The Interaction between Two Separate Propagations of Rossby Waves

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ABSTRACT

This study deals with two teleconnection patterns and the subsequent wave train propagations during an East Asian summer. Diagnostic results are as follows: 1) a stationary wave ray with zonal wavenumber 5 approximates the arc path linking the correlation centers originating from the Caspian Sea via Lake Baikal to the sea off the southeast coast of Japan (i.e., the OKJ arc path as a focus area) in a pentad correlation map between 500-hPa geopotential height (Z500) and outgoing longwave radiation (OLR) at 30°N, 150°E in June 1979–98. Ray tracing shows that it took 8–10 days for this stationary wave to propagate from an initial position around the Caspian Sea to the focus area, which roughly coincides with the observed case in July 1998. 2) A wave train pattern (P-Ja) observed in the boreal summer propagated along the arc line in the same way as the normal poleward Rossby wave train originating from the Philippines across the North Pacific (P-J), but with a phase shift northeastward of about 90°. 3) Further correlation analyses showed that the P-J-like waves belong mainly to intraseasonal propagating ones while OKJ waves belong mainly to intraseasonal stationary ones. 4) Propagation of the newly observed wave train pattern (P-Ja) occurred following another wave train along the OKJ arc path in mid-July 1998. Both northeastward and southeastward wave propagations merged off the east coast of Japan. 5) The northeastward-propagating wave train observed in mid-July 1998 was triggered by the southeastward-propagating (OKJ) wave train that produced a deep cyclonic circulation and a strong convective activity in the focus area. The link of wave forcing and deep convection was made solely because of a strong upper-level divergence in the focus area.

1. Introduction

The discovery during the last century of the teleconnection phenomenon was a major breakthrough in atmospheric science, yet the question of interaction remained. Five typical teleconnection patterns in boreal winter were found and defined by Wallace and Gutzler (1981). Based on the theory of Rossby wave propagation, a now well-known explanation for the nature of teleconnection was provided by Hoskins and Karoly (1981, hereafter HK81). Large variations in weather that can be related to the propagation of Rossby waves were observed in the warm season around East Asia (Nitta 1987, hereafter N87; Wang 1992, hereafter W92).

HK81 introduced the notion of the "great circle" along which a stationary Rossby wave disperses on a super-rotating basic state. The ray theory was later developed and applied to low-frequency Rossby waves by Karoly (1983), who derived the ray equations for a zonally varying flow. Hoskins and Ambrizzi (1993) brought in the concept of the Rossby waveguide (i.e., Rossby waves propagate along paths usually concentrated in a narrow belt district, especially in the jet region); in their paper, the authors also discussed the refraction and reflection of Rossby waves. The prospect of two Rossby propagations occurring simultaneously in a waveguide

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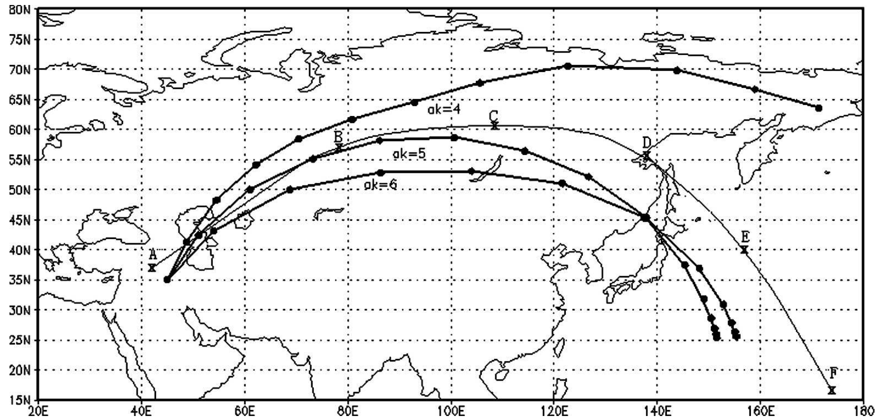


FIG. 1. The ray paths with zonal wavenumbers 4, 5, and 6 with black circles at daily intervals. The thinner arc line marked with A–F labels is the wave path picked up from Fig. 9 in W92.

region gives rise to the question of whether one Rossby wave causes an interaction if it nears or crosses another.

Only two kinds of wave trains occur frequently in an East Asian summer: one tends to propagate along a path from the Caspian Sea via the Okhotsk Sea to the area off the southeast coast of Japan (OKJ), as pointed out by W92, and the other originates from the Philippines and travels via Japan to North America (P-J), as pointed out by N87.[1] It is noteworthy that the eastern part of the OKJ path and the western part of the P-J path accompanying a westerly jet fall just inside the narrow summer waveguide introduced by Ambrizzi et al. (1995, see their Fig. 17), although these may not be the typical ones with wavenumbers 7–8. To investigate whether an interaction between them occurs when they coexist is therefore reasonable. The purpose of this study is to discover whether these Rossby wave trains occur simultaneously and, if so, how they interact to create an impact on local and large-scale circulation.

2. Data

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global atmospheric reanalysis dataset was the primary dataset used in this study. A detailed description of the data assimilation system that produces this dataset was given by Kalnay et al. (1996). We used daily (June and July 1998) and pentad (June and July 1979–98) 500-hPa geopotential heights on a 2.5° latitude–longitude grid. Note that pentads in June and July are pentads 31–42 of the 73 pentads in one year. Daily u and v components of the wind vector at 700 and 200 hPa and the vertical component of the wind vector at 700 hPa in July 1998 with the same resolution were also used in this study. The monthly zonal mean wind $\overline{u}$ in June 1969–98 was used for ray tracing. The pentad National Oceanic and Atmospheric Administration (NOAA) interpolated outgoing longwave radiation (OLR) data at the same 2.5° spatial grid were used for June and July 1979–98. The daily OLR was used in July 1998. The 3-h mean temperature of blackbody (TBB) with a 1° × 1° grid for July 1998 was provided by the Meteorological Research Institute of Japan.

3. OKJ wave train

The path of an OKJ wave train has been a source of contention among researchers who focus on its western part. Ogi et al. (2004) pointed out that a source around the Barents Sea region may excite an OKJ-like Rossby wave passing through the Okhotsk Sea. Wang and Yasunari (1994) indicated that another source produced by the land–sea temperature contrast around East Siberia could generate a wave train via the Okhotsk Sea to the focus area. On the other hand, W92 introduced a great circle–like wave path originating from the Caspian Sea via Lake Baikal to the focus area by using a one-point correlation map, as mentioned in section 1. Compared with the first two paths above, the arc path from the Caspian Sea (marked in Fig. 1) is more similar to the great circle proposed by HK81. A ray-tracing analysis was required to confirm whether the path approximates that of a stationary Rossby wave.

a. Ray tracing for an OKJ wave

The ray equations for stationary waves were derived by HK81. According to their ray theory, the group velocity (u_g, v_g) with a zero frequency, which depends on

[1] This name is originally from a teleconnection phenomenon around East Asia mentioned by N87. We extend its meaning to the related wave train pattern.

the basic-state zonal wind $\overline{u}_M$ in a Mercator projection, can be expressed as follows:

$$u_g = \frac{2\beta_M k^2}{(k^2 + l^2)^2}, \tag{1}$$

$$v_g = \frac{2\beta_M kl}{(k^2 + l^2)^2}, \tag{2}$$

$$\text{where} \quad \beta_M = \frac{2\Omega}{a}\cos^2\phi - \frac{d}{dy}\frac{1}{\cos^2\phi}\frac{d}{dy}(\cos^2\phi\overline{u}_M) \tag{3}$$

is proportional to the meridional gradient of the absolute vorticity.

The earth-angular speed of rotation $\Omega = 7.292 \times 10^{-5}$ rad s^{-1} and the mean radius of earth $a = 6.37 \times 10^6$ m were taken here. A ray was defined in case the stationary Rossby wave could propagate in the direction and speed at the local-group velocity on the sphere. The x wavenumber k is constant and the y wavenumber l varies along the ray, which was obtained closer to the realistic flows than to the ray with a constant angular velocity flow. The initial position for a Rossby wave was selected at 35°N, 45°E, which corresponds to point A of the beginning of the bold line approximating a great circle in Fig. 9 of W92 (see also the letter A marked in Fig. 1 here). The $\overline{u} = \overline{u}_M \cos\phi$ the zonal mean wind for June 1969–98 was used for the basic state, as shown in Fig. 2. Ray paths with zonal wavenumbers $ak = 4$, 5, and 6 and daily intervals (black circles) were plotted in Fig. 1 beside the original wave path picked up from Fig. 9 of W92. The ray path with zonal wavenumber 5 approximates the original wave path between them, in spite of some biases around northeast Asia. This implies that the OKJ wave train addressed by W92 behaved almost like a barotropically stationary Rossby wave with zonal wavenumber 5, which was terminated after 14.8 days when the basic zonal wind became an easterly one. Within 8–10 days, the wave with zonal wavenumber 5 could depart from its initial position and arrive at the focus area. Another wave train pattern, addressed in section 4, appeared to favor a wavenumbers-6–7 scale, as pointed out by Kurihara and Tsuyuki (1987). The ray with zonal wavenumber 6 was farther from the original OKJ path, yet the ray with zonal wavenumber 4 displayed a large departure from the original path.

b. One-point correlation maps

Figure 3 shows the one-point correlation map between pentad OLR at 30°N, 150°E and the 500-hPa geopotential height (Z500) in June 1979–98, which is the update of Fig. 9 in W92. The correlation is above 0.175 to reject the null hypothesis of no correlation at the 0.05 significance level. The correlation centers originate from point A (the Caspian Sea) via point C (Lake Baikal) to point G (the focus area). Note that subsequent significant correlation exists around Lake Baikal (near point C), the Sea of Okhotsk (near point D), and off the east coast of Japan (near point G).

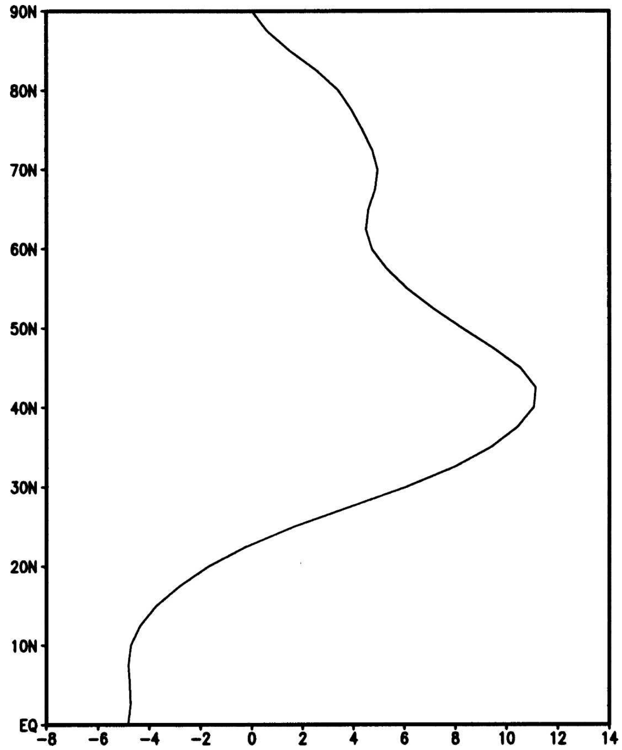


FIG. 2. The zonal mean flow $\overline{u}$ at 500 hPa in June from 1969 to 1998 used in the ray tracing (m s^{-1}).

There are some differences between the new figure (Fig. 3) and the old figure (Fig. 9 in W92). With the extension of the 84-pentad data, the confidence level for all significant correlation centers is raised to 95% in the new figure. A large positive correlation center is located at 33°N, 145°E in the new figure, which is to the west of the center marked in the old figure but basically coincides with the response of the OLR at base point to Z500. Thus, the path has been corrected to pass through the point at 33°N, 145°E in Fig. 3. The ray with zonal wavenumber 5, especially the eastern part of it marked in Fig. 1, more closely approaches the new OKJ path than the old path. The new figure shows that the correlation around Lake Baikal (near point C) is significant but the old one insignificant. Therefore the OKJ propagation from Lake Baikal via the Sea of Okhotsk to the tropical west Pacific in early summer is confirmed by the new figure. The difference between

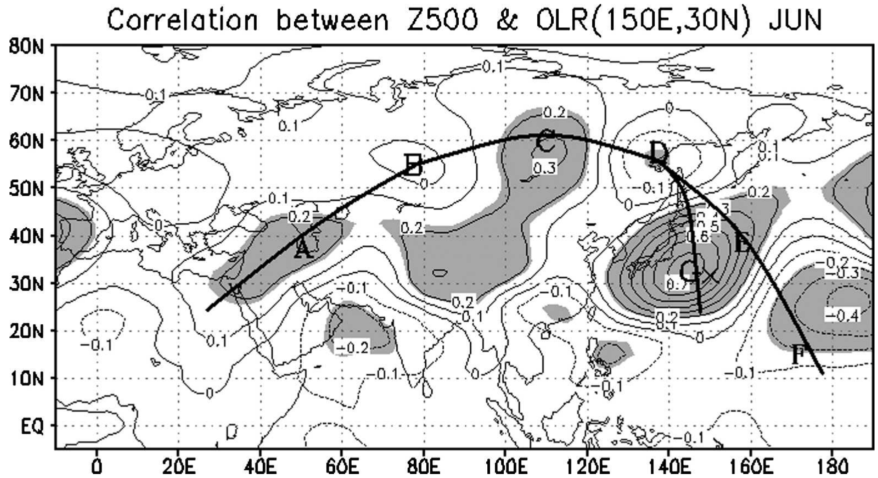


FIG. 3. The one-point correlation coefficient between Z500 and OLR at (30°N, 150°E) marked by a cross during the period of pentads 31–36 of 1979–98. Shaded areas indicate the regions over the 95% confidence level. One arc line links the positive and negative correlation centers (A, B, C, D, and G) and the other (A–F) is a linking path picked up from Fig. 9 in W92.

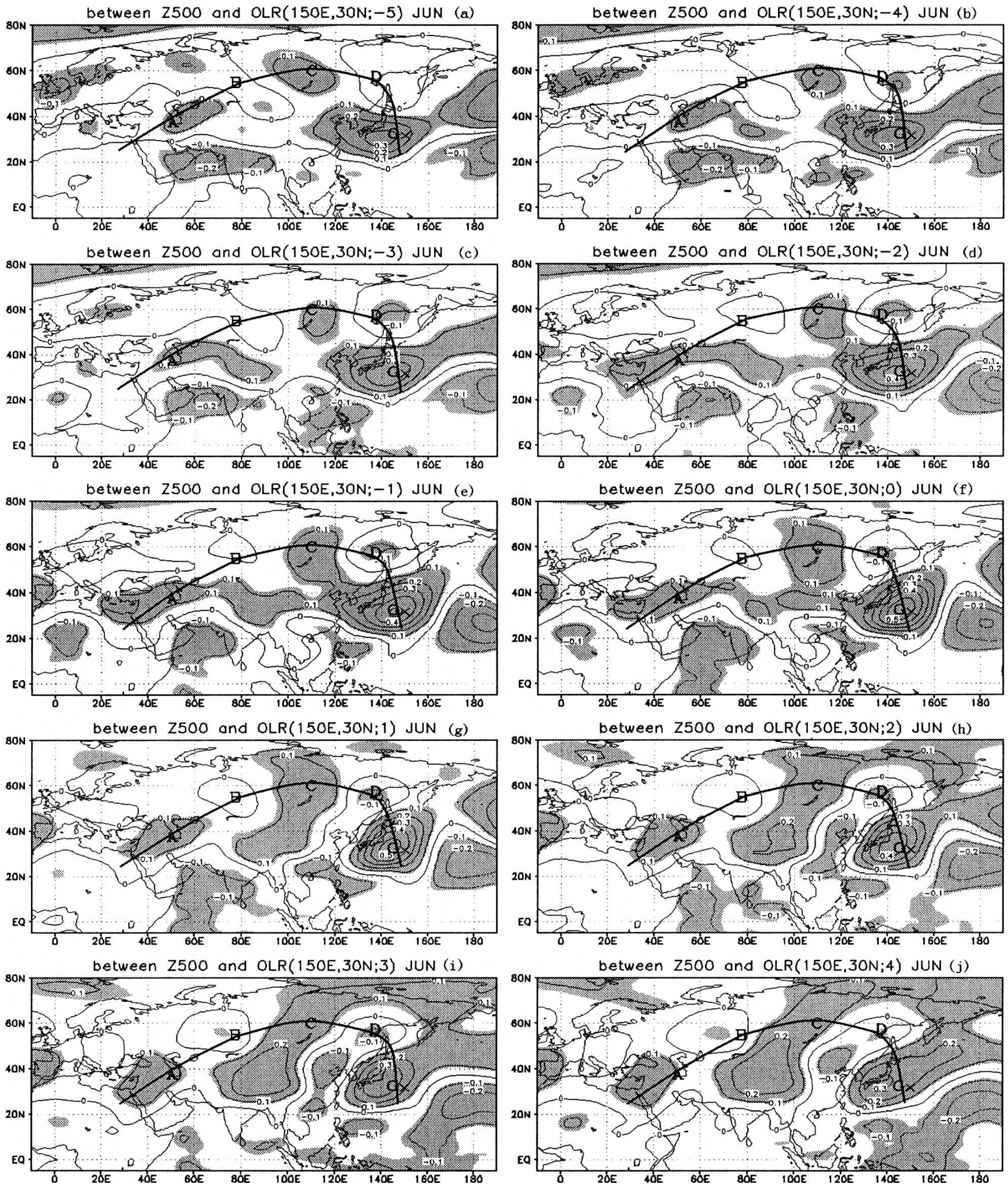
the path of A–G and the ray computed by the theory of HK81 is due to the basic state. The observed basic state in the correlation is much more complex than a super rotation or averaged zonal flow in the ray tracing, but contains most of the part of the barotropic Rossby wave dynamics. Here we refer to an arc path linking with correlation centers as the great circle.

W92 pointed out that because the correlation pattern is very sensitive when the base point is slightly changed, especially in longitudes, the variation of the OLR at 30°N, 150°E is thought to be a response to Rossby wave propagation. This is similar to the phenomenon described by Matthews and Kiladis (2000), who displayed a convection response in a tropical region by a transient wave. The OKJ propagation associated with the Okhotsk high results in a negative anomaly of Z500 to the east of Japan and a southward shift of the mei-yu front. This finding exemplifies the impact equatorward Rossby wave propagation can exert on low-latitude weather conditions. Recently, Wang et al. (2003) demonstrated that frequent OKJ propagations in the summer of 1998 could suppress the northern progression of the subtropical high.

To assess the wave train pattern in detail, we computed the lag correlations as shown in Fig. 4, which are similar to Fig. 3 but on daily time scales. We show only the lag correlations of the time series of OLR at the base points lagging Z500 by −5 days to +5 days, although lag correlations ranging from −30 days to +30 days have been produced. The correlation is above 0.09 to reject the null hypothesis of no correlation at the 0.05 significance level. The OKJ pattern is basically unchanged in the lag correlations from −3 to +3 days shown in Fig. 4, which is similar to the correlation pattern on the pentad time scale. The persistence of the wave in relation to that of the low OLR at the base point can be seen in Fig. 4, because each of the pictures with a few days' lag correlation shows nearly the same pattern. The sequentially significant correlation centers from points C to G on a daily time scale further affirm the main route of the OKJ wave train propagation, which is in agreement with the discussion about the pentad time scale. No phase shift of the lag correlations corresponds to a Rossby wave with a zero phase speed. Although there was no obvious change in the strength of the correlation centers among Figs. 4a–e, the shape of the correlation centers (points C–E) with a northeast–southwest direction in lag +1 and +3 days strongly suggests that the wave train can propagate from higher to lower latitudes, which is more similar to Fig. 3. Thus, the convection at base point tends to respond to the OKJ wave propagation due to the clearer pattern occurring when the Z500 leads the OLR at the base point by 1 or 2 days. The significant correlation centers arranged in Figs. 4e–g are a little different from those in other subfigures of Fig. 4. Besides the OKJ pattern, a wavelike train along 40°N was also found, which corresponds to the summer waveguide with stationary wavenumbers 7–8 as described by Ambrizzi et al. (1995). The correlations distributed in Figs. 4e–g display an energy dispersion more obviously eastward in a wider scope in Asia.

c. Discussion

Pentad correlation maps were produced by using base points near zero correlation contours that intersect



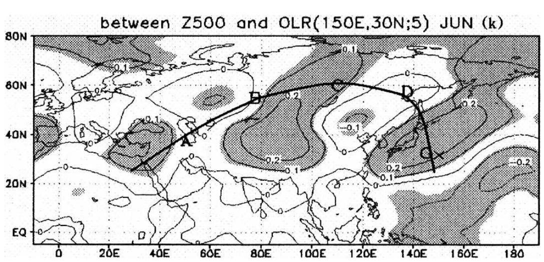


FIG. 4. Lag correlations between the OLR at (30°N, 150°E) and Z500 at every point during the period 1–30 Jun 1979–98: (a)–(e) 5 days earlier to 1 day earlier; (f) day 0; and (g)–(k) 1 day later to 5 days later. Shaded areas indicate the regions over the 95% confidence level. The arc line with A, B, C, D, and G labels is overlaid from Fig. 3.

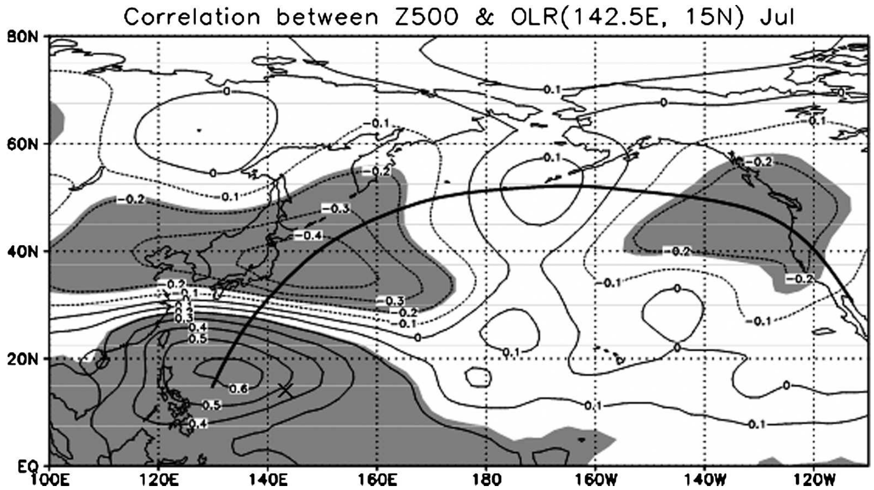


FIG. 5. The one-point correlation coefficient between Z500 and OLR at (15°N, 142.5°E) marked by a cross during the period of pentads 37–42 of 1979–98. Shaded areas indicate the regions over the 95% confidence level. The bold arc line links the correlation centers.

the arc line in Fig. 3 (figures not shown). The results of the additional correlations showed different patterns from those in Fig. 3, which indicates that the OKJ wave tends to propagate as a stationary one, at least on a 5-day time scale. However, the pattern shifts a sign when the lag times are beyond +3 or below −3 days, indicating an intraseasonal standing wave pattern.

The sources of an OKJ wave train may be located at two or three places (e.g., off East Siberia; Wang and Yasunari 1994) or the Barents Sea (Ogi et al. 2004) except for the Caspian Sea (W92). The Caspian Sea might be the main forcing region since the ray tracing with zonal wavenumber 5 is very close to the arc drawn in Fig. 3. Note that there is an insignificant correlation center in tropical Africa (20°N, 2.5°E) in Fig. 3, implying a potential OKJ wave source in the Tropics. On the other hand, correlation maps also indicate that the OKJ wave in its eastern part (i.e., from point C to G of the arc) behaves most like a standing wave, which may be due to the influence of the topography as pointed out by Wang and Yasunari (1994). Thus, sometimes this standing or stationary wave might not be the one that oscillates in place only in response to changes in forcing, but be the one that oscillates in place in response to some restoring forces. The propagation of an OKJ wave with such a standing characteristic may favor the development of an anticyclone around the Sea of Okhotsk as pointed out by W92 and Wang and Yasunari (1994).

There seems to be another wave train–like pattern from the Arabian Sea extending across the region around 35°N, 90°E into the region labeled G, and then into the central Pacific as shown in Fig. 3. The Madden–Julian oscillation (MJO) might influence the development of this second potential wave train because the train appears to originate over the tropical Indian Ocean, as discussed by Weickmann and Khalsa (1990). Similar correlations at base points around the Arabian Sea and 35°N, 90°E were also produced but omitted here for reason of brevity. However, the pattern is quite weak compared with the OKJ one and becomes weaker in the daily lag correlation maps. It appears that the decorrelation time scale of the secondary wave pattern is shorter than the primary OKJ pattern so that it "washes out" of the correlation maps earlier than the OKJ pattern. The OKJ pattern is the most obvious standing wave in the Asia–Pacific in June.

4. An exception to the normal P-J wave train

a. One-point correlation maps

A distinctly separate Rossby wave train from the Philippines to North America in late summer has been examined by many researchers (e.g., N87; Kurihara and Tsuyuki 1987). Figure 5 shows the correlation between the pentad OLR at the reference point (15°N, 142.5°E, marked by a cross) and pentad Z500 in July (pentads 37–42) from 1979 to 1998. Also in Fig. 5, positive and negative correlation centers are systematically arranged from the Philippines via the ocean area east of Japan to North America. Most of the correlation centers exceed a 95% confidence level except for the one at 52.5°N, 170°W. This wave train–like distribution coincides with that in the schematic illustration of Fig. 18 by N87, who confirmed that the Rossby waves associated with the

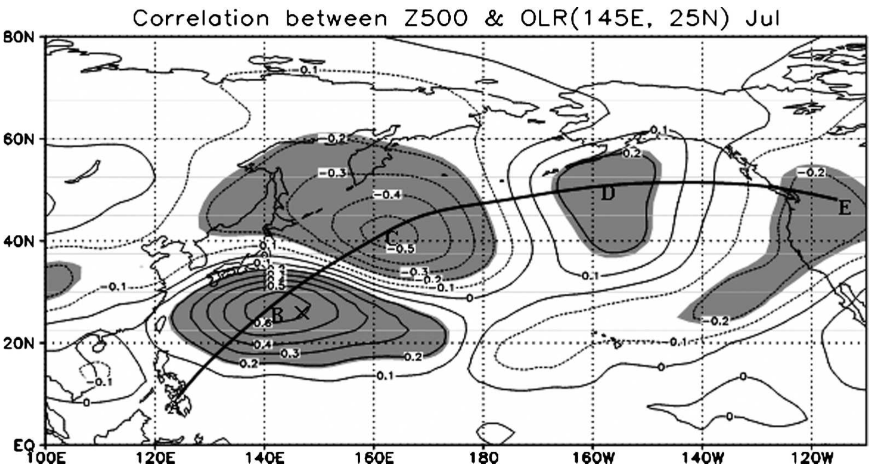


FIG. 6. Same as in Fig. 5, but for the reference OLR at (25°N, 145°E) marked by a cross. The full line (A–E) links the significant correlation centers.

convective activity around the tropical region near the Philippines (in the vicinity of the OLR reference point in Fig. 5) usually propagate along an arc route (full line in Fig. 5). The OLR base points around the Philippines slightly moving east–west do not cause a big change in the wave train pattern, which is different from the base point in the focus area for the OKJ wave train pattern. The frequent Rossby wave propagation associated with the oscillation of the convective activity between Japan and the Philippines could cause the main body of a subtropical high to be centered farther northeastward than usual and result in a hot summer in Japan (N87; Kurihara and Tsuyuki 1987). This Rossby wave propagation is referred to as "P-J propagation" in section 1.

Since the routes in Figs. 1 and 5 intersect over the area off the east coast of Japan, the two Rossby wave propagations might meet in the region when they occur during the same period. According to previous studies (N87; W92), OKJ propagation occurs preferentially in early summer and P-J propagation occurs much more frequently in late summer. This may be the reason there has been little analysis of the interaction between the two Rossby wave trains. However, the spatial pattern in the third significant empirical orthogonal function (EOF) component[2] for pentad Z500 in July and August during 1979–98 indicates a clear OKJ-like distribution (figure omitted).

The P-J propagation discovered by N87 is based on the atmospheric response to a tropical heat source. The cloud oscillation between Japan and the Philippines, clearly observable in late summer, is merely a phenomenon of the response. To discover whether the P-J propagation would still occur if the wave forcing were not limited to the Tropics, we tested the correlation between Z500 and OLR at points downstream of the Philippines roughly along the arc line in Fig. 5. Wave train–like correlation patterns similar to those in Fig. 5 were found for the reference points of OLR at ~25°–32.5°N along the arc line. For convenience, we present only the correlation between OLR at 25°N, 145°E (marked by a cross) and the Z500 field in July (Fig. 6). Significant correlation centers were arranged at point B (the focus area: 27.5°N, 142.5°E); point C (40°N, 165°E); point D (off the south coast of the Alaska peninsula: 52.5°N, 157.5°W), and point E (around the Rocky Mountains: 47.5°N, 120°W) with alternate positive and negative signs. The full line linking the significant centers in Fig. 6 indicates the great circle,[3] which almost overlaps with the one in Fig. 5. This kind of distribution is very similar to those in Fig. 5, but with a phase shift of about 90°. Figure 6 shows that a strong signal of the P-J-like pattern exists in July. However, the wave train in Fig. 6 may be explained in an alternative way since the reference point of OLR is located in the extratropical region (as opposed to the tropical region). In other words, the Rossby wave forcing may be located either over the tropical region such as near point A or over the subtropical regions (e.g., near point B in Fig. 6). For example, in the former case

[2] The statistical significance of the variance associated with each EOF was verified using the selection rules of the Monte Carlo technique (Overland and Preisendorfer 1982).

[3] Although the observed basic state is much more complex than a simple super rotation, the signal of the barotropic Rossby wave dynamics was not ignored in the observation. The path linking the correlation centers is still approximately a great circle.

the cyclonic circulation around point B (the focus area) and the active convection around the region marked by the cross are responses to tropical forcing, the negative heating anomaly around point A as pointed out by N87. But in the latter case the cyclonic circulation and the active convection around the extratropical region might imply the presence of local forcing. Since the correlation pattern is insensitive (figures not shown) when the base point is changed slightly in longitudes, the latter one might tend to occur. N87, obviously, did not include the latter although the waves propagated along a similar route. The correlation between OLR at the point 25°N, 150°E and Z500 in August and that at the reference point 15°N, 145°E in June (figures not shown) also demonstrate a very similar distribution to that in Fig. 6. Thus, P-J-like wave propagations dominate over the entire summer.

As mentioned above, however, the wave phase in Fig. 6 has a difference of about 90° from that in Fig. 5. Consequently, if the wave train in Fig. 5 is regarded as the normal P-J wave, then the one in Fig. 6 should be an abnormal one. (For convenience, hereafter we refer to the abnormal P-J wave with the positive phase in Fig. 6 as the P-Ja wave.) The P-Ja wave in the lower and midtroposphere (e.g., 500 hPa) should possess cyclonic circulation southeast of Japan (near point B) and anticyclonic circulation around point C in Fig. 6 and so on. Note that the normal P-J wave train with the positive phase[4] usually produces anticyclonic circulation around Japan, but the P-Ja wave train does the opposite.

Figure 7 is similar to Fig. 4 except for the base point at 25°N, 145°E in July. Although the correlation pattern of P-Ja is also basically unchanged with the lag correlation from −2 to +2 days, there is a slight phase shift northeastward downstream as shown in Fig. 6. A similar downstream phase shift also occurs with the OLR at (15°N, 142.5°E) on a daily time scale (figures not shown). The pattern shifts a sign more obviously when the lag times are beyond +2 or below −2 days. Therefore, the P-J-like propagation belongs to an intraseasonal phenomenon.

b. *Discussion*

As shown in Fig. 7, the downstream phase shift was obvious, which displays the phase propagation. Pentad correlation maps were also produced by using base points near the zero-correlation contours that intersect the arc line in Fig. 6 (figures not shown). The results of the additional correlations showed similar pattern with phase shifts compared with that in Fig. 6, which was different from the correlations for OKJ pattern as mentioned in section 3c. The P-J-like propagation is not the one that tends to have nearly zero phase speed as proposed by N87 and Kurihara and Tsuyuki (1987), but is the one that tends to have phase propagation. A P-J-like wave keeps some stationary features but is mainly an intraseasonal propagating one.

Nevertheless, if a P-J wave train responds to tropical convection, it is possible that a P-Ja wave train can also respond to subtropical convection because these correlations behave similarly. In fact, as HK81 pointed out, the location of a Rossby wave source in a subtropical region is normal.

5. Observations in July 1998

Severe flooding occurred around the Yangtze River in China in the summer of 1998. This flooding was associated with a blocking high located northwest of the Sea of Okhotsk and an abnormal westward-extending subtropical high in the decaying phase of an El Niño, as pointed out by Wang et al. (2001). The Okhotsk high was strong until late August 1998. The mean circulation field (figure not shown, refer to Fig. 12a in Wang et al. 2001) shows that a strong ridge between Lake Baikal and the Sea of Okhotsk developed and the negative anomaly of Z500 occurred around the northern edge of the subtropical high (including the sea area east of Japan) throughout the summer. This situation is often associated with the OKJ propagation, as pointed out by W92.

a. *Occurrence of two separate waves during the same period*

To examine the two wave train propagations occurring simultaneously in the summer of 1998, we traced observed propagations of the OKJ and P-Ja, respectively. Figure 8 shows the time evolution of daily Z500 deviations from the 360° zonal mean along the full line of (left) A, B, C, D, and G in Fig. 3 and (right) the daily OLR at point 30°N, 150°E during June and July 1998. It is noteworthy that the intervals of the abscissa of the left figure are not exactly but roughly equivalently picked up along the arc line in Fig. 3. Bold lines indicate the wave group propagation drawn subjectively. The figure shows three OKJ-like propagations in June and two in July, indicating the frequent dispersions of energy along the great circle. The second and third propa-

[4] A normal P-J wave train with a positive phase means that the propagation is associated with active convection near the reference point in Fig. 5, which produces negative height anomalies east of the Philippines, positive height anomalies off the east coast of Japan, and so on.

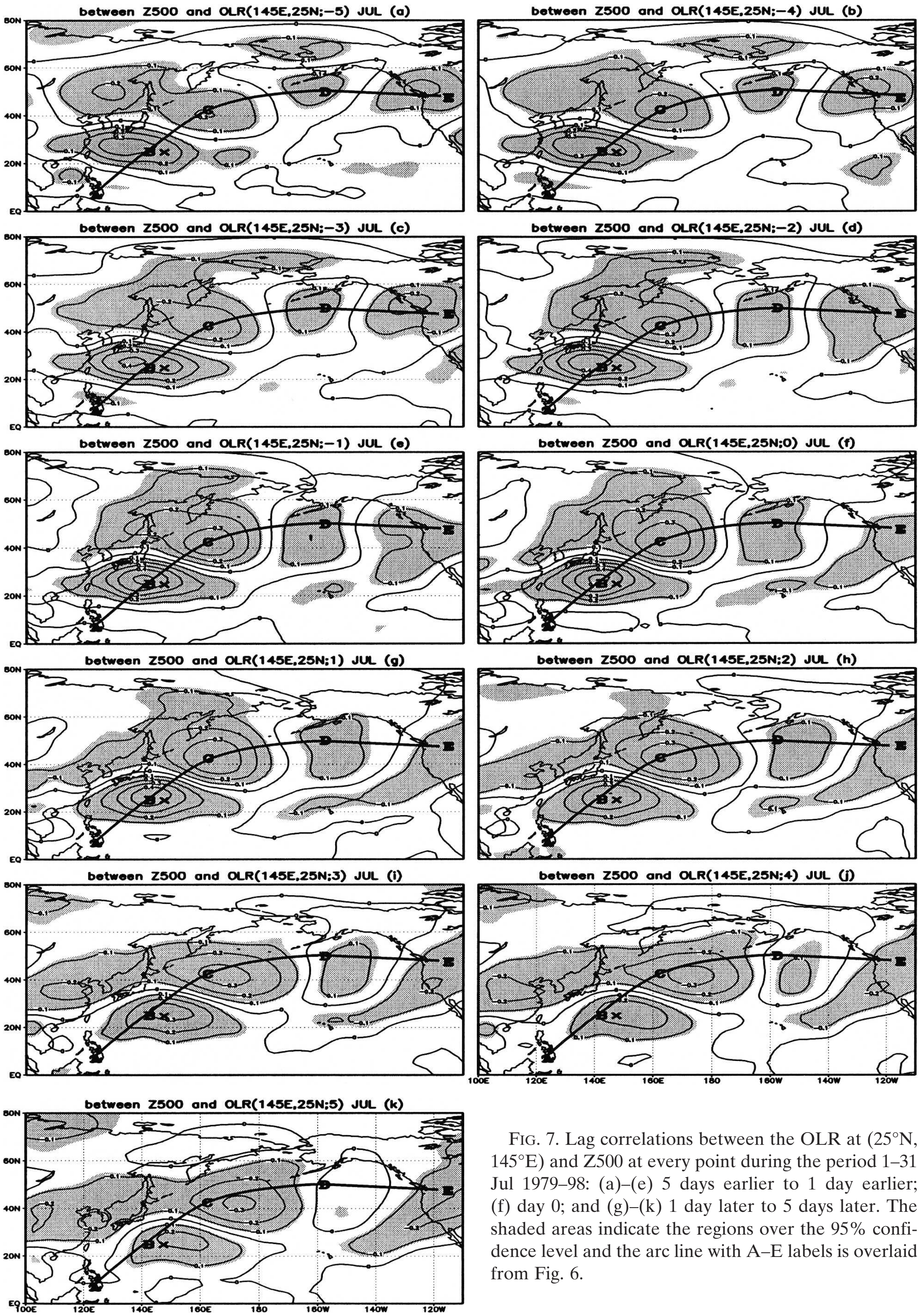


FIG. 7. Lag correlations between the OLR at (25°N, 145°E) and Z500 at every point during the period 1–31 Jul 1979–98: (a)–(e) 5 days earlier to 1 day earlier; (f) day 0; and (g)–(k) 1 day later to 5 days later. The shaded areas indicate the regions over the 95% confidence level and the arc line with A–E labels is overlaid from Fig. 6.

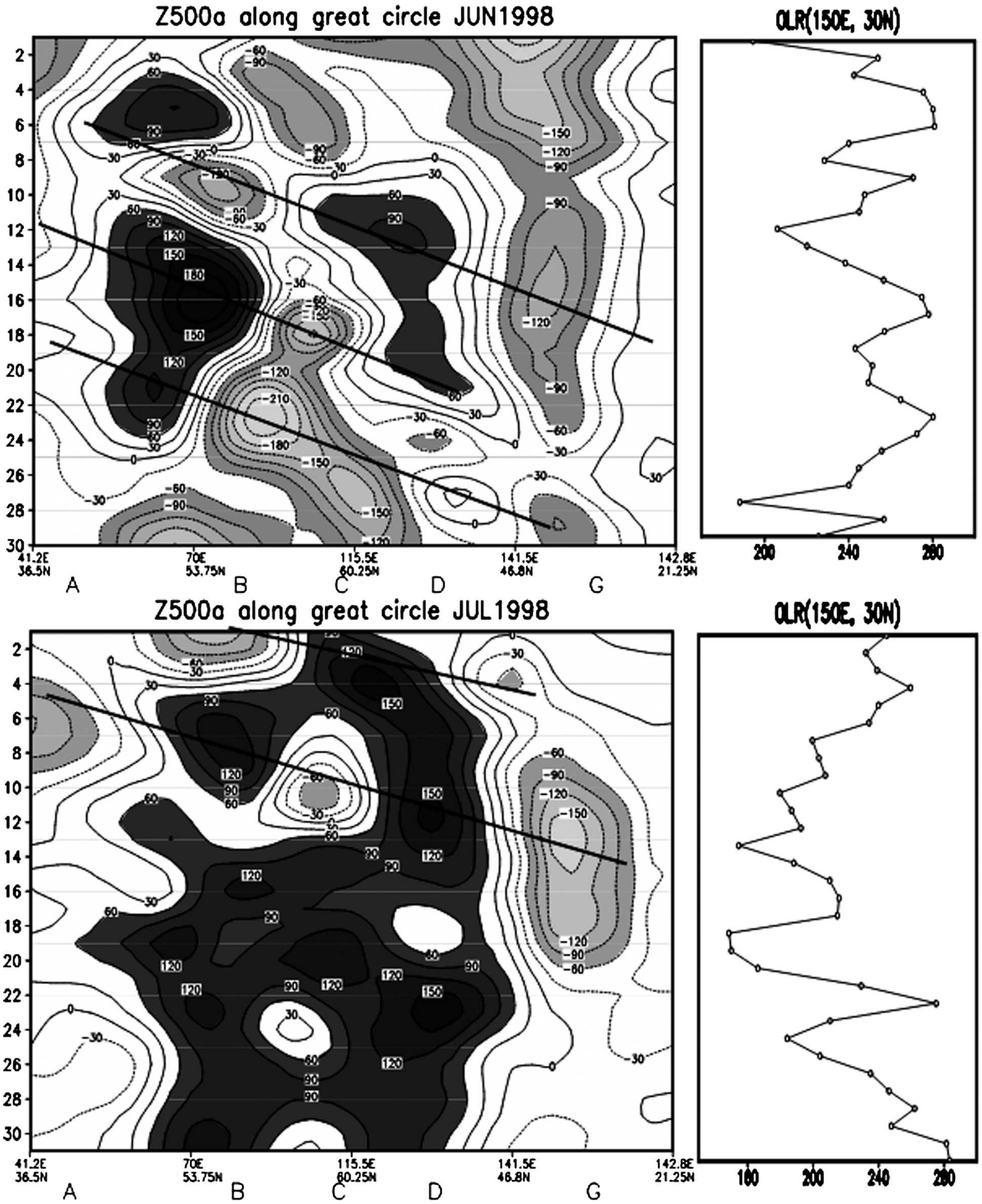


FIG. 8. (left) The daily Z500 anomaly extracted from zonal mean along the arc line (A, B, C, D, and G in Fig. 3) for June and July 1998. Solid (dashed) lines indicate positive (negative) anomalies and shaded areas illustrate the regions over absolute value of 60 gpm. The contour interval is 30 gpm. The bold lines indicate wave train propagation subjectively. (right) The evolution of daily OLR at point 30°N, 150°E for June and July 1998 (W m^{-2}).

gations in June behave in a stationary manner upstream (from near 70°E to point C) where their wave phase was almost opposite the first one, but do not generate a large amplitude downstream (to the east of point C). In contrast, the first and especially the second propagations in July have large anomaly centers downstream. The second propagation (5–13 July) was characterized mainly by a positive height anomaly center in the upstream areas of the Sea of Okhotsk (point D) and a negative height anomaly center off the east coast of Japan (point G), which intensified the local ridge and trough. This propagation is similar to that in June 1982 as analyzed by W92. The propagation from near point A to near point G took about 8 days, corresponding to

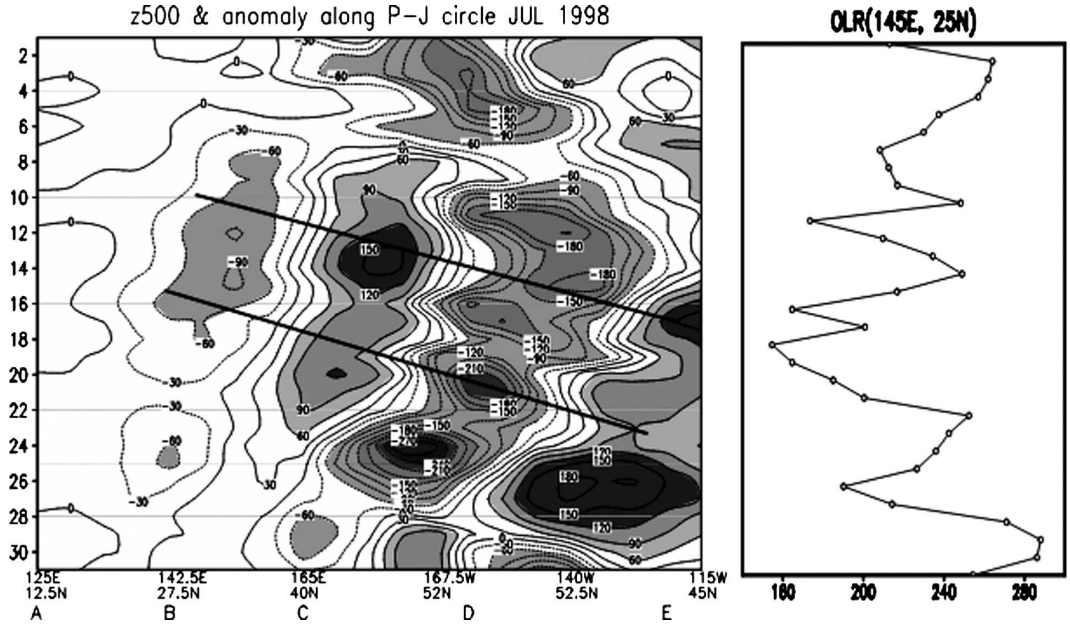


FIG. 9. (left) Same as in Fig. 8, but for the arc line (A–E) following the marks in Fig. 6 and (right) the daily OLR at point 25°N, 145°E for July 1998.

the stationary wave–tracing analysis in section 3. Note that in this wave dispersion, the negative anomalies persisted and amplified around point G, which was near the eastern end of the path the former OKJ propagations never reached. In particular, the wave dispersion generated large-amplitude height anomalies around D (maximum over 150 gpm) and G (minimum below -150 gpm) while the value of OLR at the base point (near point G) successively decreased from 234.2 to 154.6 W m^{-2}, which indicated strong in situ convections associated with the OKJ propagation.

Figure 9 is the analog to Fig. 8 for the July Z500 deviations along lines A–E in Fig. 6 and the evolution of the value of OLR at point 25°N, 145°E. The wave train propagations from the lower latitudes also occurred in July, as shown in Fig. 9. The propagations during 11–17 and 16–20 July show a negative anomaly center near point B (the focus area), a positive center between points C and D, and a negative center near point D. The OLR value kept decreasing during 2–7 July, then increased slightly for 3 days, and suddenly dropped to the minimum (173.6 W m^{-2}) on 11 July when the first propagation began. The beginning of the second propagation was also associated with a minimum value of OLR (164.6 W m^{-2}) on 16 July. This anomaly pattern was defined as the P-Ja wave train in section 4. Both the OKJ and P-Ja propagations with different directions occurred during the same period (i.e., mid-July, as shown in Figs. 8 and 9). The OKJ propagation with large negative height anomalies approached point G in Fig. 8 on 11 July when the P-Ja propagation started at point B in Fig. 9, which suggests that both OKJ and P-Ja propagations are closely related. Note that both OKJ and P-Ja propagations in mid-July were accompanied by negative anomalies off the southeast (or east) coast of Japan. The P-Ja propagation also produced a positive height anomaly over the West Coast. The P-Ja propagations in this case strongly behave as a stationary wave in spite of a phase speed about -0.03 m s^{-1} downstream.

To investigate the phenomenon in detail, we selected the period during 7–18 July, when the two wave trains coexisted, as shown in Figs. 8 and 9. Figure 10 shows the average geopotential height and the horizontal wave activity flux during this period. The horizontal wave activity flux was calculated according to Plumb (1985), using a method that indicates the horizontal magnitude and direction of the quasi-stationary wave propagation. The formula is as follows:

$$F = \begin{pmatrix} F_\lambda \\ F_\phi \end{pmatrix} = \frac{p}{p_s}\cos\phi \times \begin{pmatrix} v'^2 - \dfrac{1}{2\Omega a \sin 2\phi}\dfrac{\partial(v'\Phi')}{\partial\lambda} \\ -u'v' + \dfrac{1}{2\Omega a \sin 2\phi}\dfrac{\partial(u'\Phi')}{\partial\lambda} \end{pmatrix}, \qquad (4)$$

where u' and v' are the zonal and meridional wind deviations, respectively, from the zonal mean approxi-

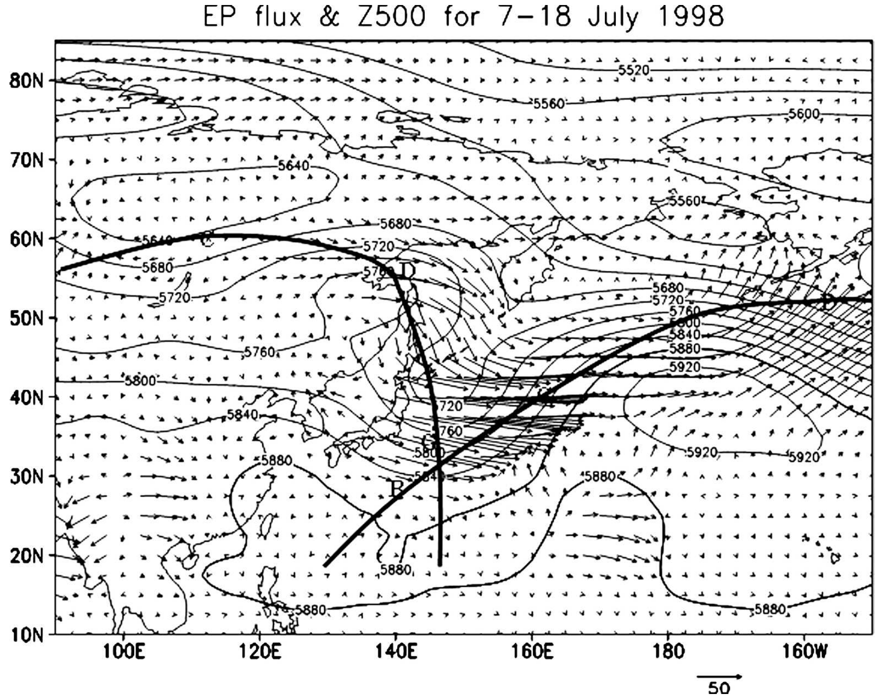


FIG. 10. Z500 and the wave activity flux ($m^2\ s^{-2}$) during the period of 7–18 Jul 1998. The line of 5800 gpm is in bold and the crossed full lines are the parts of the arcs picked up from Figs. 3 and 6, respectively. The contour interval is 40 gpm.

mated geostrophically. For detailed information on the elements, refer to Wang and Yasunari (1994). The wave activity flux is usually used to diagnose multiyear mean anomalies (Plumb 1985; Karoly et al. 1989). However, Kanaya (1986) and Wang and Yasunari (1994) effectively described Rossby wave propagation below a 10-day time scale in an East Asian summer by using this tool. Following their analysis, we used data averaged over 10 days to calculate the horizontal wave activity flux in this study. They also found that the position of the height anomaly defined as the departure from the zonal mean is very close to that computed from the time mean data in the East Asian summer. Since the geostrophic approximation for the calculation of the flux might fail in tropical regions, as pointed out by Karoly et al. (1989), we only show the flux over 10°N. A high is centered in the area west of the Sea of Okhotsk, a trough is located east of Japan, and another high is centered at 40°N, 175°W. The ridges and troughs in Fig. 10 coincide with the positive and negative height anomaly centers in Figs. 8 and 9. This suggests that the wave trains contribute to the intensification of the troughs and ridges, especially the trough to the east of Japan where both the wave trains passed simultaneously. A beam of the strong wave activity flux propagated roughly following the OKJ arc downstream (i.e., from East Siberia via the Sea of Okhotsk to northern Japan), which coincides with the large amplitude of Z500 anomaly centers along the downstream part of the bold line in Fig. 8. In contrast, another beam of the strong flux has a slight bias but roughly follows the P-Ja arc (i.e., from the focus area across the North Pacific to North America). The eastward flux off the east-southeast coast of Japan that does not follow the two arc routes is the vector composite of the southeastward and northeastward fluxes. Wave activity flux diagnostics show two distinct Rossby wave propagation routes, as a strong flux emanates from upstream areas of the Sea of Okhotsk eastward before merging with a separate wave train originating from the area east of Japan and propagating northeastward.

Figure 11 shows the time–latitude section of the TBB mean (below 270 K) and the Z500 anomaly from the zonal mean (below −40 gpm) along 145°–160°E in July. TBB minima areas describe active local convection similar to OLR. The areas below 270 K indicate strong convective activities. The region between 145° and 160°E in Fig. 11 involves the ocean area where both the P-Ja and OKJ wave trains merged in July. Variations in the convective activity are basically associated with those of the negative Z500 anomaly. Convective activity around the west Pacific began to shift southward

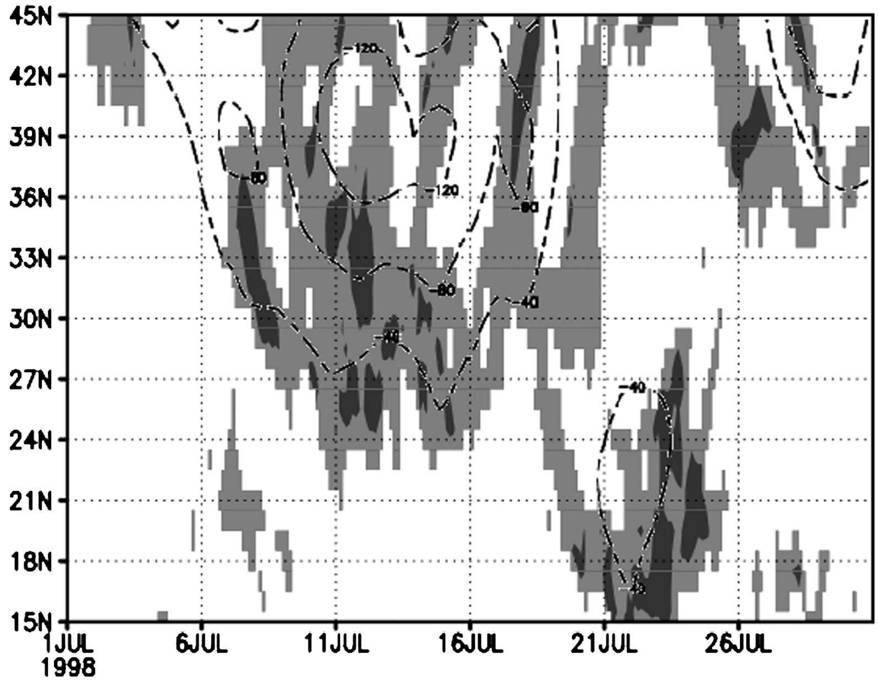


FIG. 11. Time–latitude section of TBB (<270 K; shaded areas) and the Z500 anomaly from the zonal mean below −40 gpm (dashed lines) along 145°–160°E in July 1998. The contour interval is 40 gpm.

from 31°N on 8 July to 21°N (near the reference point of OLR in Fig. 6) on 11 July, while the −40 gpm negative anomaly varied from 32° to 27°N. The TBB minima area shifted farther southward (<18°N) on 22 July. The southward shifts of the TBB minima were evidently caused by the OKJ propagation with the southeastward extension of the trough, as pointed out by W92. Note that in Fig. 9 the P-Ja wave train that originated near point B started the propagation on 11 July when the TBB minima shifted southward to ~25°N. The −40 gpm negative height anomaly with strong convection reached the lowest latitude (~26°N) on 15 July when the P-Ja propagation started. This suggests that the abnormal southern location of the western axis of the subtropical high in mid-July in Fig. 10 probably resulted in part from the coupling of the P-Ja and OKJ wave train propagations.

b. *The forcing of the P-Ja wave train*

As mentioned in section 4, the P-Ja wave forcing may be located in either tropical or extratropical regions. The wave forcing of the P-Ja wave train associated with the OKJ propagation in mid-July 1998 may be located around the focus area. This is because the P-Ja wave train started from that area after the OKJ propagation began, as shown in Figs. 8 and 9. To depict the sequence of the occurrence of the OKJ and P-Ja propagations, we calculated the 10-day mean wave activity flux and Z500 centered on days from 30 June to 9 July, as shown in Fig. 12. A ridge upstream of the Sea of Okhotsk developed into a strong high with a closed contour line around which the eastward flux became stronger from 28 June to 9 July, as shown in Figs. 12a–c. There is no P-Ja-like signal in these panels. The strong flux roughly following the OKJ arc then turned southeastward during 1–10 July (Fig. 12d). A very weak northeastward flux around southern Japan started between 1 and 10 July. Note that the flux in Tropics should not be considered due to the geostrophic approximation in the Tropics, as pointed out by Plumb (1985). This northeastward flux intensified, as shown in Figs. 12e,f. The strong ridge became a mature blocking anticyclone around the Sea of Okhotsk during the periods studied. The growing northeastward fluxes in Figs. 12d,e constitute a sign of the P-Ja wave that formally started to propagate on 11 July, as shown in Fig. 9. The information about the growing P-Ja wave is contained mainly in the second half of 2–11 July, as shown in Fig. 12e. The P-Ja signal emerged gradually from Figs. 12a–e. Since the front of the OKJ propagation with a large negative anomaly (below −90 gpm) reached point G on 8 July as shown in Fig. 8, the period between 8 and 11 July can be considered an embryonic stage for the P-Ja propagation.

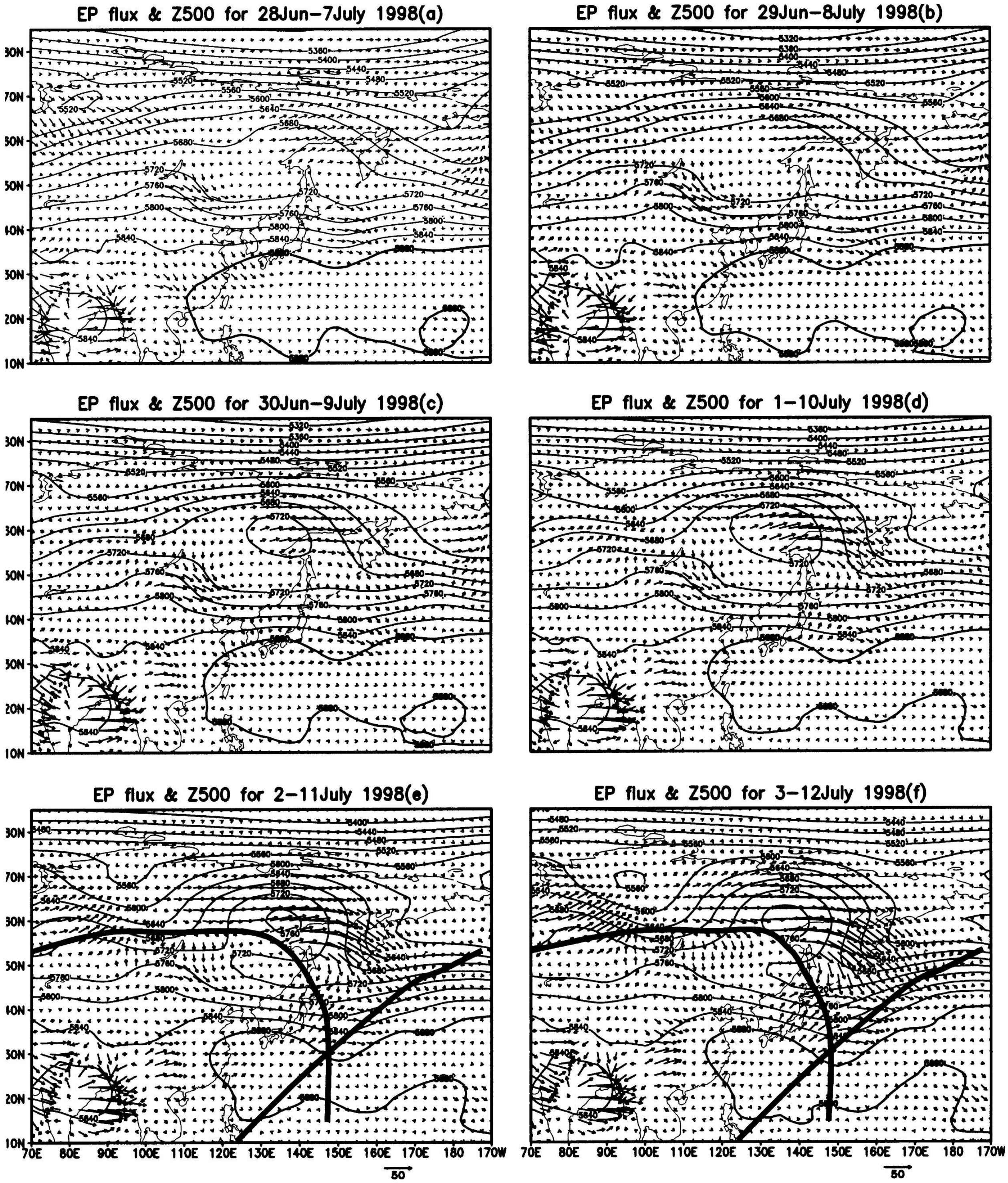


FIG. 12. Same as in Fig. 10, but for (a) 28 Jun–7 Jul, (b) 29 Jun–8 Jul, (c) 30 Jun–9 Jul, (d) 1–10 Jul, (e) 2–11 Jul, and (f) 3–12 Jul, respectively.

To examine how the P-Ja propagation was initiated, we concentrated on the evolution of the convection off the east or southeast coast of Japan in the embryonic stage. Figure 13 shows the twice-daily TBB averaged from the 3-hourly data. Only TBB below a critical value of 250 K, which represents strong convective activity, is displayed in shaded areas. The critical value of TBB here is lower than that defined in Fig. 11 because TBB

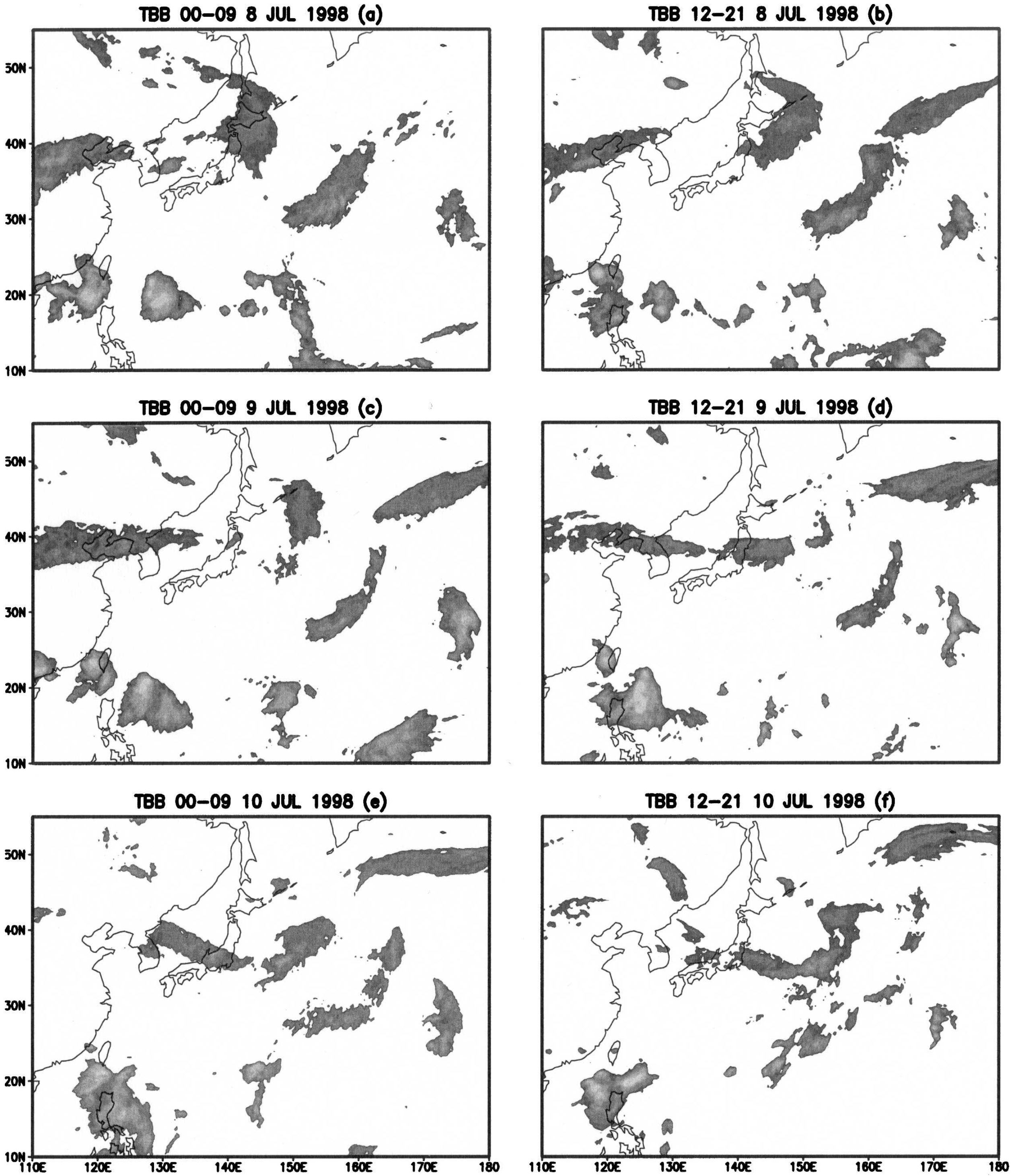


FIG. 13. Twice daily TBB distribution during 8–10 Jul 1998. The shaded areas are displayed only for the value below 250 K.

in Fig. 13 is averaged over a region 15° of longitude smaller than that in Fig. 11. Although the description of the evolution of the twice-daily TBB covers 6–18 July, only the plots from 8–10 July are shown here. The areas with TBB minima started to shift southward from north Japan on 6 July and reached 30°N, 150°E on 8 July. The southeastward shift from north Japan to the focus area continued until 14 July. The TBB minima gradually expanded to the focus area during 8–10 July. This corresponds to the enhancement of convection around 21°–31°N, 145°–160°E during 8–10 July in Fig. 11. The TBB minima stayed in the region during 8–18 July. TBB minima are also found around the Philippines during those days; this is associated with an in situ trough shown in the sequence in Fig. 12. However, the convective activity in the Tropics is not the wave forcing due to two reasons: 1) it is too far from the strong divergence off the southeast coast of Japan; and 2) it tends to generate a normal P-J wave train propagation rather than the P-Ja wave train propagation pointed out by N87 and discussed in section 4. The strong convective activity persisting in the focus area is the product of the OKJ propagation. This is because the southward shift of the TBB minima is associated with the increase of the amplitude of the negative height anomaly in the region and the southeastward wave activity flux just to the northwest of the convection, as shown in Figs. 8, 11, and 13. The TBB minima in the focus area indicate a strong local upward motion that could produce a strong divergence in the upper troposphere, which can act as a wave forcing (Ambrizzi et al. 1995; Sardeshmukh and Hoskins 1988). Compared with the daily-scale phenomenon in Fig. 13, Fig. 14 shows the 5-day running mean of OLR below 200 W m^{-2} from 1–5 to 6–10 July 1998. OLR minima were stably intensified in the focus area during 1–10 July, which gradually formed a strong forcing. Figure 15 shows the divergence and vertical velocity (shaded area) at 700 hPa and the divergence at 200 hPa, respectively. Negative values of vertical velocity indicate ascending motion. A very large area (centered at about 30°N, 153°E with the value below) with upward motion is found in the focus area where the two wave trains merged at all levels; the maximum is found at 400 hPa. The ascending motion can be found at all levels from 850 to 200 hPa (not shown), which indicates deep in situ convection. A strong divergence (over 0.9×10^{-5} s^{-1}) is centered at 30°N, 157°E at 200 hPa and a convergence (below -0.2×10^{-5} s^{-1}) is overlaid with an ascending flow (below -0.1 hPa^{-1}) at 30°N, 153°E at 700 hPa. The divergence occurs above the 400-hPa level at which the maximum upward motion occurs; convergence appears below this level. Such a forcing-like phenomenon has not occurred so far (figures omitted). Note that, outside the focus area, there is no strong vertical motion or convergence/divergence near the Philippines or other places. Therefore the deep convection associated with upper-level divergence (especially at 200 hPa) in the focus area acted as the wave forcing of P-Ja propagation in mid-July 1998.

The physical mechanism for the formation of the P-Ja propagation in mid-July 1998 is described as follows. After frequent OKJ-like propagations occurred in the second half of June, a weak negative geopotential height anomaly area formed off the east coast of Japan to provide a cyclonic circulation environment there. Then a strong OKJ propagation through the dispersion of energy downstream from early to mid-July brought a series of the southward-shifting cyclonic circulation and convective activity so that the negative height anomaly was amplified more in the focus area. A deep convective activity area was established on or to the east of the center of the enhanced cyclonic circulation during the period of 8–11 July that is thought of as the embryonic stage for the Rossby wave forcing of the P-Ja wave train. The forcing was characterized by a strong convective activity accompanied by an upper-level divergence in the focus area. It was enhanced by the southward-shifted convection from the extratropical region and resulted in the P-Ja wave propagating northeastward during 11–18 July.

6. Conclusions

The results are summarized as follows:

1) A stationary wave ray with the zonal wavenumber 5 approximates the OKJ arc path linking the correlation centers originating from the Caspian Sea via Lake Baikal to the focus area in a pentad correlation map between Z500 and OLR at 30°N, 150°E in June (Fig. 3). The ray tracing shows that a wave with the zonal wavenumber 5 propagating from an initial position around the Caspian Sea to the focus area takes 8–10 days, which roughly coincides with the observed case.
2) A wave train pattern (P-Ja) in boreal summer is defined, which propagates along the arc line in the same way as the normal poleward Rossby wave train (P-J) originating from the Philippines across the North Pacific, but with a phase shift northeastward of about 90°. The two wave trains have similar features in the correlation maps.
3) Further correlation analyses showed that P-J-like waves belong mainly to intraseasonal propagating ones, while an OKJ wave belongs mainly to an intraseasonal stationary one in general.
4) The propagation of the newly defined wave train pattern (P-Ja) occurred following another one along the OKJ arc path in mid-July 1998. Both northeastward and southeastward wave propagations merged off the east coast of Japan.
5) The northeastward wave propagation (P-Ja) in mid-July 1998 was triggered by the southeastward wave propagation (OKJ) that produced a deep cyclonic

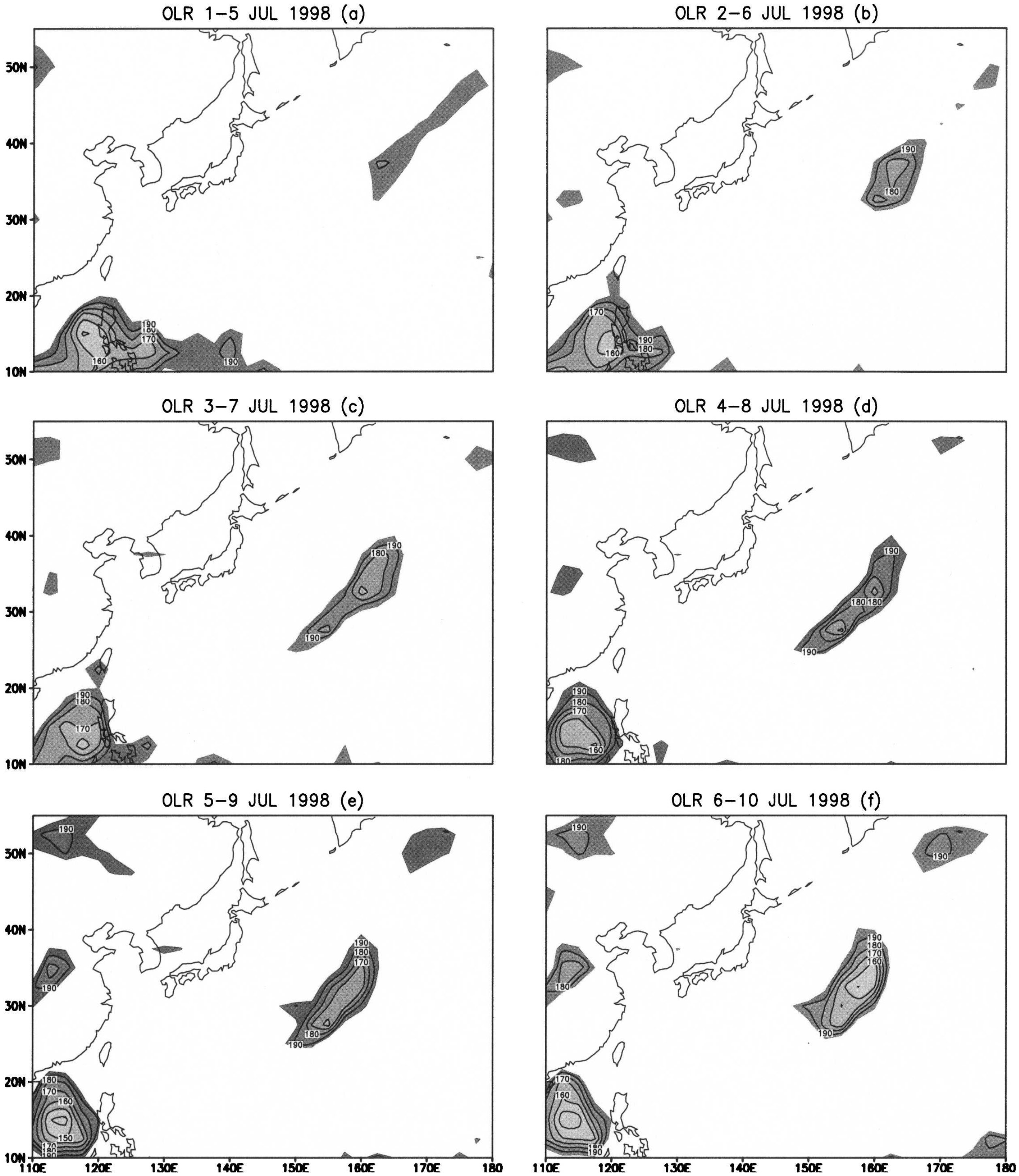


FIG. 14. The 5-day running mean of OLR from 1–5 to 6–10 Jul 1998. The shaded areas indicate the value below 200 W m^{-2} and the contour interval is 10 W m^{-2}.

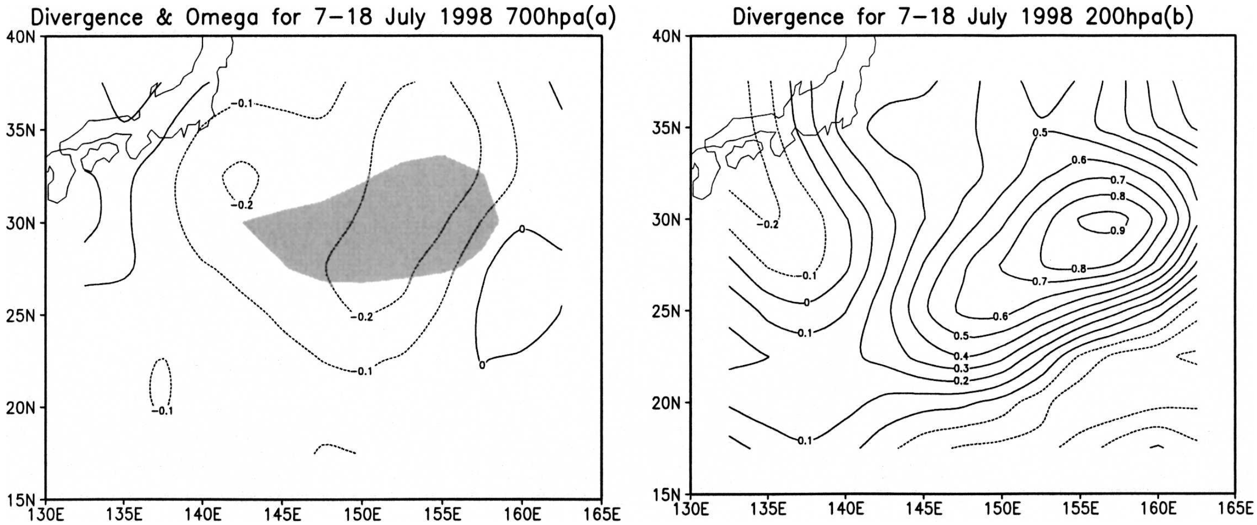


FIG. 15. Divergence of horizontal velocity at (a) 700 and (b) 200 hPa. The contour interval is 0.1×10^{-5} s^{-1}. Positive values are shown with solid lines and negative ones with dashed lines. The shaded area indicates the negative value of the vertical velocity below -0.08 Pa s^{-1} that shows upward motion averaged during 7–18 Jul 1998 at 700 hPa.

circulation and the strong convective activity in the focus area. The link of the wave forcing and strong convection was made solely because of the presence of a strong upper-level divergence in the focus area.

Although our study indicates that the wave forcing of the P-Ja propagation in mid-July 1998 was caused by the OKJ propagation, some aspects of the mechanism for the interaction between these two wave trains are still unclear. As discussed in section 5, strong convective activity persisting in the subtropical region with an upper-level divergence also acts as a wave forcing for P-Ja propagation like that in the Tropics for the normal P-J propagation. However, N87 regarded the convective activity as a heat source in the Tropics (refer to section 5 of N87). The convection around the Philippines purely represents the activity of tropical systems such as typhoons and tropical cyclones as pointed out by N87, whereas that associated with the OKJ propagation in the focus area includes extratropical phenomena (e.g., disturbances along the subtropical front, as discussed in section 5 and by W92). The wave forcing in the focus area in mid-July 1998 involved the synoptic-scale disturbances in midlatitude (i.e., the southward shift of the convective activity shown in Fig. 13). Convective activity in the subtropical regions, as in this case, plays an important role in enhancing upward motion by the release of latent heat in the midtroposphere. However, it is still possible that the wave forcing in the focus area, which generates P-Ja propagation, is the northward-shifting convection from the Tropics. The north–south mobile forcings triggering P-J-like waves might result in the propagating feature.

The blocking anticyclone around the Sea of Okhotsk was strong and stable in midsummer 1998, which was associated with a strong OKJ propagation. The subsequent occurrence of the two propagations may be partly due to abnormal background climatology, because strong OKJ propagation usually occurs in early summer.[5] As a result, the coupling of the two separate propagations produced the cyclonic circulation in the focus area (which is also the northern edge of the subtropical high); this played a role in suppressing the northward development of the subtropical high. When a steady subtropical high maintains a position farther south than normal, the convergence of the vapor flux with strong southwesterlies tends to be enhanced around the Yangtze River in China (Wang et al. 2001). Thus summer flooding of the Yangtze River could be caused in part by the coupling of the two planetary Rossby wave propagations. In addition, since the P-Ja propagation could produce a very large height anomaly over the West Coast, as shown in Figs. 6 and 9, the relationship between the coupling and the weather there should be examined in the future.

Ambrizzi et al. (1995) found a waveguide with the wavenumbers 7–8 extending from the Eurasian continent to the North Pacific in boreal summer. The P-J-like propagation seems to roughly follow the eastern part of the waveguide. Therefore, the P-J-like path with the zonal wavenumbers 6–7 might belong to the waveguide as well. The OKJ path might be different,

[5] Similar phenomena occurred several times in the summers from 1979 to 1998; however, we do not address them here.

however, since it reaches a higher latitude (about 60°N). Further analysis of the relationship between them is desirable. Note that strong signs appeared generally upstream or downstream of the OKJ propagation path, as shown in Fig. 8, which seems to be an energy dispersion relay occurring between points C and D of the path. This may imply that the energy dispersion of the OKJ pattern is weaker than that of the P-Ja pattern, although the positive anomaly alternated with a negative one continuously. The phenomenon of the wave dispersion relay was explained by Wang and Yasunari (1994), who pointed out that one of the OKJ wave sources was located around East Siberia, which results from a thermal contrast by land–sea heating. Thus, the thermal contrast may be one of the causes of the difference in the wave paths between the ray tracing and the correlation analysis. In addition, analysis, coinciding with the results of W92 and N87, indicates that both wave train patterns behave as a quasi-barotropic structure (figures not shown for brevity).

The problem of planetary-scale wave interaction is obviously not simple. Kiladis and Weickmann (1992) and many others have linked extratropical and tropical wave trains to heat released in moist deep convection. In most of these cases (but not all), these wave trains are triggered in the Tropics. Heating in moist deep convection and baroclinic processes might modulate further development of the wave trains along their trajectories. The wave trains form arcs that extend poleward from the Tropics and then occasionally curve back into the Tropics in regions of westerly winds, where they interact again with moist deep convection. Such wave-induced convective anomalies then occasionally excite further wave trains both in and out of the Tropics, consistent with the arguments in this study for the development of the second wave train that extended across the North Pacific rim. However, many of these wave trains, occurring on intraseasonal time scales, often correlate well with the MJO. Source regions for waves induced by the MJO generally range from the western Indian Ocean eastward through the west Pacific. More attention should be paid to the different processes for the interactions of the waves.

Because of its significant effect on the weather in East Asia, interaction of the two waves requires further observation. Indeed, the subject case generated a series of unanswered questions such as: what are the interactions between the OKJ propagation with a positive phase and the normal P-J propagation with a positive phase? Studies should be carried out in the case of the P-Ja propagation generated by a negative heat source in the Tropics as well. Although the observed case in this study is convincing on its own, simulations using an atmospheric model would also further the understanding of the various mechanisms of interactions between the waves.

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