clearly seen. However, the mid day peak of our diurnal cycle in the land area can be considered to coincide with their peak of 'large islands'. This maximum peak of raingauge data agrees well with Gray and Jacobson's results.

In their study, a significant early morning peak was found in their 'small islands' and was considered to be due to convection over the ocean. Early morning peaks were also found in Houze *et al.* (1981) over the sea around north Borneo in WMONEX.

Fig. 9. Lagged correlation between the zonal wind from GANAL and the rainfall rate. (a) Lagged correlation with the zonal wind at 850 hPa. (b) Lagged correlation with the zonal wind at 200 hPa. Same as Fig. 8, except for the correlation with zonal wind.

Gray and Jacobson's results were from raingauge data, and Houze *et al.*'s results are from variation of radar echo area and cloud area by satellite data. Why we did not have such early morning peaks is quite a complicated problem. It might be due to the scale selection of the calculating area or the method of obtaining data. On the other hand, in the land area, a maximum peak was found at mid day in our study, which agreed well with Gray and Jacobson's study, although the peaks in our results are one or two hours earlier than in their studies. In WMONEX, the land area had a maximum peak at midnight. However, that was caused by very strong larger scale diurnal variations found around Borneo.

In the spectrum of the rainfall rates in the sea and the land area (Fig. 4), some significant peaks were found. Spectrum peaks in the sea area have a lower spectral density at a 1-day period than the land area, but a higher spectral density in the 1.5 to 2-day periods and especially at longer than 15-day periods for the middle layer. Since the 1-day period variation was considered to be caused by the radiational convection over the island, it is expected that variation in the sea area is less dominated by diur-

nal variation and that longer variations will stand out. Therefore we will discuss the variation of the rainfall rates in the sea area to evaluate the relationship between mesoscale rainfalls and large-scale fields. Because these periods are longer than 1 day, they are expected to connect large-scale phenomena.

Variations of CAPE and the mixing ratio could play an important rôle in the recovery time of the atmospheric thermodynamic potential energy in the atmospheric mixing layer. Distinct peaks are found in the cross spectrum between CAPE and the rainfall rates (Fig. 6) for periods of 1.3, 4 and 8 to 10 days. The peaks at 4 and 8 days are also found in the spectrum of CAPE (not shown). That probably shows that the time scale of supply and consumption of atmospheric potential energy is about 4 or 8 days. However, the time scale is not a predominant one concerning the convection around Manus. The peaks at these periods in the spectrum of the rainfall rates are lower than the other peaks, and the correlation coefficients between CAPE and the rainfall rates are quite small (only correlations of the middle layer are over the significant level).

So, how could the connection between local rain-

Fig. 10. Lagged correlation between the mixing ratio from GANAL and the rainfall rate (a) Lagged correlation with the mixing ratio at 1000 hPa. (b) Lagged correlation with the mixing ratio at 500 hPa. Same as Fig. 8, except for the correlation with the mixing ratio.

fall and large-scale fields appear? In Fig. 4, several dominant spectrum peaks were found with 1 to 1.5-days and 3- to 5-days period. A 3 to 5-day oscillation period was well represented by Takayabu and Nitta (1992). In their study, the 3- to 5-day oscillation period was very weak in the southern hemisphere west of 150E. The classical easterly wave (tropical depression type in their paper) is active only in the northern hemisphere in the western Pacific, and a mixed Rossby-gravity wave type disturbance was distributed east of 150E. This is consistent with our result that the 3- to 5-day period peaks are not so high. Takayabu and Nitta related the 3- to 5-day oscillations to the westward propagation of cloud clusters in the latitude of 5N to 10N around this longitude. So we also calculated the lagged correlation between the rainfall rates and the divergence at the latitude of 5N to 10N from GANAL data (not shown). The figure shows a westward propagation of correlation, considered to correspond to westward-propagating cloud clusters in our observation period. Further, we calculated a lagged correlation between the meridional wind at various latitudes and rainfall rates (not shown). In these longitude-lag

time diagrams, westward-propagating features were also found. However, we cannot find any significant correlations, even in these relationships.

In GATE, Reeves *et al.* (1979) analyzed the relationship between precipitation rate estimated from radar data and large-scale variables. In their study, convection observed by ship-borne radar is closely connected with the Easterly Wave or the large-scale upward motion. However, we could not find such a close connection in our study, which might be due to the differences in the atmospheric wave disturbances between the tropical Atlantic and the tropical Pacific ocean.

In addition to the several-days periods, longer than 30-days propagation was found in the lagged correlation between the rainfall rates and zonal wind (Fig. 9) and mixing ratio of middle troposphere (Fig. 10). Clear eastward propagation seen in these figures is considered to be an effect of the Madden-Julian oscillation. The phase relation between them was clearly shown in this study, such that when the zonal wind direction changes from easterly to westerly, a rainfall event occurs, or after a rainfall event the mid tropospheric mixing ratios increases.

Additionally, lagged correlations between the mixing ratio by GANAL and the rainfall rates do not always agree with the results found from the sounding data. Moreover, the mixing ratio of the lower layer of the troposphere from GANAL shows very complicated results. It is considered that the spatial resolution of the GANAL data was not enough to show the local change of the mixing ratio in the lower troposphere. However, in the middle troposphere, the time change of the mixing ratio was well represented.

Through our analysis, the correlation coefficients between the rainfall rates of the middle layer and indexes of large-scale atmospheric fields are greater than that of the lower layer. Further, most peaks of the middle layer in the land area show a higher spectral density than those of the lower layer. That probably shows that a deeper convection can have a closer connection with large-scale atmospheric variation.

7. Summary and conclusion

We examined the characteristics of rainfall rates calculated from x-band radar data and relationships between the rainfall rates and the large-scale field defined by GANAL and sounding data through lagged correlation analysis and spectral analysis. The following results were obtained.

Variation of the rainfall rates in the land area of Manus island was dominated by a 1-day cycle. On the other hand, the variation in the sea area around Manus island has several significant variation periods such as 1 day, and 1.5 to 2 days. Diurnal variation of the rainfall rates in the land area has a distinct peak in 1200 to 1300 LST, which agrees with the diurnal variation observed by raingauges inland of the island. The 1-day period peak in the sea area is lower than that of the land area in its spectral density.

Lagged correlation between CAPE and the rainfall rates in the sea area has a positive value for 2 days before a rainfall event, and sharply drops to negative values after a rainfall event for about 2 days. In the cross spectrum between them, 4 days and 8-to-10-days-period peaks are found. Such variation is not found in the lagged correlation against CAPE at other observation sites that were no more than several hundred kilometers from Manus island.

Lagged correlation between the mixing ratio of the middle and the upper troposphere obtained from the sounding data and the rainfall rates increases predominantly after a rainfall event and keeps its high value for a few days. Lagged correlation between the mixing ratio in the atmospheric mixing layer and the rainfall rates did not show such variation, but had a similar variation to the lagged correlation with CAPE.

Lagged correlation between divergence obtained

from GANAL and the rainfall rates showed no significant correlation.

Lagged correlation between zonal wind obtained from GANAL and the rainfall rates showed an eastward-propagating feature whose cycle was about 40 days. That variation can be considered as corresponding to the Madden-Julian oscillation. The maximum correlations are over the significant level of 95 percent confidence. The phase relation is such that, when lower tropospheric zonal wind changes its direction from easterly to westerly, a rainfall event occurs. A similar eastward-propagating feature is found in the relationship between the mixing ratio in the middle troposphere obtained from GANAL and the rainfall rates. The mixing ratio in this layer increased after a rainfall event. However, lagged correlation between the mixing ratio in the lower troposphere and the rainfall rates were very complicated and did not have a significant correlation.

Through the lagged correlation analysis and the spectral analysis, the correlation or spectral densities of the middle layer of the rainfall rates are larger than that of the lower layer.

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西部熱帯太平洋における降水現象の時空間変動と大規模場との関連

牛山朋来・佐藤晋介・竹内謙介

(北海道大学低温科学研究所)

TOGA-COARE IOP (Tropical Ocean and Global Atmosphere-Coupled Ocean Atmosphere Reserch Experiment Intensive Observation Phase) に観測されたデータを用いて、メソスケール降水現象と大規模場との関係について調べた。用いたデータは、パプアニューギニアマヌス島 (2S, 147E) で約2カ月間連続観測された x-band レーダーデータ、オメガゾンデデータ、および GANAL (気象庁客観解析データ) であ

る。レーダー観測データは、対流活動度の指標として用い、理解の簡便のため降水強度に変換した。そして、島の影響を評価するため陸上域と海上域に分けた。また、対流の強度を評価するため鉛直方向にも3つの層に分けた。これらのそれぞれの区域について降水強度を平均して時系列データを作成し、解析に用いた。

降水強度の日変化を調べた結果、陸上域では日中にピークを持つ強い日変化に支配されていた。これに対して海上域では、スペクトルには1日周期のピークが現れていたが、陸上域に比べ日変化はかなり弱かった。また、海上域では、1.5–2日、3–5日の周期のピークが陸上域に比べ強かった。

この海域の降水強度と大規模場との関係について調べるため、ラグ相関解析及びクロススペクトル解析を行った。CAPEと降水強度とのラグ相関から、CAPEは降水現象の2日前から上昇し、降水現象の直後に減少していた。また、東西風速または水蒸気混合比と降水強度とのラグ相関が、約40日周期で東方伝播しているのが見られた。これは、Madden-Julian oscillation (季節内変動) に該当すると考えられる。位相の関係は、東西風の風向が東から西に変わるときに降水現象が発生し、また降水現象の後、500 hPaの高度で、混合比が上昇した。この混合比の上昇は、オメガゾンデによるデータにも見られた。