Analysis of the Deep Convective Activity Over the Western Pacific and Southeast Asia

Part I: Diurnal Variation

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Abstract

Using the infrared (IR) irradiance data observed by GMS-1 geostationary satellite, it was tried to quantitize the deep convective activity in a manner which is physically more interpretable than the conventional areal average. This was partly accomplished by defining the intensity index of the deep convective clouds within the 1° longitude-latitude square mesh in the manner which takes the horizontal variation of the observed temperature and the vertical distribution of the atmospheric temperature into account.

Diurnal variation of the deep convective activity was investigated by using the above-mentioned intensity index for the period during northern hemispheric winter (December 1978–January 1979) and summer (July–August 1979). During northern winter, the amplitude of the diurnal variation is large over the Indonesian region and the northern Australia. Within this area it was found that there exist a distinct contrast in the phase of diurnal cycle between the land and the adjacent ocean. Composite analysis has revealed that the land shows the suppressed convective activity in the morning hours with the minimum around 9 o'clock local time. The convective activity is rapidly enhanced in the afternoon and reaches the maximum at around 18 o'clock local time. In contrast, the adjacent ocean clearly shows the enhancement of the convective clouds in the local morning and the suppressed convective activity in the afternoon and night.

During northern summer the intense diurnal variation was observed over the southern part of Tibetan Plateau. The amplitude is also large over the western Pacific to the east of Philippines. Composited diurnal cycle shows that there exists a contrast between the continent and the ocean, being similar to the one observed during northern winter. The continent and the large islands generally show the minimum convective activity around 9 o'clock in the local morning and the maximum enhancement around 18 o'clock in the evening. In contrast the oceanic area like western Pacific shows the maximum enhancement of the deep convective clouds around 6- to 9 o'clock local time in the morning and the suppressed activity in the afternoon. In addition to this land-ocean contrast, the evidences which suggest the regional effect on the diurnal variation are also discussed.

1. Introduction

Since the launch of the first meteorological satellite in 1960, it has been highly expected that the satellite observation would help us to overcome the difficulties in tropical meteorology due to the inadequate spatial coverage of radiosonde stations. This was especially the case over the tropical ocean where the genesis of typhoons and hurricanes take place. Satellite imagery has not only proved its usefulness in detecting these systems and tracking their movement, but many investigators have also achieved considerable success in quantitative studies by the use of imagery such as estimating the maximum wind velocity and the intensity of tropical cyclones. (Fritz et al., 1966; Timchalk et al., 1965; Dvorak, 1975 and others)

In the course of these investigations, satellite imagery has also revealed the various kinds of organized patterns of convective clouds in the tropics other than typhoons and hurricanes. Among them, the pattern called "cloud clusters" appears most frequently over the tropical oceans.
(ICSU-WMO Joint GARP Organizing Committee, 1970). Chang (1970) was one of the first investigators who looked into the systematic behavior of these clusters. He revealed that the cloud clusters over the tropical Pacific show systematic westward propagation and quasi-periodic appearance with the time interval around 4 days in his time-longitude section of satellite photographs. Reed and Recker (1971) further exhibited the close association of the passage of these clusters with the passage of westward-moving, synoptic-scale disturbances in the wind field over the tropical Pacific. Williams and Gray (1973) have performed an extensive composite analysis on the atmospheric circulation around cloud clusters by using both satellite imagery and upper air observations. All these studies have clearly exhibited the existence of the large-scale organization of individual cumulus cloud in the tropics.

The improvement of the capacity of high-speed computer has enabled us to compile satellite observations in the form of digital data. Almost all the meteorological satellites launched so far have observed infrared (IR) irradiance through the so-called “atmospheric window” (10.5 to 12.5*μm in wavelength). From the values of this IR irradiance, one can estimate the cloud-top temperature and infer its altitude. Madden et al. (1974) was among the first who utilized IR data in order to investigate the large-scale distribution of deep convective clouds in the tropics. Recently T. Murakami (1980a, b, c) has made comprehensive studies on the temporal and spatial behaviors of these IR values over the monsoonal region during northern hemispheric summer and winter.

Above studies have dealt with IR irradiance or equivalent black body temperature (\(T_{BB}\)) averaged over the sub-areas which are larger than individual convective clouds (e.g. 1° latitude-longitude squares in Madden et al., 1974). However, these areally averaged values raise some ambiguity when one try to infer the convective activity. Other than the cloud tops of convective clouds, they can be biased by the existence of stratus clouds and the averaged values can vary from case to case just due to the change of sea surface- or ground surface temperature. This is especially serious when one looks into the diurnal variation of convective activity over the land, because the ground temperature shows the intense diurnal variation. Although both Riehl and Miller (1978) and Short and Wallace (1980) have managed to show that the high-top clouds become enhanced in the evening over the land and enhanced in the morning over the sea by the use of orbiting NOAA satellite IR data, they could not go further to show the diurnal phase sequences of the convective activities over the land and the sea. Murakami (1979) used the areally averaged IR values obtained by the SMS-1 geostationary satellite during GATE (GARP Atlantic Tropical Experiment) in 1974. He showed that the convective activity becomes enhanced in the afternoon over the eastern half of the tropical Atlantic. However, the diurnal variation of the areally averaged IR values over the continent turned out to be largely contaminated by the change of ground temperature to the extent that they were not appropriate to use in the investigation of the diurnal convection.

Systematic investigation with satellite data on the diurnal convection over the land has been mainly carried out using satellite imagery in terms of cloud amount. For example, McGarry and Reed (1978) used the IR imagery obtained by the SMS-1 during GATE period and showed that the maximum convective cloudiness over the northwest Africa generally occurred near midnight. However, since their conclusion on the diurnal cycle is based on the cloud extent, it is not yet clear as to how the convective clouds grow in time and how high they penetrate in the upper troposphere in the sense of ensemble mean. The IR observation could bear such informations temperaturewise and it is highly desirable to extract them quantitatively both over the land and the sea.

In this study we have tried to make use of IR digital data in terms of \(T_{BB}\) and quantitize the activity of deep convective clouds in a manner which yields clearer interpretation than the simple areal average. Data and our method of analysis to accomplish above purpose are described in Section 2. Section 3 will show the resultant monthly mean distribution of convective activity during the northern winter of 1978-79 and northern summer of 1979. In Section 4 we shall discuss the characteristic features of the diurnal variation during both periods.

2. Data and method of analysis

In order to see the deep convective activity in the large-scale sense, we have used IR data obtained by the GMS-1 geostationary satellite which has been located at (0°, 140°E). We have taken two months of observations for both winter and
Fig. 1 Horizontal distribution of monthly mean values of $T_{BB}$ (upper) and $\sigma_B$ (lower) at each mesh during December 1978. Contours are drawn at every 10 K in $T_{BB}$ diagram and at every 2 K in $\sigma_B$ diagram. Values smaller than 260 K and larger than 10 K are shaded in the upper and lower diagrams, respectively.

Summer seasons. That is, December 1978 and January 1979 for northern hemispheric winter, and July to August 1979 for northern summer. During these periods we have edited 3-hourly IR observations (about 5 km in spatial resolution) in terms of $T_{BB}$ for every 1° longitude-latitude square mesh. The $T_{BB}$ values were compiled in such a way that it yielded temperature histogram along with their mean value and the standard deviation ($\sigma_B$) due to the spatial variance within the mesh.

Fig. 1 represents the resultant monthly mean distributions of the $T_{BB}$'s and $\sigma_B$'s during December 1978. This diagram also represents the area of analysis. Shaded area denotes the region where observed $T_{BB}$ is colder than 260 K (upper diagram) and $\sigma_B$ is larger than 10 K (lower diagram). In many investigations performed so far, the cold $T_{BB}$ has been considered to indicate the existence of high-top clouds. This inference seems plausible over the tropical ocean. In fact, the upper diagram of Fig. 1 shows the east-west oriented belt of cold $T_{BB}$'s to the south of the equator over the South Indian Ocean and over the tropical Pacific in agreement with the tropical cloud distribution deduced by Ramage et al. (1972) and Sadler et al. (1976). However, it becomes questionable when we examine much wider area including large islands and continents. For example, the cold mean $T_{BB}$'s appearing over Tibetan Plateau (30–40°N, 80–100°E) are likely due to the cold ground temperature rather than
the existence of high-top clouds. Its evidence can be seen in the distribution of $\sigma_B$'s shown in the lower diagram of Fig. 1. Usually the value of $\sigma_B$ is large when patches of clouds exist within the mesh. It is especially large when many cumuli exist in the mesh because of the spatial variation of their cloud tops and also due to the temperature contrasts between the clouds and surrounding clear areas. Over the Tibetan Plateau this diagram shows only small values of $\sigma_B$ compared with the ones in the tropics. This indicates that it is unlikely that the many convective clouds occur over the region at this time.

Somewhat contrasting situation appears over the northern Australia (10–15°S, 125–135°E). Comparing the upper- and the lower diagrams of Fig. 1, we can see that the above area shows large values of $\sigma_B$ whereas the mean values of $T_{BB}$ are not so cold. This fact seems to suggest that the warm ground surface temperature during southern hemispheric summer has biased the areally averaged $T_{BB}$ toward the higher values though there exist many cumuli over that region. These situations clearly indicate that we should be careful to interpret the areally averaged $T_{BB}$'s in relation to the convective activity. It also appears that the additional information on the spatial variance of $T_{BB}$'s can be useful to reduce the ambiguity as we have seen in Fig. 1.

The relationship between the cloud type and the value of $\sigma_B$ is schematically illustrated in Fig. 2. The value of the standard deviation $\sigma_B$ is quite large (more than 10°K for 1° square mesh) when many deep cumuli exist due to the distinct temperature contrast between high cloud tops and adjacent areas. The value becomes medium as the depth of cumuli becomes shallower and the distribution becomes sparse. $\sigma_B$ shows small value when the mesh is covered with stratiform cloud. It approaches zero when the mesh is clear and the surface temperature is nearly uniform. Comparing the daily distributions of $\sigma_B$ with the actual satellite imagery (visible), we have got an empirical criterion that the 1° square mesh with the value of the $\sigma_B$ larger than 5°K can be regarded as a convective area.

The above criterion was used in this study as a threshold to distinguish the convective meshes from the other ones. For those meshes picked up as convectively active, we have defined the intensity index of convection ($I_c$) in the following manner. First we have retrieved the atmospheric temperature at 400 mb ($T_{400}$) and tropopause level ($T_{tr}$) on each mesh from the GMS Standard Atmosphere (monthly climatological data set prepared by Meteorological Satellite Center in Japan). The monthly values of these temperatures were interpolated in time so that they can be applicable as the daily values. Since it was not possible to obtain the actual daily temperature at every mesh, these interpolated values were used as the plausible temperatures representing the 400 mb- and the tropopause level on the day to day basis. Then, at each observation time, we picked up the cloud tops which show the $T_{BB}$ values colder than $T_{400}$ and obtained their mean value ($T_{CBB}$) over the mesh. Using these three quantities, the intensity index $I_c$ can be defined as,

$$I_c = \frac{T_{CBB} - T_{400}}{T_{tr} - T_{400}} \times 10$$

For those meshes with $\sigma_B$ less than 5°K, we set $I_c = 0$.

Above formula means that, if all the cumuli are shallow and reach only up to 400 mb level, the value of $I_c$ is zero, because $T_{CBB} = T_{400}$ in that situation. On the other hand, if all the cumuli reach tropopause level, $I_c$ becomes 10. In this sense, the value of $I_c$ represents the mean degree of penetration of cloud tops above 400 mb level in the range from 0 to 10. As one can notice in the definition, the use of $I_c$ is expected to exclude the effect due to the surface temperature. It is also expected to be applicable at any place as well as any season by incorporating the atmospheric temperature of each case. Examination of $\sigma_B$ has made it possible to reduce the ambiguity between the situations of prevailing stratiform clouds and the prevailing cumuliform clouds. We shall use this $I_c$ as a measure of deep convective activity in the following sections.

3. Mean distribution of convective activities

3.1 Northern winter (December 1978–January 1979)

Figs. 3a and 3b represent the horizontal dis-
tributions of monthly mean values of $I_c$ during December 1978 and January 1979, respectively. Shaded area denotes the region where the mean values of $I_c$ is larger than 2.0. Following the definition in the previous section, these large values indicate the frequent occurrence of deep convective clouds over the area. During December 1978 shown in Fig. 3a, the major convective area is oriented roughly east-westward along and to the south of the equator. The latitudinal location of this zonally oriented convective area is in good agreement with the climatological location of ITCZ during northern winter discussed in Yoshino (1971). Within this convective belt,
we can pick up three major local areas which show large mean values of $I_c$. One is located over Indonesian Islands around Java Sea including Sumatra, Java and Borneo. To the east of this area we can see another convective area over New Guinea. Convective activity is also high over the South Pacific Ocean to the east of Solomon Islands (10°S, 160°E). T. Murakami and Sumi (1982) examined the wind field during the 1978-79 winter MONEX period and also showed that the low-level convergence took place over the range from Java Sea to equatorial South Pacific during December 1978.

In the mean distribution during January 1979 exhibited in Fig. 3b, we can still see the zonal orientation of the convectively active area. However, comparing with the distribution in Fig. 3a, it is clear that the distinct southward displacement occurred over the New Guinea—Australia region. During January 1979 the high convective activity appeared over the northernmost part of Australia whereas it was observed over New

Fig. 4 Same as Fig. 3 except for July 1979 (a) and August 1979 (b).
Guinea in December 1978. This southward shift of the monthly mean position corresponds to the fact that the onset of Australian monsoon took place at the end of December in 1978 as reported by McAvany et al. (1981). The convectively active area over the equatorial South Pacific also appears to be shifted southward in January 1979. This agrees with the wind field analysis by T. Murakami and Sumi (1982) who showed that the mean position of low-level convergence lay along 10°S in January 1979.

3.2 Northern summer (July–August 1979)

Figs. 4a and 4b represent the monthly mean distributions of $I_c$ during July and August 1979, respectively. The distribution of July shown in Fig. 4a has revealed that the intense activities of deep convection exist over the region extending from head Bay of Bengal up to the southeastern part of Tibetan Plateau. Convective activities are also intense over the South China Sea close to Philippines. From there one can see that a belt of convectively active area is oriented east-south-east and reaches the region close to Solomon Islands in the equatorial South Pacific. There is also an indication that the double convective belts exist on both sides of the equator to the east 160°E. It is of some interest to see that the convective activity is relatively weak over Indo-China to the east of Burmese mountains which range roughly along 100°E meridian. This region corresponds to the lee side of low-level monsoonal westerlies which were prevailing during most of the period of this month.

The distribution of August in Fig. 4b shows the persistent large convective activity over the head Bay of Bengal through the southeastern part of Tibetan Plateau. The area around Philippines and the one to the east of Solomon Islands also show the large convective activity during both July and August. However, comparing with the distribution in Fig. 4a, it can be seen that the latitudinal location of the major convective area over the western Pacific has shifted northward from July to August. To the east of 160°E it seems that the longitudinally oriented convective belt to the north of the equator was relatively intensified in August. Longitudinally oriented convective belt also appears just to the south of the equator over the South Indian Ocean. This belt seems to reflect the characteristic feature associated with the break monsoon over India, as it is well known that the major cloudiness is observed only over the foothills of Himalayas and to the south of India during the period of break monsoon. This break situation actually took place during the latter half of August 1979 as reported by Sikka and Grossman (1980).

4. Diurnal variation

4.1 Northern winter

During northern hemispheric winter, it has been often observed that the intense diurnal cycle of the convective activity appears over the Indonesian region. For example, Holland and Keenan (1980) demonstrated the distinctive change of the population of convective clouds between the local morning and afternoon over the Indonesian Islands by comparing the two satellite imageries corresponding to each time. Recently Johnson (1982) showed the existence of the diurnal cycle of convective activity over the coastal ocean close to Borneo in his investigation on the vertical motion of the meso-scale convective system.

Fig. 5 shows the temporal variation of 3-hourly $I_c$ and the variation of the histogram of the observed $T_{BB}$ in the upper and the lower diagrams, respectively. Both diagrams represent the variation over the mesh at (7°S, 108°E) located over Java Island for the period from 1 through 5 December 1978 as an example of the diurnal variation. Since the ordinate of the lower diagram denotes the observed temperature in the reverse order, the upper zero-contour in the diagram represents the minimum observed temperature and the lower one represents the maximum temperature. Comparing the upper- and the lower diagrams of this figure, one can see that the occurrence of the large values of $I_c$ well corresponds to the occurrence of the colder minimum temperature. In addition, one can also see that the temperature difference between the upper- and the lower zero-contour in the lower diagram is large when the value of $I_c$ is large. This means that there exists distinct temperature contrast even within the 1° longitude-latitude square mesh, which is unlikely to occur if the mesh is covered with stratiform clouds. On the other hand, temperature histogram concentrates itself (there are about 1,200 overlapped fields of view of the IR senser within the 1° square mesh at the sub-satellite point) on the certain warm temperature when the value of $I_c$ is zero. Probably the mesh was clear at that time and the histogram represented the prevalence of the warm surface temperature. This situation also verifies
our previous definition of $I_c$ that it represents the mean degree of penetration of the deep convective clouds.

As for the characteristic feature of the temporal variation in Fig. 5, it is very apparent that the diurnal cycle dominated during this period. It was, in fact, very dominant during the whole period of December 1978 and January 1979. This dominance can be seen in the power spectrum of $I_c$ shown in Fig. 6. It was obtained from the time series of $I_c$ during the same period mentioned above. A well-defined spectral peak appears quite distinctively at the period of 1 day. One can also see the well-defined spectral peak at 0.5 day period. However, this half-day periodicity is not obvious in the actual time series as can be seen in Fig. 5. Besides it turned out that the pattern of the amplitude distribution of this half-day mode (not shown) is almost identical with that of the diurnal mode which we are going to discuss in the followings. Currently we have concluded that the half-day peak in this power spectrum is the one which was produced artificially by the non-sinusoidal behavior of the prevailing diurnal variation.

In order to investigate the amplitude distribu-
tion of the diurnal mode, we have obtained the power spectra of $I_c$ for every meshes over the area of analysis. Then we have calculated the spectral power integrated for the period range from 0.75 through 1.5 days on each spectrum. Fig. 7 represents the resultant horizontal distribution of the spectral power obtained from the time series covering December 1978 through January 1979. During this period of northern hemispheric winter, major amplitudes of the diurnal oscillation appear over the region from Indonesian Islands to northern Australia. Within this region, the local maxima take place over the area around Java Sea including Sumatra, Java and Borneo along with the area over New Guinea and the northwestern part of Australia. The diurnal oscillation over the equatorial South Pacific seems not so intense compared with the large mean values of $I_c$ which can be seen in Fig. 3.

Our next interest is to examine the phase sequence of the diurnal variation. It is natural to anticipate that the maximum convection occurs in the afternoon over the land. Over the sea, however, there appear various observational evidences which indicate that the convective activity reaches its maximum in the morning as comprehensively discussed by Gray and Jacobson (1977) and also by McBride and Gray (1980a, b). In the following discussions we shall investigate whether this kind of contrast appears over the Indonesian region.

First, a digital high-pass filter was applied to each time series of $I_c$ in order to eliminate the oscillation with period longer than 2 days. Then each 3-hourly time series with respect to GMT was converted into the one with respect to the local time referring to the longitude of each mesh. The resultant time series were further interpolated to the values at 00, 03, 06, ..., 21 o'clock local time and the time-composite technique was applied with respect to these times in order to obtain the mean diurnal cycle. Fig. 8 represents thus obtained composited anomalies of $I_c$ from its time-mean value as a function of the local time (LT). The upper diagram exhibits the variation at (7°S, 108°E) which is located in Java Islands, while the lower diagram shows the variation at (5°S, 113°E) located in Java Sea.

In the upper diagram, one can see that the negative anomalies, which mean suppressed convective activity, occur in the local morning. The convective activity is rapidly enhanced after passing local noon and reaches the maximum at about 18 o'clock local time. On the other hand, the lower diagram shows that the positive anomalies take place in the morning. This lower diagram also shows that the convective activity becomes decreased through the afternoon to
evening and reaches its minimum around midnight. Considering that above two diagrams are picked up from the meshes over the land and the sea, the difference of the diurnal cycle mentioned above suggests the existence of the contrast between these two areas.

In order to examine whether the above-mentioned contrast appears commonly between the land and the sea, we have applied the same procedure for obtaining the composited diurnal cycle to every mesh within the area of analysis. As a result we have managed to investigate the horizontal distribution of the diurnal anomalies at the same local time for every mesh. Figs. 9a and 9b exhibit the horizontal distributions of the composited diurnal anomalies of $I_c$ obtained in this manner at 9 o'clock and 18 o'clock local time, respectively. The thick solid line in the diagrams surrounds the area where the power of the diurnal oscillation exceeds 0.5 (see Fig. 7) so that we can pick up the area in which diurnal oscillation has a significant amplitude*. Within that area, contours are drawn at every 0.4 units and the negative values, which mean suppressed convective activity, are shaded.

The distribution of anomalies in the morning shown in Fig. 9a reveals that the suppressed (negative) situation of the convective activity prevails over the northern part of Australian continent, New Guinea, Borneo, Sumatra, Java and other large islands within the equatorial region. On the other hand, the oceanic area extending from Java Sea through Arafura Sea to the north of Australia clearly shows the enhanced (positive) situation of the convective activity at the same local time. Although the anomaly distribution over the equatorial South Pacific to the east of 150°E appears somewhat irregular, it turned out that the convective activity over this region shows overall enhanced situation at around 6 o'clock local time (not shown).

Quite contrasting situation appears at 18 o'clock local time shown in Fig. 9b. At this time of local evening, the Australian continent and the large islands such as New Guinea all show definite positive anomalies indicating the existence of the enhanced deep convective clouds. On the contrary, the adjacent ocean experiences the suppressed convective activity at the same local time. One can see that the equatorial South Pacific also shows overall suppressed situation at this time. From these results discussed above, it emerges that a distinct contrast does exist commonly between the land and the sea in the diurnal cycle of the deep convective activity. The Australian continent and the Indonesian Islands show enhanced convective activity in the late afternoon around 18 o'clock local time, while the adjacent ocean shows the enhanced activity in the local morning around 9 o'clock local time (around 6 o'clock for equatorial South Pacific).

4.2 Northern summer

As previously discussed in Section 3, the mean distribution of the deep convective activity during the northern hemispheric summer shows distinctly different configuration from the one over the northwestern Pacific to the east of Japan has also show large power in Fig. 7. This area was omitted, because it turned out that the large power over this region is mostly due to the high noise level rather than the existence of the diurnal oscillation.
during northern hemispheric winter. During northern summer, the major convective activities take place over the head Bay of Bengal, southeastern part of Tibetan Plateau, southern China and over the western Pacific to the east of Philippines. The amplitude distribution of the diurnal oscillation during the same period is exhibited in Fig. 10 in terms of the spectral power. This figure shows the distribution of the spectral power of $I_c$ in the same manner as in Fig. 7. It can be clearly seen that the significant amplitude of the diurnal variation also appears in the above
Fig. 10 Same as Fig. 7 except for the period from July through August 1979.

Among the major amplitudes of the diurnal variation, it is remarkable in Fig. 10 that the southern half of Tibetan Plateau shows very intense diurnal variation. The large diurnal amplitude also appears over the western Pacific to the east of Philippines though the distribution is somewhat spotty. The difference in the diurnal cycle was first examined by comparing the composite diurnal cycle over these two areas. Fig. 11 shows the composited diurnal anomalies of $I_c$ in the same manner as in Fig. 8. The upper diagram represents the variation at (30°N, 88°E) which is located in the southern part of Tibetan Plateau, while the lower one represents the variation at (10°N, 140°E) located in the western Pacific. In the upper diagram, the negative anomalies of $I_c$ appear in the morning, indicating that the convective activity is suppressed during this time. The minimum anomaly occurs at around 9 o'clock local time. After passing the local noon, the convective activity rapidly becomes enhanced and the maximum activity occurs in the evening around 18 o'clock local time. On the contrary, the lower diagram clearly shows that the enhanced convective activity takes place in the local morning with the maximum around 6- to 9 o'clock local time, though the amplitude is smaller compared with the upper diagram. The

Fig. 11 Composited anomalies of $I_c$ due to the diurnal oscillation with respect to local time (LT) during July through August 1979. The upper and the lower diagrams represent the variations at (30°N, 88°E) and (10°N, 140°E), respectively.
anomalies in this lower diagram also indicate that the convective activity is suppressed in the afternoon through night.

Above results reveal that the similar contrast exists between the land and the oceanic area both during northern hemispheric winter and summer. This situation is clearly exhibited in Figs. 12a and 12b. These figures represent the horizontal distributions of the composited diurnal anomalies of $I_c$ at 6 o'clock and 18 o'clock local time obtained in the same manner as Fig. 9 except that the 6 o'clock was chosen instead of the 9 o'clock in order to show the typical situation over the open ocean. The thick solid line surrounds the area where the power of the diurnal oscillation exceeds 0.5 (see Fig. 10). Within that area, contours are drawn at every 0.4 units and the negative anomalies are shaded.

Fig. 12  Same as Fig. 9 except for 6 o'clock (a) and 18 o'clock (b) local time during July through August 1979.
In the early morning shown in Fig. 12a, one can see that the area over the continent and large islands such as Philippines shows overall suppressed (negative) situation of the convective activity. Suppressed condition appears very intense over the southern part of Tibetan Plateau except for the region around Brahmaputra Valley (27°N, 95°E) where the enhanced (positive) condition occurs at this time. In contrast it can be seen that the positive anomalies take place over the large portion of the western Pacific in this early morning. This fact supports the Gray and Jacobson (1977)'s argument that the diurnal cycle of deep cumulus convection exists over the tropical ocean and it bears the maximum activity in the morning.

Similar but opposite situation takes place after 12 hours in the local evening as shown in Fig. 12b. At this time the areas over the Asian continent and the large islands show very enhanced convective activities. The positive anomalies are especially large over the southern part of Tibetan Plateau and over the northeast India. On the other hand, tropical western Pacific show nearly uniform suppressed condition in the local evening. It is also noticeable that the coastal ocean over the eastern half of the Bay of Bengal indicates the suppressed convective activity, while the western portion of the South China Sea still shows weak but positive anomalies. Considering that the former area corresponds to the windward side of the prevailing monsoonal westerlies and the latter corresponds to the lee side of Indochina peninsula, it seems to indicate the existence of the interaction between the land-sea breeze circulation and the large-scale monsoonal flow.

It is also interesting to see in Fig. 12b that the region around Brahmaputra Valley shows definite suppressed (negative) anomalies in the middle of the enhanced area. Prasad (1974) investigated the diurnal variation of rainfall in this region. He found a well-marked diurnal variation with a maximum in the morning and a minimum in the afternoon hours. Present results also shows positive anomalies in the morning and negative anomalies in the afternoon in agreement with his findings. This characteristic situation over Brahmaputra Valley could be a good example of the controlling effect of the large-scale orography on the diurnal cycle of the cumulus convection.

5. Summary and remarks

In this study we have first explored the way to quantitize the deep convective activity which can be applicable to both land and ocean by using the satellite-observed IR data. This was partly accomplished by taking the horizontal inhomogeneity of the observed $T_{BB}$ into account and incorporating the atmospheric temperature to pick up the high cloud tops. Utilizing these quantities we have defined the intensity index of deep convective clouds ($I_c$) which represents the mean degree of cloud top penetration above 400 mb level within each 1° longitude-latitude square mesh. The monthly mean distributions of this index during northern hemispheric winter and summer have revealed that they well represent the distribution of deep convective clouds when we compare them with the past climatological survey which used satellite imageries. Besides it appears that our index is also suitable for investigating the regional characteristics of the convective activity. For example, the distribution of the index during July 1979 has clearly shown the weak convective activity in the lee side of Burmese mountains with respect to the prevailing monsoonal westerlies.

The investigation on the temporal variation of the index has revealed that there often exists a distinctive diurnal cycle in the region where the mean convective activity is also intense. The spectral power distribution of the diurnal oscillation has shown that the significant amplitude takes place over the Indonesian region and over the northern Australia during northern winter. Weak but discernible diurnal oscillation also appears over the equatorial South Pacific. It appeared remarkable that the Java Island and the adjacent Java Sea showed the distinctive contrast when we investigated the composited diurnal cycle on these two areas. Over Java Island the composited diurnal cycle of our index indicates an intense enhancement of the convective activity in the late afternoon, while Java Sea shows the enhanced convective activity in the local morning.

In order to examine whether the above contrast is observed in common over the much wider area, the composite analysis was performed on every mesh within the area of analysis. The composited diurnal cycles were obtained as a function of the local time at each mesh and their horizontal distribution was examined with respect
to the same local time. As a result it turned out that the above contrast does exist commonly between the land (Indonesian Islands and northern Australia) and the adjacent ocean (Java Sea and Arafura Sea). The composited distribution has revealed that the land shows the minimum convective activity at around 9 o'clock in the local morning and the maximum activity at around 18 o'clock in the evening. In contrast, the adjacent ocean shows the enhanced convective activity in the local morning with the maximum at around 9 o'clock local time. It becomes suppressed in the evening and night. Equatorial South Pacific also shows the enhanced activity in the morning, but the maximum occurs at around 6 o'clock local time, being somewhat earlier compared with the ocean adjacent to the land. It is speculated that the existence of the land-sea circulation may contribute to this time difference.

During the northern hemispheric summer, very intense diurnal variation of the deep convective clouds was observed over the southern part of the Tibetan Plateau. The amplitude of the diurnal oscillation is also large over the northeast India, southern China and over the western Pacific as well. The examination of the composited diurnal cycle has also revealed the contrast between the land and the ocean, being similar to the one observed during the northern winter. That is, the land area generally shows a rapid enhancement of the convective activity in the afternoon with the maximum around 18 o'clock local time, while the oceanic area such as western Pacific shows a clear enhancement in the morning hours with the maximum at around 6- to 9 o'clock local time.

We have also found the evidence which indicates the possible large-scale orographic effect on the diurnal cycle of the convective activity. Over the region around Brahmaputra Valley close to the southern periphery of Tibetan Plateau, the present analysis has shown that the convective activity is enhanced in the morning hours in sharp contrast with the afternoon enhancement over the surrounding continental area. This result agrees with the Prasad (1974)'s findings in his rainfall analysis and seems to suggest the interaction between the mountain-valley circulation and the large-scale monsoonal flow. Similar evidence which seems to indicate the interaction between the local land-sea breeze circulation and the large-scale flow has been also found over the coastal ocean along Indo-China during northern summer.

Through our investigations discussed above, it emerged that the intensity index of the deep convective clouds defined in this study fairly well represents the deep convective activity in the large-scale sense. It can be applicable both to the land and the ocean in a consistent manner and can give us the information on the cloud-top penetration through the upper troposphere. This vertical extent is also an important parameter to investigate the large-scale behavior of the convective activity, along with the horizontal cloud extent which has often been employed in many investigations performed so far.

The difficulty we have faced with our index was to pick up the shallow convective clouds which do not reach as high as 400 mb level. It becomes increasingly difficult to distinguish the cloud tops objectively from the earth's surface as they become shallower. This is especially the case over the tropics where large amount of water vapor is accumulated in the lower troposphere, causing the distortion in the observed $T_{BB}$. In fact, the choice of the 400 mb level was a kind of technical compromise between the effort to pick up as many cloud tops as possible and the objective (digital) discernibility of the cloud tops from the surrounding area. Although we have confined ourselves to examine the deep convective clouds which reach upper troposphere, the activity of the shallow convective clouds is nonetheless important to account for the heat and moisture budget of the tropical atmosphere. Since we need the precise measurement of the surface temperature as well as the vertical profile of the temperature and water vapor to estimate the penetration of shallow convective clouds, it would be highly desirable in the future work to incorporate the measurement by the recently advanced remote-sensing technique.

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References


西太平洋および東南アジア地域における深い積雲対流活動の解析

第1部：日変化

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静止気象衛星 GMS-1 によって観測された赤外放射資料を用いて、深い積雲対流の活動度を従来の空間平均値よりもよりよく物理的解釈に耐え得るように定量化することを試みた。この試みは経度・緯度1度四方の各領域において深い積雲の強度指数を定義し、その際に各領域での放射温度のばらつきと大気温度の垂直分布を取り入れることによりある程度達成された。

上記の強度指数を用いて深い対流活動の日変化を北半球の冬（1978年12月～1979年1月）、および夏（1979年5月～8月）の期間について調査した。北半球の冬においては日変化の振幅はインドネシア領域およびオーストラリア北部で大きな値を示す。この領域内外に陸上部とそれに隣接した海洋では日変化の位相が対照的な振舞を示すことが見出された。コンポジットによる解析によれば、陸上では午前中対流活動が抑制され、地方時で9時頃最小値を示す。地方時の正午を過ぎると対流活動は急速に発達し、18時頃最大値に達する。隣接した海上においてはこれと対照的に対流活動が午前中まで発生であり、午後から夜間にかけて抑制されている。

北半球の夏においては、活発な日変化がチベット高原南部にあらわれる。またフィリピン東方の西太平洋上においても日変化の振幅は大きい。コンポジットされた日変化の振舞をみると、北半球の冬において観測されたものと同様の対照性がこの期間にも大陸上と海洋上との間に存在することが分かる。大陸や大きな島の上では、対流活動は午前中の地方時で9時頃最小であり、夕刻の地方時で18時頃最大値を示す。これに対して西太平洋のような海洋上では、対流活動が午前中の地方時で6時から9時にかけて最も活発であり、午後に抑制されているのが分かる。さらにこのような対照性を加えて、日変化に対する地域的な効果も存在していることも明らかになった。