An Intraseasonal Amplitude Modulation of the Short-term Tropical Disturbances over the Western Pacific

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Abstract

The intraseasonal change of the activities of the short-term tropical disturbances are investigated in terms of their amplitude modulation. It has been revealed that the amplitude modulation in the tropics bears a periodicity around 30 days. It was also found that the enhanced phase of the amplitude modulation is often accompanied by the clustered genesis and/or development of tropical cyclones. The space-time analysis of the amplitude modulation has shown that it consists of two characteristic modes. One is the eastward-propagating mode with zonal wavenumber 1. Another mode shows a westward propagation and zonal wavenumber 4 to 6 as a characteristic longitudinal scale. Both modes appear equally significant in leading to enhanced disturbance activity.

The large-scale circulation changes associated with the intraseasonal amplitude modulation are also investigated referring to the modulation over the tropical western Pacific. The composite analysis has revealed that the lower tropospheric westerly and the upper-level easterly are enhanced at the time of the enhanced activity of the tropical disturbances. The horizontal distribution of the circulation anomalies indicates that an intrusion of the low-level westerlies into the western Pacific takes place at this stage from the equatorial Indian Ocean through the South China Sea. This intrusion is also accompanied by enhanced cross-equatorial southerlies over the Indonesian region. In the upper levels, the intensification of the mid-Pacific trough is observed at the same stage.

1. Introduction

In recent years, a surge of interest in the 30–60 day period, intraseasonal variation has induced many investigations from various points of view. After the pioneering works by Madden and Julian (1971, 1972) which showed the eastward-moving, east-west circulation cell along the equator, Yasunari (1980, 1981) revealed the existence of the northward-moving circulation anomalies associated with the 30–40 day, active/break cycle of the Indian summer monsoon. Further investigations have followed, especially after the data set produced by the Global Weather Experiment (GWE) 1978–79 became available. Krishnamurti and Subrahmanyam (1982) illustrated a steady meridional propagation of a train of troughs and ridges which form near the equator and migrate northward across the Indian subcontinent. Lorenc (1984) analyzed the large-scale divergent wind field at 200 mb level during GWE year and showed that a 30–50 day period variation exists throughout the year. His study further revealed that the above variation is associated with an eastward-propagating wave with zonal

wavenumber 1 and this planetary-scale wave is coupled with the smaller-scale divergence bands propagating northward over the monsoon region.

In a series of intensive studies on the intraseasonal variation, T. Murakami *et al.* (1984) examined its structural features during the 1979 northern hemisphere summer over an extensive region, including both the Asian summer monsoon region and the western Pacific. They showed that the 40–50 day perturbations propagate northward and eastward over the monsoon region extending from 60°E to 150°E. In addition they also obtained an interesting result which showed that the activity of the short-term, synoptic-scale disturbances also changes with a period of 40–50 days. They discussed it in conjunction with the group velocity phenomena, stating that it is prominent mainly in the central monsoon region (10–20°N, 60–150°E). Nakazawa (1986) also found that the short-term variations in the outgoing longwave radiation (OLR) show an amplitude modulation with a period of 30–60 days. These phenomena are clearly indicative of the strong interaction between the short-term disturbances and the intraseasonal period variation which is likely due to the planetary-scale circulation changes.

Concerning the interaction mentioned above, it has been realized that the activity of tropical cyclogenesis also undergoes substantial intraseasonal changes. Gray (1978) discussed a "clustering" of the tropical cyclogenesis in which the active periods of 1–2 weeks are separated by 2–3 week inactive periods. In his study using OLR data, Nakazawa (1986) discussed the response of the clustering to 30–60 day intraseasonal variations. Their studies suggest that the large-scale circulation changes are crucial to the creation of favorable conditions for the tropical cyclogenesis. In fact, by using a rawinsonde composite technique, Love (1985) discussed how the winter hemisphere events influence the genesis of tropical cyclones in the summer hemisphere. However, the questions as to how these large-scale conditions materialize and how they behave in space and time are not fully understood. This paper aims to investigate these aspects in terms of the amplitude modulation of the short-term tropical disturbances and the associated large-scale circulation changes. In Section 2, we shall explain our method for analyzing the amplitude modulation. We shall discuss its space-time characteristics in Section 3. Section 4 will describe its association with the tropical cyclogenesis over the western Pacific and the spatial structure of the composited circulation anomalies.

2. Data and method of analysis

In order to investigate the atmospheric variations in the tropics, we have utilized the GWE level 3B data set produced by European Center for Medium-range Weather Forecasts (ECMWF). In the GWE year ranging from 1978 through 1979, an unprecedented amount of the observational data has been compiled in the global framework. This experiment was especially beneficial for the observational study in the tropics where data used to be very sparse. We have taken horizontal winds, geopotential height and humidity values from the above data set and converted the original 1.875° latitude-longitude grid interval into 2° . Variables we have deduced are divergence, relative vorticity and temperature. Temperature was derived from the geopotential height and humidity data using the hydrostatic relationship. The period of analysis ranges from April to November 1979 in which we can expect the major occurrence of the tropical cyclogenesis during the northern hemispheric summer.

As the first step to investigating the amplitude modulation of the short-term disturbances, we have examined the temporal variation of the meridional wind at 850 mb level along the tropical latitude. This quantity is presumed to reflect the intensity of synoptic-scale disturbances in the lower troposphere. We can also expect good quality data at the 850 mb level with the aid of the satellite cloud wind observations. Fig. 1 represents its 12-hourly

Fig. 1. Longitude-time cross section of the 850 mb meridional wind at 10 N. The contour interval is 5 m/s. Northerly winds are shaded.

longitude-time section along 10 N. Although no time filter was applied to this diagram, one can easily observe the dominance of short-term disturbances around 3- to 10 day period exist over most of the longitudes. The westward propagations appear especially clear over the tropical Pacific (from 120 E eastward to 100 W) and tropical Atlantic (from 60 eastward to 0 W).

The dominance of short-term disturbances in the tropics can be also verified in terms of their percentage variance. Fig. 2 represents the horizontal distribution of the 2.5–10 day percentage variance during April through November 1979. The percentage variances of this short-term period range are large over the tropical Pacific and the Atlantic Ocean near the equator. In these areas 2.5–10 day variations occupy more than a half of the total variance. The axes of their maxima are located roughly along 10 N during this northern hemispheric summer. Outside the tropics, one can also observe the large percentage variances in the middle latitudes of both hemispheres. They are presumably due to frequent passage of the synoptic-scale cyclones/anticyclones during the same season. The separation between the tropical maxima and the mid-latitudinal ones reflects the persistent prevalence of the subtropical

Fig. 2. Horizontal distribution of percentage variance of the 2.5-10 day period, meridional wind variation at 850 mb level during April through November 1979. The shaded area denotes values of more than 50 %. Contours (interval: 10 %) are drawn within this area.

anticyclones. In the following discussions we shall focus on the tropical situation mainly around 10°N.

In the above discussion we have seen that the 2.5-10 day variation accounts for the major portion of the total variance. In order to examine the behavior of this short-term variation more closely, a recursive bandpass filter designed by Murakami (1979) was applied to pick up the above periodicity. Fig. 3 depicts the same longitude-time section as Fig. 1 except for the 2.5-10 day bandpass-filtered meridional wind anomalies. This diagram clearly shows a prominent westward propagation of the 2.5-10 day period disturbances in the tropics. In addition, one can also infer that their longitudinal wavelength is around 30° to 40°, by taking a look at the horizontal interval between the anomalies. This situation agrees with Nitta *et al.* (1985)'s comprehensive analysis of the tropical lower tropospheric disturbances during the same season. In their study it was reported that the spectral peaks around 3-4 days and 6 days over the tropical oceans are associated with the westward-moving disturbances whose horizontal scale measures zonal wavenumber 10 to 12. It was also shown that the activity of short-term disturbances is greater in the northern equatorial region than in the southern equatorial region.

The interesting aspect one can observe in Fig. 3 is the fact that the clustered developments of the short-term disturbances take place with much longer time scale than the individual disturbance. T. Murakami *et al.* (1984) also noted this aspect and referred to it as a group velocity phenomenon. They pointed out that the clustered development tends to

Fig. 3. Same as Fig. 1 except for the 2.5-10 day bandpass-filtered anomalies. The contour interval is 2 m/s. Negative (northerly) anomalies are shaded.

Fig. 4. Schematic diagram of the amplitude modulation. $v(t)$ represents the time series of the filtered short-term variation and T_s denotes the period of average in Eq. (1). $AMP(t)$ represents the resultant time series of the amplitude.

occur with the 40–50 day, intraseasonal time scale and the area of development tends to move eastward. They have also discussed whether the above phenomena would be peculiar to the monsoon region (60–150°E). However, in Fig. 3 it can be observed that the clustered development also takes place over the eastern Pacific (180–90°W) and the Atlantic (60–0°W). Moreover, when one examines this diagram closely, it emerges that the development mentioned above occurs to various extents, ranging from moderate to intensive ones. These findings have led us to look into the phenomenon in the broader term, i.e. in terms of the amplitude modulation of the short-term disturbances.

In order to investigate the above-mentioned amplitude modulation objectively, we have defined a quantity $AMP(t)$ based on the 2.5–10 day bandpass-filtered time series $v(t)$ as follows;

$$AMP(t) = \sqrt{\int_{t-T_s/2}^{t+T_s/2} v(\tau)^2 d\tau / T_s},$$

where T_s is supposed to represent the period of one cycle of the filtered oscillation. Therefore $AMP(t)$ is the root mean square of $v(t)$ averaged over its one cycle. Fig. 4 schematically depicts the definition of $AMP(t)$. It can be seen that the $AMP(t)$ also represents the variation of the envelope of $v(t)$. We have taken this quantity as a measure of the slowly-varying amplitude of the short-term variation whose characteristic period is represented by T_s . In the present study, $v(t)$ represents the 2.5–10 day bandpass-filtered, meridional wind anomalies at 850 mb level and T_s was specified as 6 days. In the following section, we shall investigate the long-

Fig. 5. Longitude-time section of the amplitude $AMP(t)$ averaged over 6°N–16°N. The time-mean value is subtracted for each longitude. The contour interval is 0.2 m/s and negative anomalies are shaded. Tracks of tropical cyclones are also shown by thick lines.

term amplitude modulation of the tropical disturbances by analyzing the space-time characteristic of $AMP(t)$.

3. Space-time characteristics of the amplitude modulation

Based on the algorithm mentioned in the previous section, we have calculated the time series of $AMP(t)$ for each grid point. Fig. 5 represents a longitude-time section of the AMP deviations from the time-mean values averaged over 6°N to 16°N. The existence of tropical cyclones (maximum wind speed exceeding 17 m/s) are also denoted by thick solid lines. This latitudinal belt runs through the areas where short-term tropical disturbances show major contributions as we have seen previously in Fig. 2. Variations of the AMP deviation are large over the western Pacific, especially over the longitudes ranging from 120°E through 150°E. It means that the area is subject to intensive amplitude modulation. Relatively large amplitude modulations can also be observed over the eastern Pacific (120–100°W) and

Fig. 6. Space-time spectrum of the amplitude $AMP(t)$ averaged over 6 N–16 N. Spectral densities multiplied by frequency are shown as a function of the period and zonal wavenumber. The contour interval is $5 \cdot 10^{-5} \text{ m}^2/\text{s}^3$.

over the Atlantic (60–20 W). They show a typically intraseasonal time scale of about a one month period. It is interesting to see that these areas coincide with the ones where frequent developments of the tropical cyclones are observed. Furthermore, one can observe in this diagram that almost all the development of tropical cyclones occur during the period when AMP deviations show positive anomalies. It means that the enhanced phase of the amplitude modulation also denotes the favorable period for the genesis and/or development of tropical cyclones. This point will be elaborated further in the following section.

As for the longitudinal phase propagation of the amplitude modulation, no dominant tendency appears in Fig. 5 for eastward- or westward propagations. Instead, it turned out that the diagram represents the mixed situation of both westward- and eastward propagations associated with different horizontal scales. This conclusion was obtained by performing the space-time spectral analysis designed by Hayashi (1977) on the AMP deviations shown in the same diagram. Fig. 6 represents the resultant distribution of the space-time spectra. The distribution shows two major spectral peaks which constitute the actual variation of AMP. One noticeable peak appears in the eastward-moving regime, being associated with the zonal wavenumber 1 of about a 45 day period. Another major power can be seen in the westward-moving regime along with zonal

wavenumber 4–6 components of about a 30 day period. These results indicate that the amplitude modulation along the tropical belt comprises two components which propagate in opposite directions with different zonal wavenumbers. They bear a similar quasi-monthly intraseasonal time scale, though each peak shows the maximum value at a slightly different periodicity. It is clear that both components should be taken into account when we investigate the quasi-monthly variation present in the amplitude modulation over the tropics.

This eastward-moving component of the amplitude modulations is in a remarkable agreement with 30–60 day intraseasonal oscillation mentioned in the Introduction. T. Murakami *et al.* (1984) discussed possible influences of the transient disturbances on the intensification of 30–60 day oscillation of the monsoon westerlies. The above result may support T. Murakami's discussions.

The co-existence of two components can be demonstrated clearly when we apply a quasi-monthly (20–40 day) bandpass filter to the time series of AMP and pick up characteristic wavenumbers. Fig. 7 exhibits a longitude-time section of the bandpass-filtered AMP anomalies. As we have seen in the previous Fig. 5, large amplitudes of the 20–40 day oscillation take place over the western Pacific (120–150 E), eastern Pacific (120–100 W) and the Atlantic (60–20 W). One can see that the 20–40 day mode reproduces the original variation of AMP,

Fig. 7. Same as Fig. 5 except for the 20–40 day bandpass-filtered anomalies.

though the time filtering tends to make the variation more sinusoidal. However, neither this figure nor the previous Fig. 5 shows any dominant tendency of the longitudinal phase propagation. That tendency emerges when we pick up the components due to zonal wavenumber 1 and wavenumbers 4 to 6 according to the results of the spectral analysis mentioned above.

Figures 8a and b illustrate the resultant longitude-time sections for the components with zonal wavenumber 1 and combined wavenumbers 4–6, respectively. Both diagrams reveal contrasting behavior within the quasi-monthly amplitude modulation as expected from the results of the space-time spectral analysis. In Fig. 8a one can observe the tendency of the eastward propagation for zonal wavenumber 1, while Fig. 8b shows a westward propagation for wavenumber 4–6. These tendencies appear throughout the period of our analysis though there are some occasional interruptions. Fig. 8c represents the reproduced 20–40 day oscillation of AMP anomalies which is composed of two components exhibited in Figs. 8a and 8b. When one compares this diagram with Fig. 7, one can observe good agreement between the two variations, though the amplitudes in Fig. 8c are somewhat moderated due to the elimination of small horizontal scale components.

Fig. 8. Same as Fig. 7 except for the component due to the zonal wavenumber 1 (a), the component due to the combined wavenumbers 4 to 6, (b) and the reproduced variation composed of wavenumbers 1, 4, 5 and 6(c). The contour interval is 0.2 m/s. Negative values are shaded. Thick lines denote the tracks of tropical cyclones.

This agreement indicates further that the two variations in Figs. 8a and 8b represent the major modes which account for the actual amplitude modulation shown in Fig. 5 previously. Furthermore, the thick lines in Fig. 8c reveal that the genesis and/or development of the tropical cyclones occur when the composed oscillation shows positive anomalies. In particular, it seems that the favorable period for the above genesis and/or development is phase-locked to the time when both components in Figs. 8a and 8b show positive anomalies.

Figures 8 also shows that the quasi-monthly amplitude modulations have maximum power in Northern Hemisphere summer. Space-time spectral analyses at different latitudes (not shown) indicate that spectral power of the quasi-monthly oscillation becomes maximum at about 10°N, where the percent variance of the short-term variations of meridional winds as seen in Fig. 2 is also large. From these seasonal and latitudinal dependences it is found that actual periods of the amplitude modulations roughly

Fig. 8. (continued)

agree with those of tropical cyclones.

Through the results of the analysis discussed above, it emerges that the amplitude modulation of the short-term tropical disturbances has definite characteristic space and time scales. As for its time scale, the space-time spectrum has shown the characteristic quasi-monthly periodicity which is composed of two different horizontal modes. What draws our interest is that the same characteristic time scale also appears to regulate the activity of the genesis and/or development of tropical cyclones. In the following section, we shall investigate this aspect by looking into the situation over the most active region of the tropical cyclogenesis, *i.e.* over the tropical western Pacific.

4. Regional characteristics over the western Pacific

4.1 Relationship with tropical cyclogenesis

In order to investigate the relationship between the amplitude modulation and the tropical cyclogenesis, a time series of areally averaged values of AMP was compiled. The averaging area ranges from 120°E to 150°E in longitude and from 6°N to 16°N in latitude. This area represents the most active region of the tropical cyclogenesis within the western Pacific. We have also seen in the previous Fig. 5 that the area shows the large variation of $AMP(t)$. Hereafter

it will be referred to as the reference area.

The upper diagram in Fig. 9 represents the 12-hourly time series of AMP deviations from the time-mean value over the reference area. This time series clearly exhibits the existence of the quasi-monthly periodicity in the amplitude modulation in accordance with the results of our spectral analysis. In fact the 20–40 day bandpass-filtered anomalies in the lower diagram of Fig. 9 show an excellent agreement with the variation in the upper diagram. The thick bars in the lower diagram denote the period when tropical cyclones are situated within the reference area. There are nine such occasions during our period of analysis and all cases show in-situ development from the intensity of tropical depression within the reference area. When we compare these thick bars with the bandpass-filtered time series, a remarkable coincidence can be easily observed between the bars and the enhanced (positive) peaks of the amplitude modulation. On all such occasions, the thick bar appears close to the positive peak of the 20–40 day bandpass-filtered AMP anomalies shown in the lower diagram. It indicates that the activity of the tropical cyclogenesis is strongly regulated by the 20–40 day time scale. Considering that each thick bar in the diagram does not necessarily represent an individual tropical cyclogenesis, the amplitude modulation exhibited in this diagram

Fig. 9. Time series of the AMP deviations from the time-mean value averaged over the reference area (upper) and its 20–40 day bandpass-filtered anomalies (lower). The thick bar represents the period when tropical cyclones exist in the reference area.

appears to be a good measure of the favorable period of the clustered genesis and/or development of tropical cyclones.

In his comprehensive review, Gray (1978) pointed that the cyclones tend to cluster in time and space. He mentioned, “One often observes 5–15 cyclones about the globe within 1–2 weeks, separated by 2–3 week periods when there is very little cyclone activity”. Although he discussed the phenomenon from the global viewpoint, our results presented above reveal that the clustering also occur as a regional phenomenon with a quasi-monthly time scale. As he also discussed in the same work, it is likely that cyclones are a result of the larger-scale general circulation changes in the tropical atmosphere. In the following subsections, we shall discuss this aspect in terms of the large-scale atmospheric anomalies associated with the 20–40 day amplitude modulation over the western Pacific.

4.2 Vertical structure of the associated atmospheric anomalies

In this subsection, we shall examine the vertical structure of the wind-, temperature- and moisture anomalies associated with the amplitude modulation over the reference area. Fig. 10 represents the 12-hourly time-height section of the areally averaged zonal wind anomalies over the reference area. The thick bars denote the period of tropical cyclones in the same manner as the previous Fig. 9. The temporal variation in this diagram shows the existence of the monthly-scale, intraseasonal variation in addition to the shorter-term, day-to-day variations. Our first interest is to examine what kind of vertical structure would appear in the zonal wind anomalies in association with the 20–40 day amplitude modulation over the same area. Although no time filter except for the subtraction of the time-mean values was applied to this diagram, one may be able to observe the tendency that the low-level westerlies increase (or easterlies decrease) during the period of tropical cyclones. The opposite tendency seems to appear in the upper levels. In fact, these features appeared more clearly when we applied the 20–40 day bandpass filter to the same diagram. In the following part of this subsection, we shall exhibit the results by means of the composite analysis.

The composite in this study was performed with reference to the bandpass-filtered amplitude modulation shown previously in Fig. 9. We have divided each cycle of the filtered variation into eight categories. Categories 1 and 5 are assigned to the times when the AMP anomaly reaches the minimum and the maximum, respectively. Category 3 denotes the transition from negative anomalies to positive ones and Category 7 stands for the opposite transition. Categories 2, 4, 6 and 8 are assigned to the intermediate times. Since we have divided a quasi-monthly (~30 day) oscillation into eight, the time interval between each category roughly corresponds to 4 days. All other time series of the atmospheric variables averaged over the reference area were bandpass-filtered in the same manner and the composites were made referring to above categories.

We examined statistical significance for all composite fields corresponding to Figs. 11–18, following Livezey and Chen (1983), Lau and Chan (1983), and T. Murakami (1987). A common confidence level of 95 % is used for testing local and global significance. To test global significance we made 400 Monte Carlo experiments. It turned out that all composite fields tested are globally significant at the 95 % confidence level.

Figure 11 represents the category-height section of the composited zonal- and meridional wind anomalies in the upper and lower diagrams, respectively. Both diagrams reveal that the associated wind anomalies vary out of phase between the lower- and

Fig. 10. Time-height section of the zonal wind anomalies averaged over the reference area. Time-mean values are subtracted for each level. The contour interval is 2 m/s and easterly anomalies are shaded. Thick bars at the top denote the periods when tropical cyclones exist within the reference area.

the upper troposphere. On the other hand, one can see that the phase relationship between these two wind components is nearly in phase at the same level. The maximum anomalies in both components appear at Categories 1 and 5, *i.e.* when the amplitude modulation reaches the minimum and the maximum activities, respectively. The levels of maxima are located around the 200- and 850 mb levels for the zonal wind. They appear around 150 mb and near the surface for the meridional wind. The zonal wind component at Category 5 shows negative (easterly) anomalies in the upper troposphere and positive (westerly) anomalies in the low levels. The meridional wind also shows negative (northerly) anomalies in the upper levels and the positive (southerly) anomalies in the lower levels.

These results indicate that the south-westerly wind is intensified in the lower troposphere at the time when the short-term disturbances become active. The north-easterly wind is intensified in the upper troposphere at the same time. When one takes into account our previous results on the relationship between the tropical cyclogenesis and the amplitude modulation, it can be further inferred that the above composited wind structure characterizes the active period of the tropical cyclogenesis over the western Pacific. These features are also very similar to the ones discussed by Love (1985). In his analysis of rawinsonde composite, it is shown that the westerly to south-westerly winds are strong in the lower levels over the equatorial western Pacific prior to the tropical cyclogenesis. He showed that

the low latitude, upper-level easterlies are above average at the same stage. This agreement also seems to support our inference. The opposite wind structure takes place at Category 1 when the tropical cyclone activity is suppressed.

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The composited structure of the divergence and vorticity anomalies are shown in the upper and the lower diagrams of Fig. 12, respectively. The similar out-of phase relationships between the upper and lower levels also appear in both diagrams though the depth of the low-level divergence/convergence

Fig. 11. Category-height section of the composited anomalies for zonal wind (upper) and meridional wind (lower) averaged over the reference area. Negative anomalies are shaded. The contour intervals are 0.5 m/s and 0.2 m/s for the upper and lower diagrams, respectively.

appears to be quite shallow. What is characteristic in these diagrams is the fact that the maximum/minimum anomalies take place in between Categories 1 and 5. By comparing this variation with the previous figure, it can be observed that the vorticity anomaly reaches the maximum or minimum close to the time when the zonal- and meridional wind anomalies change sign. The vorticity anomalies in the lower diagram reveal that the positive (cyclonic) vorticity in the lower troposphere is most enhanced around Category 3 to 4, *i.e.* about 1.5 categories (~ 6 days) before Category 5. In the upper troposphere, the negative (anticyclonic) vorticity is enhanced at the same time. The similar timing can be also observed in the low-level convergence and the upper-level divergence shown in the upper diagram of Fig. 12.

These results indicate that the large-scale wind

Fig. 12. Same as Fig. 11 except for divergence (upper) and vorticity (lower). The contour intervals are $2 \times 10^{-7} \text{ s}^{-1}$ and $5 \times 10^{-7} \text{ s}^{-1}$ for the upper and lower diagrams, respectively.

field in the lower troposphere is most cyclonic and convergent at the stage when the activity of the short-term disturbances is increasing. In their efforts to predict the tropical cyclone formation, Perone and Lowe (1986) suggested that the low-level (900 mb) vorticity is a good predictor for the formation of tropical storms about 24 to 72 hours after. Our result seems also to have picked up a similar precursory sign in terms of the intraseasonal circulation changes. This feature further implies that the atmospheric structure obtained above is due to a system different from the short-term disturbances themselves, because short-term disturbances are supposed to reach their maximum amplitude at Category 5. One can also see that the above structure represents the system whose horizontal scale is much greater than the one associated with the tropical cyclones or easterly waves, by taking into account the longitudinal extent of the reference area.

The thermal structures associated with the quasi-

Fig. 13. Same as Fig. 11 except for temperature (upper) and equivalent potential temperature (lower). The contour intervals are 0.1 deg. and 0.2 deg. for the upper and lower diagrams, respectively.

monthly atmospheric change are exhibited in Fig. 13 in terms of the potential- and equivalent potential temperature anomalies. The potential temperature shows a nearly in-phase relationship throughout the troposphere below 150 mb level except for the lowermost layers below 850 mb. The warmest anomalies take place in the upper troposphere maximum around 200- to 250 mb level through Category 4 and 5. This timing nearly coincides with the maximum activity of the amplitude modulation. A similar behavior can be observed in the anomalies of the equivalent potential temperature shown in the lower diagram. This diagram reveals that the maximum positive anomaly occurs in the middle troposphere around 500 mb level through Category 4 and 5. Since the increase of the equivalent potential temperature includes the effect of the moisture increase, anomalies in the lower diagram indicate that the atmospheric moisture is likely to increase at this stage. It is especially true in the lower tro-

Fig. 14. Composited variation of the 20-40 day bandpass-filtered anomalies of the convection index averaged over the reference area.

posphere below 500 mb level where the significant increase of the equivalent potential temperature can be seen around Category 5, in contrast with the relatively minor increase of the potential temperature. In fact, it has been also confirmed that the variation of the composited moisture anomalies (not shown) closely follows that of equivalent potential temperature in the lower troposphere.

The above composite of thermal anomalies indicates that the lower troposphere becomes moist and the upper troposphere experiences warming around or shortly before Category 5. This suggests that the large-scale convective activity is also enhanced at this stage. Fig. 14 exhibits a composited variation of anomalies of the convection index devised by M. Murakami (1983, 1984). As discussed in his studies, the convection index expresses the degree of the mean cloud-top penetration of convective clouds in the upper troposphere above 400 mb level. For more detailed discussions, readers are guided to the above articles. In this study, the 20-40 day bandpass-filtered anomalies of the convection index were averaged over the reference area and the composite analysis was performed in the same manner as we have done to the variables discussed above. This composite is statistically (locally) significant at 95% confidence level. The composited one cycle in Fig. 14 shows that the positive anomalies take place from Category 3 through 5, indicating that the large-scale convective activity is enhanced during this period. One can see that the most enhanced convective activity occurs around Category 4. Considering these results with the previous ones

Fig. 15. Horizontal distributions of the composite wind anomalies at 200 mb level (upper) and 850 mb level (lower) at Category 5. The reference area is shown by a solid rectangle.

on the vorticity and divergence, one can get the sequence that the most enhanced convective activity is preceded by the enhanced cyclonic vorticity in the lower troposphere and the enhanced convergence near the surface. The maximum activity of the short-term disturbances (Category 5) measured by the amplitude of the meridional wind oscillation (AMP) closely follows the enhancement of the large-scale convective activity. In the next subsection, we shall see what kind of the horizontal circulation is associated with the atmospheric changes discussed above.

4.3 Horizontal circulation anomalies

In this subsection, we shall discuss the horizontal distribution of the composited wind anomalies over the western Pacific and its neighborhood, *i.e.* over the region ranging from 60°E to 150°W in longitude and from 30°S to 40°N in latitude. We have taken 200 mb and 850 mb levels as the representative levels of the upper- and the lower troposphere, respectively. The composite was performed in the same manner as we have done in the previous subsection. Fig. 15 shows the resultant distributions of the composited wind anomalies in Category 5. The rectan-

gle within the diagram denotes the reference area defined before. As discussed earlier, this category represents the most active stage of the short-term disturbances in the reference area. At 200 mb level shown in the upper diagram, one can see that the north-easterly wind anomalies are dominant over the reference area. It is in accordance with our previous discussion on Fig. 11. In addition, this diagram reveals the existence of the large-scale anticyclonic circulation to the north of the reference area. Its center is located over the East China Sea, indicating that the intensity of the upper-level, summer anticyclone is intensified off the east coast of Asian continent. Another notable feature is the intensification of cyclonic circulation near the central Pacific, roughly along 150°E to 180°E meridian. Considering that the so-called mid-Pacific trough is often observed around these longitudes, our results indicate that the mid-Pacific trough is also intensified at this stage.

The composited circulation anomalies at 850 mb level are shown in the lower diagram of Fig. 15. At this level, marked westerly- to southwesterly anomalies appear over the reference area. The intensification of the westerly component can be observed over a wide longitudinal extent through the South China Sea and the equatorial Indian Ocean. It is interesting that the distribution of the wind anomalies over these regions appears to indicate the enhanced intrusion of the westerlies into the western Pacific. At this stage, one can also observe the intensification of the cross-equatorial southerlies over the South China Sea through the Indonesian longitudes. To the north of the reference area, anomalies show the enhancement of the cyclonic circulation whose center is located in the East China Sea. By comparing both diagrams of this figure, one can see that there exists the out-of-phase relationship between the circulation changes in the upper troposphere and the lower levels. It is especially clear over the western Pacific, including the East and the South China Sea. The three-dimensional configuration of wind anomalies in the study bears some similarity to the one discussed by McBride and Zehr (1981). In their composite referring to the pre-tropical storm disturbances, they showed that those systems are surrounded by the very large cyclonic circulation in the lower levels and anticyclonic circulation in the upper levels. Although our composite refers to the areally averaged amplitude modulation rather than the individual storm center, our results have also shown the large-scale cyclonic- and anticyclonic circulation anomalies in the lower- and upper levels, respectively. In addition our results have shown that these circulation anomalies influence the wide area over the western Pacific.

As we have discussed earlier, Category 5 exhibited in Fig. 15 corresponds to the favorable period of

Fig. 16. Horizontal distributions of the composite wind anomalies at 850 mb level from Category 1 through Category 4.

the genesis and/or development of tropical cyclones. However, when one observes the horizontal extent of the major circulation changes described above, it can be easily seen that their characteristic scale is far more greater than the ones associated with the individual cyclones. This aspect verifies our previous discussion that the atmospheric changes associated with the quasi-monthly amplitude modulation is due to the system different from the short-term disturbances themselves. As stated by McBride and Zehr (1981), it appears that genesis occurs when an organized tropical cluster or its corresponding tropical disturbance exists in a favorable large-scale environment.

The systematic, large-scale circulation changes also appear through other categories of the composite which we shall discuss in the following. Fig. 16 represents the temporal evolution of the circulation anomalies at 850 mb level, starting from the minimum stage (Category 1) of the amplitude modulation. At Category 1, the opposite situation from Category 5 in the previous figure appears over the area of our analysis. The western Pacific close to the Philippines is under the large-scale anticyclonic circulation. However, when one examines the equatorial area closely, one can observe the weak cyclonic

circulation cell around 160°E just to the north of the equator. The sequential diagrams from Category 2 through 4 reveal that the cyclonic cell moves northwestward accompanied with westerly wind anomalies to its south. The phase speed of its northwestward propagation is approximately 4 m/s.

Another interesting sequence appears over the South Indian Ocean. Through the categories exhibited in this figure, one can observe that the westerlies are first intensified along 30°S and then approach toward the equator. It is associated with the deepening of the large-scale trough over the South Indian Ocean to the west of Australia. It can be also seen that the cross-equatorial southerlies appear over the Indonesian longitudes as the trough deepens and expands toward the equator. This sequence seems to be a manifestation of the cross-equatorial influence of the winter hemisphere. In his study of the cross-equatorial interaction, Love (1985) discussed that a cold surge in the winter hemisphere propagates equatorward prior to the tropical cyclogenesis in the summer hemisphere. Our study has revealed that the deepening and the equatorward expansion of the subtropical trough occur to the west of Australia with a quasi-monthly characteristic time scale. The correspondence between the two analyses may

Fig. 17. Same as Fig. 16 except for 200 mb level.

be indicative of such influences of the winter hemisphere. Nevertheless at present it is fair to say that further studies are needed to clarify the nature of cross-equatorial influences.

The temporal evolution of the circulation anomalies at the 200 mb level is exhibited in Fig. 17. The distribution of anomalies at Category 1 again constitute the nearly opposite situation from Category 5 shown in Fig. 15 previously. At this stage, the area around the East China Sea is covered with the large-scale cyclonic circulation and westerly wind anomalies prevail over the tropical western Pacific. The circulation along 150°E through 180°E meridian generally shows the anticyclonic anomalies, indicating the suppression of the mid-Pacific trough over the same area. As for the alternation of the zonal wind direction over our reference area to the east of the Philippines, it can be observed that the weak easterly anomalies already appear at Category 1 just to the north of the equator along 130°E to 160°E meridian. Through the sequence from Category 2 to 4, these easterlies are intensified and move northwestward. One can also observe that they are associated with the formation and the movement of the large-scale anticyclone to their north. Through the same sequence, the cyclonic cell over the East China Sea moves north-westward toward the inland area of

the Asian continent. Keeping pace with this movement, the westerlies around the Philippines also shift north-westward. In addition, one can also observe that a part of the westerlies show the tendency of the north-eastward propagation when one takes a look at the westerly regime initially situated over the Philippines at Category 1.

T. Murakami *et al.* (1984) discussed the north-eastward phase propagation of the 40–50 day, zonal wind perturbation at the 200 mb level over the western Pacific. According to their results, its characteristic zonal wavenumber is around 1 to 2. Although the periodicity we have picked up is slightly shorter than theirs, the north-eastward propagation noticed above seems to reflect the same intraseasonal disturbances. However, the existence of the north-westward propagation in our analysis indicates that there exists a different mode of the atmospheric variation from the one discussed by them. This mode also contributes to the north-westward movement of the cyclonic/anticyclonic cell relevant to the quasi-monthly amplitude modulation of the tropical disturbances.

When we compare the above sequence with the ones at the 850 mb level shown in the previous Fig. 16, we can see the good correspondence between the lower tropospheric circulation and the one in the up-

per troposphere are overlaid by the westerly (easterly) anomalies in the lower level and, in the tropics, the easterly (westerly) anomalies in the upper troposphere. The same relationship holds for the large-scale cyclonic/anticyclonic circulation cells in the tropical latitudes. By contrast, one can observe the tendency to an in-phase correspondence between the lower- and upper level circulation anomalies in the middle latitude poleward of 30 degrees. In any case, the systematic correspondence observed above seems to support the physical significance of our composite.

5. Concluding remarks

In this study, we have investigated an intraseasonal change of the activity of the short-term tropical disturbances in terms of their amplitude modulation. The analysis of the percentage variance has shown that the short-term (2.5–10 days) disturbances account for a major portion of the variance over the tropical oceans where we can observe frequent genesis of tropical cyclones. It has been also our interest to investigate the relationship between the above amplitude modulation and the clustered genesis of tropical cyclones discussed by Gray (1978) and others.

In order to analyze the amplitude modulation objectively, we have devised a method to measure a temporal variation of the amplitude by combining a time-filtering and a subsequent integration of the squared anomalies. The time series of the resultant quantity was taken into consideration as a measure of the slowly-varying amplitude of the short-term disturbances. In the present study, we have applied this method to the variation of the meridional wind at 850 mb level. The results of our analysis have revealed that a significant amplitude modulation does exist with a quasi-monthly periodicity over the tropical latitudes. It tends to occur intensely over the area of frequent tropical cyclogenesis. Moreover, it turned out that the enhanced phase of the amplitude modulation is strongly associated with the favorable period of the genesis and/or development of tropical cyclones.

The space-time behavior of the amplitude modulation was first examined by the method of spectral analysis. The results show that it consists of two characteristic modes. One is an eastward-propagating mode with zonal wavenumber 1. Another mode shows a westward propagation and zonal wavenumber 4 to 6 as a characteristic horizontal scale. These two modes appear equally significant in the actual amplitude modulation over the tropical latitudes. It further turned out that the favorable period of the tropical cyclogenesis tends to be phase-locked to the time when both modes show positive (enhanced) anomalies.

The large-scale circulation changes associated

with the above-mentioned intraseasonal amplitude modulation were also investigated over the tropical western Pacific by the method of composite analysis. Over this region, we have observed an intense, quasi-monthly amplitude modulation of the short-term tropical disturbances. The positive (enhanced) peak also agrees quite well with the favorable period of the tropical cyclogenesis over the same area. The composite analysis has revealed that the low-level westerly and the upper-level easterly are enhanced at the time of the enhanced activity of the short-term disturbances. The results also show the enhancement of the low-level southerly and the upper-level northerly at the same time.

The anomalies of divergence and vorticity associated with the above circulation change show a different behavior. The anomalous low-level convergence and the upper level divergence take place at the stage prior to the enhanced peak of the amplitude modulation. This timing coincides well with the maximum enhancement of the cyclonic- and the anticyclonic vorticities in the lower- and the upper tropospheres, respectively. Our results indicate that the large-scale circulation shows the enhancement of the low-level convergence and the cyclonic vorticity about 6 days before the maximum enhancement of short-term disturbances. These features also infer the favorable conditions for the large-scale enhancement of convective activity. In fact the composited thermal structures showed the upper-level warming and the tropospheric moistening following the enhancement of the convergence and the cyclonic vorticity mentioned above. The convection index derived from the satellite IR observation has confirmed that the intraseasonal variation of the large-scale convective activity also reaches its maximum. Considering these results over the tropical western Pacific, the sequence can be summarized as follows: The atmosphere first shows the convergent/cyclonic enhancement in the lower levels and divergent/anticyclonic anomalies in the upper levels. Then the enhancement of the large-scale convective activity, the associated upper-level warming and the tropospheric moistening follow. The maximum activity of the short-term disturbances appears immediately after this stage.

The large-scale, horizontal circulation anomalies accompanying the enhanced amplitude modulation were also examined over the wider area including the western Pacific. It turned out that the enhanced low-level westerlies and southerlies discussed above are a part of the large cyclonic circulation cell located to the north of the Philippines. The enhancement of the low-level westerlies to south-westerlies can be also observed over the equatorial Indian Ocean and the South China Sea along with the enhanced cross-equatorial southerlies over the Indonesian region. This configuration of anoma-

lies suggests that the intrusion of the westerly flow into the tropical western Pacific occurs along with the enhanced cross-equatorial flow from the southern hemisphere at the time of the enhanced activity of the short-term tropical disturbances. On the contrary, a large anticyclone appears in the upper levels over the same area. It brings the enhanced easterlies and northerlies over the tropical western Pacific. Another notable feature in the upper levels is the intensification of the large-scale trough close to the dateline. Considering its geographical location, this feature is indicative of the intensification of the mid-Pacific trough at the stage of the enhanced activity of short-term tropical disturbances.

The sequence of the composited map through the 1/2 cycle (from the minimum to the maximum) of the amplitude modulation has revealed the north-westward propagation of the cyclonic and anticyclonic cells from the equator toward the subtropics. In the lower levels, a cyclonic circulation cell first appears near the equator around 160°E and moves north-west toward the Philippines as the amplitude modulation over the western Pacific turns into the enhanced phase. In the upper troposphere, an anticyclonic circulation cell follows the similar track through the same stages. In addition, however, we have also picked up a sign of the north-eastward propagation especially in the upper-level, zonal wind anomalies. It appears relatively clear over the region ranging from the Philippines to the east of Japan and behaves similarly to the north-eastward-propagating mode discussed by T. Murakami *et al.* (1984).

Through the investigation summarized above, it emerged that the activity of the short-term tropical disturbances undergoes a substantial intraseasonal amplitude modulation. This amplitude modulation is also closely related to the clustering phenomenon of the tropical cyclogenesis. One of the interesting points is that the above amplitude modulation has its own characteristic modes. Our analysis of the atmospheric variation has revealed that the each mode of the amplitude modulation is associated with the characteristic circulation change. These circulation changes bear much greater horizontal scale than the individual tropical disturbances or cyclone. This fact indicates that there is a different atmospheric system which regulates the activity of short-term tropical disturbances and tropical cyclogenesis. The investigation of its dynamical implication is one of the major remaining problems. It is also of interest to investigate the global distribution of the amplitude modulation itself. We have already seen that the amplitude modulation consists of the planetary scale components and we know that the tropical oceans other than the western Pacific also experience the clustered cyclogenesis. Further investigation on the global behavior of the above amplitude

modulation may yield intriguing results on the inter-regional aspects of the tropical cyclogenesis.

In a recent study Nakazawa (1988) showed that 30–60 day global-scale intraseasonal variations consist of several “super cloud cluster” (a large-scale convection complex). Each super cloud cluster propagates eastward with a horizontal scale of several thousand kilometers and a time scale less than 10 days. The super cloud cluster is further decomposed into westward-moving synoptic-scale cloud cluster with a period of 1–2 days. Although our study started with the analysis of meridional winds in the lower troposphere, our results seem to have correspondences with Nakazawa’s results in which the OLR data were mostly used. The short-term variations (less than 10 days) of meridional winds seen in Fig. 3 may correspond to the westward-moving synoptic-scale cloud cluster discussed by Nakazawa, though the space-time structure of the short-term variations in Fig. 3 is a little larger. The amplitude modulation is enhanced over a whole domain where super cloud clusters are embedded. Since this domain has a horizontal scale of wavenumber 1, it suggests that if we make a wavenumber analysis of the amplitude modulation of super cloud clusters themselves, we would also get the results corresponding to the zonal wavenumber 1. Therefore the eastward-moving mode with zonal wavenumber 1 seen in Fig. 6 appears to be related to the enhancement of the super cloud clusters. More study is necessary to clarify the above conjecture.

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西太平洋における短周期熱帯擾乱の季節内振幅変調

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短周期熱帯擾乱の活動にみられる季節内変動を振幅変調の観点から調べた。熱帯における振幅変調は約30日の周期性を持つことが明らかになった。振幅変調の活発期は、しばしば群発的な熱帯低気圧の発生ないしは発達を伴うことも見いだされた。振幅変調の時空間解析は、この変動が二つの特徴的なモードから成っていることを示した。一つは東進する東西波数1のモードである。他の一つは西進し、東西波数4から6の特徴的な経度スケールを示す。両者のモードとも、擾乱の活動度の活発な状況を形成するうえで同等に重要である。

季節内振幅変調に伴う大規模な大気循環の変化についても、西太平洋熱帯域での変調を基準にして調べた。合成図による解析により、熱帯擾乱の活動度の活発期には下部対流圏の西風および上部対流圏の東風共に強化されていることが分かった。大気循環の偏差の水平分布によれば、この時期に赤道インド洋から南シナ海を通り西太平洋へ至る下層の西風の貫入が起こっている。この貫入はインドネシア地域での赤道越え南風に強化をも伴っている。上層においては、中部太平洋トラフの強化もこの時期に観測された。