Convective Activities in the Tropical Western Pacific
and Their Impact on the Northern Hemisphere Summer Circulation

By Tsuyoshi Nitta

Meteorological Research Institute, Tsukuba, Ibaragi, 305 Japan
(Manuscript received 17 December 1986, in revised form 20 March 1987)

Abstract

Interannual and intraseasonal variations of convective activities in the tropical western Pacific during summer and their impact on the Northern Hemisphere circulation are investigated by using satellite cloud amount, sea surface temperature (SST) and geopotential data for 7 years (1978–1984).

During summers when SST in the tropical western Pacific is about 1.0°C warmer than normal, active convection regions consisting of a number of typhoons and tropical depressions are shifted northeastward from the normal position near Philippines to the subtropical western Pacific around 20°N and cloud amounts both in the middle latitudes and in the equatorial regions are greatly suppressed. A high pressure anomaly with little vertical tilt predominates in middle latitudes extending from East China, through Japan Islands to North Pacific during these summers.

Analyses of 5-day mean cloud amount reveal that the convective activity is largely modulated by the intraseasonal variations (ISV). The amplitude of ISV of convective activity in the Philippine Sea around 15°N–20°N is more intensified in warm SST summers than in cold SST summers resulting in stronger season mean convective activities in the former than in the latter.

Correlation computations between 5-day mean tropical cloud amount and 500 mb geopotential height show that there exist wave trains of geopotential height emanating from the heat source region near Philippines to North America. Daily analyses of geopotential height indicate that these wave trains appear to be generated when convective activities in the Philippine Sea become intense and that the amplification occurs downstream from the western Pacific to the west coast of North America taking about 5 days.

It is concluded that Rossby waves are generated by the tropical heat source associated with ISV, and high pressure anomalies over East Asia and Northwest Pacific during warm SST summers can be understood as the results of frequent occurrence of Rossby wave generation.

1. Introduction

Recent observational and theoretical studies have shown that heat sources in the tropics play an important role in interannual and intraseasonal variations of global-scale atmospheric circulations (ex. Horel and Wallace, 1981; Hoskins and Karoly, 1981 and others). Since the condensation heating in the tropics is not uniformly distributed in space but largely confined to the Indian Ocean and western Pacific regions, temporal and spatial variations of heat sources in these regions might have a significant impact on global weather systems not only in low latitudes but in middle and high latitudes.

Quite recently Nitta (1986, hereafter referred to as N) analyzed long-term variations of heat sources in the tropical western Pacific by using high-cloud amount data derived from the Geostationary Meteorological Satellite (GMS) and found two dominant fluctuation patterns. One is an east-west oscillation of the heat source along the equator between the western Pacific and the central Pacific which was extremely amplified during the 1982–83 El Niño period. The other is a north-south oscillation between the subtropical western Pacific near 20°N and middle latitudes crossing Japan Islands which
is called PJ* (Pacific-Japan) pattern. Fig. 1 shows a one-point correlation map with a reference point at 18°N, 146°E obtained by using monthly mean high-cloud amount data during June–September in 1978–1983. Large positive correlation areas are located in the subtropical western Pacific extending zonally from South China Sea to the dateline. Negative correlation regions are found in middle latitudes extending from East China through the Islands of Japan to near the dateline. Negative correlations are also found in the equatorial region west of the dateline. The PJ pattern becomes dominant during summer seasons with timescales of about 1–2 months and has strong relationships with extremely hot or cool summers in Japan. However, since his analyses were based on monthly mean data, detailed temporal variations of convective activities were not clear.

Subsequently Nitta et al. (1986, hereafter referred to as NM) obtained wind anomaly fields corresponding to the PJ heat source anomaly by using cloud wind vectors derived from GMS. NM found that north-south dipole anomaly circulations with an anticyclonic cell to the north of 30°N and a cyclonic cell to the south are intensified when the positive heat source anomaly in the Philippine Sea (15°N–25°N, 120°E–150°E) is enhanced. However, their analyses were limited to the western Pacific region and global views of atmospheric teleconnection associated with the PJ heat source have not been analyzed in detail.

In this study we focus on the PJ variations following the studies by N and NM to obtain detailed features of convective activities in the tropical western Pacific and their effects on Northern Hemisphere (NH) circulations. A global teleconnection pattern associated with PJ are examined by using the monthly mean NH geopotential data. Relationships of sea surface temperature (SST) and activities of typhoons with PJ are also analyzed. Next, intraseasonal variations of convective activities relating to PJ and the atmospheric response to tropical heating will be detailed, based on 5-day mean cloud amount and geopotential height data. Observational evidence of Rossby wave propagation emanating from tropical heat source anomalies will be demonstrated.

2. Data and method of analysis

Monthly mean data of high-cloud amount in the western Pacific for about 6 years from 1978 to 1983 as used in N are also utilized in this study. High-cloud amount data are routinely derived from the Geostationary Meteorological Satellite (GMS) as a fractional ratio of cloud pixels within a 1° × 1° area whose top height is above 400 mb. Previous studies using the high-cloud amount data (Nitta, 1986; Maruyama et al., 1986) showed that the high-cloud amount is a good indicator of convective activity and precipitation rate over the tropical oceans.

Monthly mean NH surface pressure and geopotential height data at 500 mb, 300 mb and 100 mb during summer months (June–September) for 6 years (1978–83) are analyzed to obtain teleconnection maps associated with PJ. These surface pressure and geopotential data have been routinely arranged by the Japan Meteorological Agency (JMA) and provided on 10° × 10° grids in NH from 20°N to 80°N.

---

* This pattern was originally called SJ (South Japan) pattern in Nitta (1986)
Numbers and genesis positions of typhoons and tropical depressions tabulated in Geophysical Review published by JMA are used to examine relationships between typhoon activities and PJ. Monthly mean SST and NH geopotential height data for 17 years (1968–1984) provided by JMA are utilized to get relationships between tropical SST anomalies and intensities of the oceanic high in the mid-latitude western Pacific.

In addition to monthly mean data, 5-day mean data of high-cloud amount and NH surface pressure and geopotential height during May–September for 7 years from 1978 to 1984 are used to analyze detailed temporal variations of convective activities in the tropical western Pacific and their impact on the large-scale atmospheric circulations. Daily geopotential height data at 500 mb during 1979–84 analyzed by the European Center for Medium-Range Weather Forecasts (ECMWF) and those for 1978 by JMA are used to detect Rossby wave propagation from the tropical heat source.

Similar correlation computations as used in N are applied to both monthly and 5-day mean data in this study.

3. Teleconnection pattern associated with the Pacific-Japan cloud anomaly variations and their relationships with SST and typhoon activities

3.1. Global teleconnection pattern

NM showed using the GMS cloud-tracking wind data that a cyclonic anomaly circulation in the upper troposphere exists to the northwest of the heat source anomaly center located in the subtropical western Pacific and that an anticyclonic cell is found in middle latitude around the Islands of Japan where reduced cloud amount is observed. Since the data coverage used by NM is limited to the western Pacific regions, we analyze NH teleconnection patterns associated with PJ using geopotential height data in this subsection.

The index of the PJ cloud variation is defined by cloud amount differences between the positive center (16°N–20°N, 142°E–150°E) and the negative center (32°N–38°N, 134°E–142°E) as in N and the correlation coefficients between the PJ index and NH geopotential height are computed using monthly mean data for June–September in 1978–1983. Fig. 2 shows distributions of the correlation coefficients at the surface, 500 mb, 300 mb and 100 mb. The 95% significance level for a sample size of 24 months corresponds to a correlation coefficient of 0.39. Large positive correlations are found in Far East Asia extending from the China Continent through Japan to around the dateline with the maximum value just east of the Islands of Japan at all levels. There exist negative correlation regions south of about 30°N. Other noticeable negative correlations are found in Siberia and Canada. The correlation patterns at different levels are nearly similar to each other except for the surface where the positive correlation center in Northwest Pacific is slightly to the east of those at higher levels. Similar spatial patterns are obtained by the composite analysis in which five extreme positive PJ index cases are averaged (not shown). The composite results at 300 mb show that the largest positive height anomaly is found over the middle of the Islands of Japan with amplitudes of about 50 gpm. North-south dipole anomaly patterns found in the western Pacific regions are consistent with wind anomaly patterns obtained by NM.

These results indicate that global-scale atmospheric anomaly circulations extending from the China Continent to North America might be closely related to the PJ cloud variation. Especially in the middle latitudes over East Asia, anticyclonic circulations are intensified when convection in the Philippine Sea becomes active. These anomaly circulations possess large horizontal scales in a zonal direction but short scales in a meridional direction with an equivalent barotropic vertical structure. Similar north-south oscillations of the geopotential height between mid-latitudes and the subtropics over the western Pacific have been found by Gambo and Kudo (1983) in their analyses during the NH summer.

3.2. SST anomalies

N found that the PJ cloud oscillation correlates quite well with SST in the tropical western Pacific, especially during June. To examine more detailed distributions and magnitudes
Fig. 2. Correlation maps of surface pressure and geopotential height at 500-mb, 300-mb and 100-mb levels with respect to the PJ index. Contours show correlation coefficients multiplied by 100 with intervals of 20. Negative correlation regions are shaded.

of interannual variations of SST, we analyze monthly mean SST for 7 years (1978–84). Fig. 3 shows isolines of 28°C during June for 7 years. It can be found that there exist large interannual variations of 28°C isolines in the regions east of 150°E. During years when positive extreme PJ cloud anomalies occur (thick solid lines; 78, 81, 84) 28°C lines stretch rather uniformly in a zonal direction north of 20°N, but during years when a negative PJ pattern appears (dashed lines; 80, 82, 83) 28°C lines east of about 150°E shift southward.

Differences of mean SST in June between contrasting years (78, 81, 84 – 80, 82, 83) are shown in Fig. 4. Positive SST anomalies are found in the areas extending in a southwest–northeast direction from equatorial regions north of New Guinea to subtropics near the dateline. These anomaly patterns are generally...
similar to composite results for warm SST cases over the equatorial western Pacific obtained by Kurihara (1985). Especially large SST anomalies more than 1.0°C are located near 20°N east of about 155°E, where large interannual variability of 28°C lines are observed in Fig. 3. N has shown that the cloud PJ index has the largest correlation with SST near 20°N, 160°E where the maximum positive SST anomaly exists as shown in Fig. 4.

These results confirm earlier results by N, i.e., during summers when SST in the tropical western Pacific especially in the region east of about 150°E between 10°N and 25°N is warmer than normal, convective activities in the Philippine Sea around 20°N are greatly intensified and then positive PJ cloud anomaly patterns appear.

It is interesting to note that negative SST anomalies are found close to the equator in the central Pacific. These east-west SST distributions along the equator (warmer in the west and colder in the east) are generally similar to those of the composite SST for August-October of the year preceding El Niño obtained by Rasmussen and Carpenter (1982; their Fig. 17), but are opposite to their results for August-October of the El Niño year and those of the year following El Niño (their Figs. 20 and 21; warmer in the east and colder in the west). Since our analysis period includes the 1982-83 El Niño, SST anomaly distributions shown in Fig. 4 might be affected by the El Niño-Southern Oscillation (ENSO) cycle. Positive phases of the PJ oscillation seem to correspond to anti-El Niño. It might be suggested that interannual variations of SST in the tropical western Pacific which largely control convective activities in this region might be closely related to SST variations associated with ENSO, but further observational and theoretical studies will be needed to clarify the physical processes and mechanism producing long-term SST variations in this region.

3.3. Typhoon activities

As will be shown in the next section, convective activities in the tropical western Pacific are mostly attributed to the activities of typhoons and tropical cyclones. The occurrence of the PJ cloud variation might be linked to interannual variations of characteristic features of typhoons and tropical cyclones. In this subsection we examine spatial distributions of the generation positions of typhoons and tropical cyclones in connection with the PJ variation.

We classify the analyzed years (1978-84) into two contrasting years, i.e., warm SST summers (78, 81, 84) in which positive phases of the PJ cloud variation dominate and cold SST summers (80, 82, 83) corresponding to negative PJ phases. Fig. 5 describes spatial distributions of the generation positions of typhoons (large black circles) and depressions (dots) during June-August for warm SST summers and those for cold SST summers, respectively. Total numbers of typhoons generated during these months for each year are also listed in the figure. These distributions are constructed from the data in Weather Summaries written by JMA. Generation points are defined as those where closed isobars with an interval of 2 mb are first detected. Larger numbers of typhoons are generated during warm SST years than during cold SST years. Moreover, generation distributions are different between these contrasting years. During cold SST years most of typhoons are generated in low latitudes of 8°N–16°N and little is initiated north of 20°N. On the other hand, during warm SST years, typhoons and depressions are initiated in higher latitudes around...
15°N–25°N. These regions of dominant typhoon genesis during warm SST summers are where the center of the PJ cloud oscillation is located as shown in Fig. 1.

It is speculated that during warm SST summers in which warm water pools in the tropical western Pacific expand northward as shown in Figs. 3 and 4, the generation region of weak depressions and pre-typhoon disturbances may be shifted northward accordingly, since the Conditional Instability of the Second Kind (CISK) process may operate more effectively in higher latitudes so long as sufficient moisture is supplied from the warm ocean as suggested by Charney (1971). These weak depressions and pre-typhoon disturbances may propagate westward and develop into typhoons. As a result, heat source centers are shifted northward to around 20°N during the warm SST years resulting in the establishment of the PJ cloud anomaly pattern. The spatial gap between the center of the typhoon generation region (~140°E) and large positive SST anomaly regions (east of 150°E) may be partly explained by the time lag in developing weak disturbances into typhoons, but further detailed observational and numerical studies might be needed to understand how organized convective systems such as typhoons respond to SST anomalies.

Recently, Aoki (1985) has performed a climatological study of typhoon formation based on the 30-year period data set. He classified months into frequent typhoon formation months and infrequent months and obtained composite maps of generation distributions, 500 mb NH geopotential height, cloudiness and SST in the Pacific for each case. His results for frequent typhoon formation cases resemble to our results for warm SST cases (positive PJ cloud anomaly cases) with many respects. For example, relatively more typhoons form in the north of 15°N for frequent months. Also he found positive cloud amount anomalies around 20°N but negative anomalies both in middle latitudes and in equatorial regions for frequent months which are quite similar to the PJ cloud pattern.

4. Intraseasonal variations of convective activity

In order to resolve short-period variations of convective activity associated with the PJ variation, we analyze 5-day mean cloud amount data during May–September for 7 years (1978–84). Fig. 6 shows series of 5-day mean cloud amount distributions for July in 1978 when the typical PJ pattern appears. It is found that several typhoons and tropical depressions line up along the zonal direction around 15°N–20°N during the latter half period. This lineup of typhoons and tropical depressions makes the significant PJ cloud anomaly pattern. The
Fig. 6. Mean cloud amount distributions for 6 pentad periods in July of 1978. Cloud amount larger than 5.0 is contoured with intervals of 1.0. Regions of larger cloud amount than 1.0 are shaded. Numerals denote typhoon number and TD denotes tropical depressions.

relationship between typhoon activities and the PJ variation was discussed in the previous section.

It can be also noted in Fig. 6 that convection is inactive during the first half period of July in contrast to the strong activity during the latter half period indicating that the convective activity varies with intraseasonal time scales (1–2 months). The center of the active convective system seems to move northwestward in time. Detailed movement of the convection center will be examined later using lagged correlations.

Differences in convective activity between warm and cold SST years and their temporal variation can be more clearly seen by time-latitude and time-longitude sections of cloud amount as shown in Fig. 7 and Fig. 8, respectively. Fig. 7 describes time-latitude sections of cloud amount in $130^\circ$E–$140^\circ$E for two contrasting years of 1978 (warm SST) and 1980 (cold SST). Large differences in convective activity between two summers are found in $15^\circ$N–$25^\circ$N latitudes. Convection in these latitudes is quite active for 1978 but weak for 1980. Tropical convection is limited south of $15^\circ$N for 1980. On the other hand cloud amount in middle latitudes around $35^\circ$N is larger for 1980 than for 1978. For both warm and cold SST years convective activities vary intraseasonally. Active convective regions corresponding to the intraseasonal variations (ISV) appear
Fig. 7. Latitude - time sections of cloud amount in 130°E-140°E for 1978 (left) and 1980 (right). Contour interval is 1.5 and shaded areas denote larger cloud amount than 3.0. Dashed lines denote 15°N and 25°N latitudes lines.

Fig. 8. Longitude - time sections of cloud amount in 15°N-20°N for 1978 (left) and 1980 (right). Contour interval is 2.0 and shaded areas denote larger cloud amount than 4.0.

to move northward from near the equator.

Fig. 8 shows the time-longitude sections in 15°N-20°N for 1978 and 1980. For both years convective activity in these latitudes varies intraseasonally as observed in Fig. 7. However, active convective regions are generally limited to the west of about 140°E for 1980 but extend further eastward to around the dateline for 1978. Most of the convection centers associated with the ISV appear to move westward, although some move eastward.

Similar differences in convective activity as observed between 1978 and 1980 are also found between other warm SST years (1981 and 1984) and cold SST years (1982 and 1983).

The results in Figs. 7 and 8 demonstrate that the convective activity in the tropical western Pacific varies both interannually and intraseasonally. We divide the total non-seasonal variations of the cloud amount ($C'$) into two parts, i.e., one is the interannual component ($C'$) and the other is the intraseasonal component ($C'^*$). $C'$ is determined by the deviation from 7-year averages for each 5-day period.
Then $C'$ is estimated by averaging $C'$ for each summer season (June–August) and $C'^*$ is obtained from the difference between $C'$ and $\bar{C}'$. The relationship between $C'$, $\bar{C}'$ and $C'^*$ is written by

$$C' = \bar{C}' + C'^*$$ (1)

Since the interannual and intraseasonal components seem to be different between warm SST years and cold SST years, $\bar{C}'$ and the standard deviations of $C'^*$ are averaged separately for these two types of years.

Fig. 9 shows distributions of $\bar{C}'$ and standard deviations of $C'^*$ averaged for warm SST years and those for cold SST years, respectively. For warm SST years a positive cloud amount anomaly exists along the subtropical regions extending from near the Philippines to around the dateline, but negative anomalies exist both in equatorial and mid-latitude regions. This anomaly pattern generally corresponds to the PJ pattern obtained by the correlation computations (Fig. 1). This result is expected from the result of the close relationship between the PJ index and SST and discussed in 3.2. The distribution of $\bar{C}'$ for cold SST years is nearly opposite to those for warm SST years. The amplitude of the interannual variability of summer season-mean cloud amount is about 1.0.

Amplitudes of ISV for warm SST years are quite large in latitudes of 10°N–20°N stretching northeast-eastward from around Philippines through the dateline. These regions generally correspond to positive anomaly regions of $\bar{C}'$, suggesting that the positive season-mean cloud anomaly for warm SST years might be the result of enhanced ISV of the convective activity. The ISV for cold year is also large near the Philippines but large amplitude areas do not extend further eastward as compared for warm years. A large ISV is also found in the mid-latitudes around the Islands of Japan for

---

Fig. 9. Distributions of standard deviations of $C'^*$ (upper) and $\bar{C}'$ (lower) averaged for warm SST years (78, 81, 84) (a) and for cold SST years (80, 82, 83) (b). Shaded regions denote larger standard deviations than 1.5 (upper) and negative values (lower), respectively.
cold years as already shown in Fig. 7. It is interesting to note that the amplitude of ISV is more than twice that of the season-mean anomaly corresponding to interannual variations, especially for warm SST years.

The above results as shown in Figs. 7, 8 and 9 indicate that convective activity in the western Pacific is strongly modulated by intraseasonal variations and that the amplitude of ISV is more enhanced in the subtropical regions from near the Philippines to the dateline for warm SST years, resulting in the enhanced season-mean convective activity in that region.

In order to see more detailed movement of ISV, lagged correlations are computed by using ISV cloud amount data \( C^* \) for 7 years. Fig. 10 shows one-point correlation maps of cloud amount for lags of \(-5, 0\) and 5 days with respect to \( C^* \) at 15\(^\circ\)N, 125\(^\circ\)E where large ISV is observed. The 95% significance level for a sample size of 126 corresponds to a correlation coefficient of about 0.18. The simultaneous correlation map indicates that the ISV of convective activity has a horizontal scale of about 2000 km–3000 km in a zonal direction and about 1000 km in a meridional direction. This horizontal scale generally corresponds to that of organized convective groups found in individual 5-day mean maps such as shown in Fig. 6. The simultaneous correlation map also indicates that there exist negative and positive correlation areas along the southwest–northeast direction from the reference point toward North Pacific, suggesting the existence of some sort of wave propagation. Detailed features of Rossby wave propagation from the tropical heat source will be examined in the next section.

Takeda and Ikeyama (1985) showed in their analysis of the cloud amount in the western Pacific that there exist prominent fluctuations of the cloud amount with about 30-day period and horizontal scales of about 2000 km in a zonal direction and 1000–1500 km in a meridional direction. Characteristic features of ISV of the convective activity analyzed in this study might correspond to those of the 30-day variation found by them.

The lagged correlation map for \(-5\) days shows that large correlation areas are located in the equatorial region to the southeast of the reference point. This suggests that the ISV cloud amount moves northwest–westward. Wave-like patterns of large correlation areas can be also seen along the southwest–northeast direction from the equatorial regions. The lagged correlation result for 5-days shows that positive areas seem to move northward from the reference point, but wave-like patterns as found for \(-5\) and 0 days are not found.

Phase propagation of the cloud ISV is obtained by computing the ±5 day lagged correla-

Fig. 10. One-point correlation maps \((\times100)\) with lags of \(-5, 0\) and 5 days with respect to the cloud amount at 15\(^\circ\)N, 125\(^\circ\)E. Areas with absolute coefficients larger than 0.2 are shaded.
tion at $5^\circ \times 10^\circ$ grid points. Fig. 11 plots the phase propagation vectors at grid points where large lagged correlation coefficients are obtained. As shown in Fig. 10, ISV moves northwestward in $10^\circ\text{N}-20^\circ\text{N}$ latitudes where its amplitude is large. Its propagation speed is about $5 \text{ m s}^{-1}-10 \text{ m s}^{-1}$ which corresponds to the mean wind speed in the lower troposphere. ISV near the equator from the Indian Ocean to Borneo moves eastward with a speed of about $10 \text{ m s}^{-1}$, although its amplitude is not so large (Fig. 9). ISV in middle latitudes moves eastward, probably corresponding to eastward migration of cloud associated with mid-latitude frontal systems.

Quite recently Lau and Chan (1986) have obtained similar northwestward propagation of ISV of convective activities over the western Pacific during Northern summer using outgoing longwave radiation (OLR) data. They have also shown that ISV of convection in the western Pacific is tightly linked to that in the Indian Monsoon region.

5. Rossby wave propagation generated by tropical heat sources

The results in the previous section indicated that there exists large ISV of convective activity moving northwest-westward from the equatorial western Pacific toward the subtropical regions. The cloud systems associated with ISV consist of several numbers of typhoons and tropical depressions with horizontal scales of about 2000–3000 km and may have great impact on large-scale atmospheric circulations in higher latitudes as demonstrated by the monthly mean data analysis. In this section we will investigate the atmospheric response to the tropical heat source anomaly based on 5-day mean data.

Since we are interested in the atmospheric response to the ISV of tropical convection, ISV for cloud amount derived from eq. (1) and those for NH geopotential height during summer seasons (June–August) for 7 years (1978–1984) are used for computing the correlation coefficients.

Fig. 12 shows a teleconnectivity map defined as the maximum correlation coefficients between 500 mb geopotential height north of $30^\circ\text{N}$ and cloud amount in tropical regions between the equator and $30^\circ\text{N}$. There are two centers of tropical convection which have large positive correlations with NH 500 mb height. One is the convection near the Philippines around $10^\circ\text{N}–15^\circ\text{N}$, $120^\circ\text{E}–130^\circ\text{E}$ which relates to height anomalies to the south of the

![Fig. 11. Phase propagation vectors computed by lagged correlations. Only results with larger correlation coefficients than 0.4 are plotted.](image1)

![Fig. 12. Teleconnectivity map defined as the maximum correlation (x100) between the 500 mb geopotential height north of $30^\circ\text{N}$ and the cloud amount in the tropical western Pacific ($0^\circ–30^\circ\text{N}$). Areas with larger coefficients than 0.35 are shaded.](image2)
Islands of Japan and the other is the convection over the middle of Peninsular Malaysia around 10°N, 100°E which correlates to height anomalies in Southeast China around 30°N.

One-point correlation maps of 500 mb height with respect to cloud amount at two centers are illustrated in Fig. 13. For the case of the convection center near the Philippines (Fig. 13b) there exist negative correlation areas on and to the west of the heat source center and large positive correlation areas to the south of the Islands of Japan corresponding to northeast of the heat source center. This north-south dipole structure of the correlation map is generally similar to that obtained by using the monthly mean data (Fig. 2). However, in addition to this dipole pattern, wave-like correlation patterns, such as negative to the west of the dateline, positive to the east and negative along the west coast of North America, can be seen in Fig. 13. These wave-like patterns are obtained if we shift reference positions of the cloud amount within regions of 10°N–20°N, 110°E–150°E (not shown).

Similar wave-like patterns can be found in the correlation maps with time lags of ±5 days for the convection near the Philippines and the positive correlation centers to the south of Japan seem to move westward as the time lag increases from -5 days to +5 days, although the correlation coefficients are not so high as for the zero lag (not shown). These results suggest that wave-like atmospheric anomalies respond to the ISV of the tropical convection moving northwest-westward as shown in Fig. 11. Detailed time evolution of the atmospheric responses to the tropical heating will be examined afterwards by using daily geopotential height data.

For the case of the convection center near Peninsular Malaysia (Fig. 13a), a north-south dipole structure of the correlation is also found, but wave-like correlation patterns such as found for the case of the convection center near Philippines are not obtained.

The correlation results for the surface pressure and the 300 mb geopotential height indicate that these atmospheric responses have an equivalent barotropic vertical structure as found by using the monthly data (not shown).

Wave-like patterns are found not only in the correlation map but also in the 5-day mean anomaly maps of geopotential height. Fig. 14 shows a 500-mb height anomaly during August 19–23 in 1978 as a typical example. Cloud amount distributions during this period are also shown in the figure. Intense convection develops near the Philippines, and an anticyclonic cell near Japan and its downstream wave-like patterns similar to those in Fig. 13.

Fig. 13. One-point correlation maps (x100) of the NH geopotential height at 500 mb with respect to the cloud amount at 10°N, 98°E (a) and at 12°N, 126°E (b). X denotes reference positions of the cloud amount and negative correlation regions are shaded.
can be noted. These results strongly suggest that Rossby waves might be generated by the heating near the Philippines.

To examine a more detailed time evolution of the Rossby wave propagation we construct time sections of 500-mb height along the great circle using daily geopotential height data. Rossby waves are thought to propagate along the great circle in an idealized atmosphere with solid-rotation mean winds. Fig. 15 shows the time — great circle section of 500-mb height during 17–27 August, 1978 which includes the 5 days shown in Fig. 14. The subtropical high pressure to the southeast of Japan was intensified on 19–20-th and the downstream trough to the west of the dateline had a peak after about one day. The North Pacific high east of the dateline amplified around 23-rd, and then the trough along the west coast of North America deepened on 24-th. These results indicate that the energy of the waves propagate from the western Pacific subtropics to the west coast of North America for about 5 days. Its propagation speed is about 15–20 m s⁻¹ and this speed is generally consistent with the energy speed due to Rossby waves, although the group velocity of Rossby waves depends on several factors such as mean wind velocities and zonal and meridional wavelengths. Daily synoptic charts at 500 mb during these periods also indicate the downstream amplification (not shown).

Similar Rossby wave propagation from the tropical western Pacific to North America can be detected in other summer seasons. Fig. 16 demonstrates other examples indicating Rossby wave propagation during 1981 and 1983. In these figures monthly means are subtracted at each grid point. Downstream amplifications can be clearly seen for both cases. Propagation speeds in these cases are almost the same as the 1978 case. These events can be found more
Fig. 16. Time-great circle sections of the 500 mb height deviations (x10 m) from monthly averages for July 1981 (a) and for August 1983 (b). Contour interval is 30 m and solid and dashed lines denote positive and negative deviations, respectively. Thick solid lines correspond to straight lines passing through amplitude peaks.

frequently during warm SST summers (1978, 1981, 1984) than during cold SST summers (1980, 1982, 1983), probably due to more intense ISV of convective activities in the Philippine Sea during the former than during the latter as shown in Fig. 9.

The existence of Rossby wave propagation from the tropical western Pacific has been suggested by Kurihara and Tsuyuki (1987) for their case-study analyses for the 1984 summer. They have also examined the atmospheric response to a forcing around the north of the Philippines by using a linear shallow-equation model. Fig. 17a showed their results of height anomalies generated by the wave forcing at 20°N, 125°E, indicating that a trough is formed on and to the west of the source region, while a ridge is found around Japan. Their results also showed

Fig. 17. Height anomaly patterns in the model atmosphere responding to the forcing at 20°N, 125°E computed by Kurihara and Tsuyuki (1987) (a) and the one-point correlation map of the 500-mb geopotential height as in Fig. 13 except for using the cloud amount at 20°N, 126°E as the base. Negative regions are shaded and X denotes the forcing (a) and the reference points (b).
a wavetrain over the North Pacific extending to the west coast of North America. A one-point correlation map of 500 mb height with respect to the cloud amount at 20°N, 126°E, where the model forcing in Kurihara and Tsuyuki (1987) was prescribed, is also shown for the comparison (Fig. 17b). Both patterns agree quite well with each other indicating that Rossby waves are generated by the heat source anomaly near the Philippines and propagate through North America.

6. Discussions and conclusions

Detailed characteristic features of convective activity in the tropical western Pacific corresponding to the PJ (Pacific-Japan) cloud anomaly pattern and their impact on higher-latitude atmosphere are investigated by using monthly mean and 5-day mean data of GMS cloud amount, SST and NH geopotential height during about 7 years from 1978 to 1984. The results are summarized in Fig. 18. SST in the tropical western Pacific varies interannually with periods of 2–4 years, as will be shown in Fig. 19. During summers in which SST in this region is warmer than normal, intense convection regions are shifted northward by about 5°–10° latitude from the normal position south of the Philippines. These convective activities consist of typhoons and tropical depressions and are largely modulated by the intraseasonal variations. The convective systems associated with ISV have horizontal scales of about 2000–3000 km and propagate northwestward from the equatorial region. When these ISV of convective systems reach near the Philippine Sea, atmospheric Rossby waves respond to the heating and propagate downstream over the North Pacific to North America for about 5 days. As a result of the Rossby wave response, East Asian regions including the China Continent and Japan are covered by anticyclonic circulation anomalies, resulting in hot days. Although these atmospheric responses happen to occur even during cold SST summers (see Fig. 16 for the 1983 case), these events develop more frequently during warm SST years than during cold SST years and therefore it is likely that the anticyclonic anomaly circulations predominate over East Asia during the whole summer season for the warm SST years.

Although the north-south dipole structure of the teleconnection pattern in the western Pacific is obtained both by using monthly mean data (Fig. 1) and by using 5-day mean data (Fig. 13b, Fig. 14 and Fig. 17b), the former result does not show wavetrain-like patterns. These non-wavetrain-like patterns might be partly due to phase cancellation of Rossby waves generated from different heat sources which vary in time and space within an one month. Blackmon et al. (1984a, b) found two types of teleconnection patterns during Northern Hemisphere winter depending upon different time scales, i.e., one is a meridionally oriented dipole structure dominant in the time scale longer than 30 days and the other is a wavetrain structure dominant in the intermediate time scale of 10–30 day periods. They speculated that the dynamical mechanism might be different for generating these two types of teleconnection. Their results may be relevant to our results in some degree, but further observational and theoretical studies might be needed for understanding the dynamical mechanism responding to different time scale variability.

The PJ oscillation obtained by using monthly
mean high-cloud amount data may be understood as the mixture of the interannual and intraseasonal variations of convective activity. ISV of convective activity is enhanced (suppressed) during warm (cold) SST summers, especially over the positive (negative) SST anomaly regions east of the Philippines and thus positive (negative) PJ patterns may be apt to appear during these summer months (June–September). However, since monthly mean convective activity is affected by time evolution of each ISV, negative (positive) PJ patterns may happen to occur even within warm (cold) SST summer months.

For the propagation of Rossby waves in higher latitudes it may be necessary that tropical heat sources move northward and reach the westerly regions as suggested from the theoretical point of view (ex. Lim and Chang, 1983). This might be why these Rossby wave responses seldom occur during the cold SST summers in which active tropical convection is mostly limited in the equatorial regions.

Our analyses also suggest that there exist suitable longitudes for Rossby wave generation. Since the zonal winds in the western Pacific region vary largely in the east-west direction affected by the Southeast Asian summer monsoon, atmospheric responses may depend on the longitudinal positions of heating. It is probable that non-propagating features obtained for the cases of tropical heating west of about 110°E might be due to a predominance of upper tropospheric easterlies south of the Tibetan High. Further investigations for the atmospheric responses under zonally non-uniform winds are desirable.

The above scenarios among interannual variations of tropical SST, convective activity and atmospheric responses in middle latitudes can be confirmed by a longer-period dataset, although satellite data are not available for periods longer than about 10 years. Fig. 19 shows the time variations of monthly mean SST anomalies in June averaged in the tropical western Pacific area of 10°N–20°N, 150°E–170°E where large SST anomalies relating to the PJ pattern (Fig. 4) are obtained and those of monthly mean 300 mb geopotential height anomalies in July at 40°N, 150°E just east of the Islands of Japan for 17 years from 1968 to 1984. Both variations correlate quite well with a correlation coefficient of 0.7, indicating that a warmer tropical SST corresponds to intense high pressure systems in mid-latitudes and a colder SST corresponds to weak anticyclonic circulations.

The SST in the tropical western Pacific varies with a time scales of 2–4 years as shown in Fig. 19. Most of the years affected by El Niño exhibit colder SST in this region and convection is inactive over the Philippine Sea and thus mid-latitude East Asia is dominated by a low pressure anomaly system resulting in relatively cool summers. On the other hand, warm SST years seem to correspond to anti-El Niño years (or La Niña). These results suggest that interannual variations of SST in the tropical western Pacific which produce large interannual fluctuations of NH summer circulations are not local phenomena but a part of the global-scale SST variations probably related to ENSO. The mechanism of ENSO cycles has not yet been understood and remains one of great unresolved problems.

Another important unresolved problem is the ISV in the tropics. It is found from 5-day mean cloud amount data during 7 years that the ISV of convective activity in the tropical western Pacific has twice the amplitude of the interannual variation. Moreover, it is shown that the interannual variation itself seems to be the result of the different behavior of the ISV in different SST years. It is concluded that the ISV is a key phenomenon which determine long-term variations of convective activities.

![Fig. 19. Time series of SST anomalies in June averaged in the area of 10°N–20°N, 150°E–170°E (dashed line) and height anomalies at 300 mb in July at 40°N, 150°E (solid line) for 17 years from 1968 to 1984. Arrows denote El Niño years.](image-url)
with time-scales ranging from about 10 days to years. The ISV in the analyzed domain might be largely related to the global-scale ISV which are so called "40–50 day oscillations". Previous analyses showed that the tropical ISV exhibits global features propagating eastward with a wavenumber of 1–2 on the one hand (Murakami and Nakazawa, 1986; Lorenc, 1984), but has localized characters such as northward movement of the convection center in the Southeast Asian Summer monsoon regions on the other hand (Yasunari, 1979; Krishnamurti and Subrahmanyam, 1982; Murakami, 1984). ISV found in this study seem to possess local ISV characters propagating northwest-westward with 2000–3000 km horizontal scales. These results are consistent with those analyzed by Lau and Chan (1986) using OLR data. Further studies are needed to clarify how ISV in the western Pacific region is related to the global-scale ISV. More basically it is desirable in the near future to determine why ISV does exist in the tropics and how ISV affect the general circulations over the globe.

Acknowledgement

The author would like to express his thanks to Mr. T. Motoki for providing GMS cloud amount data. The author wishes to thank Mr. M. Chiba and Mr. K. Yamazaki for their help in using NH datasets. Thanks are also due to Dr. T. Tokioka for many valuable discussions. The computations were made on the HITAC M-280D and the S-810/10 Computers of Meteorological Research Institute.

References


熱帯西部太平洋の対流活動と夏期北半球大気循環への影響

新 田 孝
（気象研究所・台風研究部）

1978〜1984年の約7年間の衛星による雲量、海面水温、高度場データを用いて、熱帯西部太平洋の対流活動の年変動と季節内変動の実態、および北半球大気循環に与える影響を調べた。

西部太平洋熱帯域の海面水温が例年より1℃程度高い年の夏には、例年フィリピン付近に位置している対流の活発域が東方方向に移動し、20°N付近の亜熱帯域に達する。これらの強発達対流群は多くの台風や熱帯低気圧で成り立っている。この時期、北側の中緯度帯と、南側の赤道域では逆に雲量の減少が見られる。このような夏には、中国大陸東部から日本を横切り、北太平洋にかけての中緯度帯で、垂直に立った構造を持った高気圧偏差が卓越する。

5日平均雲量の解析から、この領域の対流活動の変動には、大きな季節変動成分があることがわかった。対流の季節変動は、高水温の夏に、15°N〜20°Nのフィリピン海でより活発化し、その結果、表層を通して見てても、高水温の年の方が低水温の年に比べて大きな雲量が見られる。

5日平均の雲量と500mb高度との相関計算から、フィリピン付近の熱帯域から北米に達する波列が存在することが明らかになった。日々の高度データの解析から、これらの波列は、フィリピン海で対流活動が活発化する時に発生し、振幅の増大が、西太平洋から北米西岸にかけて、約5日間で伝わっていることがわかった。

以上のことから、季節内変動に伴う対流活動の強まりによって、大気中にロスピーロ波が発生されており、高水温年の夏には、これらのロスピーロ波の発生が頻繁に起きる結果、東アジアから北西太平洋にかけての中緯度で、高気圧が強まるものと考えられる。