A Diagnostic Analysis of the Wave Train Propagating from High-latitudes to Low-latitudes in Early Summer

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Abstract

By using the stationary wave activity flux of Plumb (1985), the present study carried out a diagnostic analysis of the phenomenon in which a Rossby wave propagating from high to low latitudes affects the Baiu front around Japan in early summer.

According to one composite and one case (during 20–29 June of 1982) analysis, there is a large horizontal southeastward component of the flux occasionally stretching from the Okhotsk Sea, via east of Japan (or Japan) to the sub-tropical region (about 25–27.5°N/155°E), when the blocking anticyclone around the Okhotsk Sea (the Okhotsk blocking anticyclone) establishes itself.

On the other hand, a wide and strong ascending flux covering the area from East Siberia to the Okhotsk Sea (exactly where there is a wide and large divergence of the flux) was found during 20–29 June, 1982. These suggest that this area is one of the important forcing-source-areas for the quasi-stationary wave propagation, although a complete forcing mechanism of the propagation has not been found yet.

1. Introduction

Studies of the connection between the Baiu (or cool summer) in Japan and the Okhotsk High (surface level) in relation to a blocking anticyclone or a strong ridge from East Siberia to the Okhotsk sea have been made before by many researchers (see the introduction by Wang, 1992 in detail). Kudo (1984) and Ninomiya et Mizuno (1985a, b) found that the cold northeasterly wind blowing from the eastern side of the Okhotsk high plays an important rôle in the cold summer in the Tohoku District of Japan. In addition, they pointed out that the cold air from high latitudes is warmed by the warm ocean current (so-called Kuroshio) around 30–35°N. Kanno (1988) found that the polar air mass can not reach the Baiu front directly.

The traits of a strong ridge over the Okhotsk high (generally from East Siberia to the Okhotsk sea at 500 hPa level) were put forward by Suginaka (1965) and Kurashima (1969). It has also been reported by the Japan Meteorological Agency (JMA, 1971) that a blocking anticyclone tends to occur with the Okhotsk high, at the same place as the strong ridge. At first, Kurashima (1969) thought that only cold air and vorticity advections around Okhotsk sea can form the Okhotsk high. However, Okawa (1973, 1976) pointed out that the temperature contrast between East Siberia and the sea surface around the Bering Sea favored the formation of the ridge around East Siberia at the 500 hPa level, and that the existence of a strong ridge is the most important factor in the development of a Type-E of the Okhotsk high. Kato (1985), on the other hand, showed that the sudden increase in temperature in the lower atmospheric layer from Huabei in China to Mongolia in May and June favored the development of the ridge there. This provides independent support for Okawa's view.

However, neither the relationship between the blocking anticyclone around the Okhotsk Sea (the Okhotsk blocking anticyclone) and the Baiu frontal zone, nor the mechanism of the formation of the blocking anticyclone have yet been understood clearly. Wang (1992) presented a new finding on it.[1] According to him, a wave train pattern, starting from the Okhotsk sea, passing the waters east of Japan and ending in the sub-tropics, can be found in June (Point D to Point F, as shown in Fig. 1). He pointed out that the wave train may be attributed to a Rossby-wave propagation. Figure 1 shows the map of the one-point-correlation between Outgoing Longwave Radiation (OLR) pentad-mean-values at the key point (30°N/150°E, a slightly southern po-

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[1] An analogous circulation pattern is also pointed out by Tsuyuki and Kurihara (1989) and Kodera and Chiba (1989), but not related to the Baiu front.

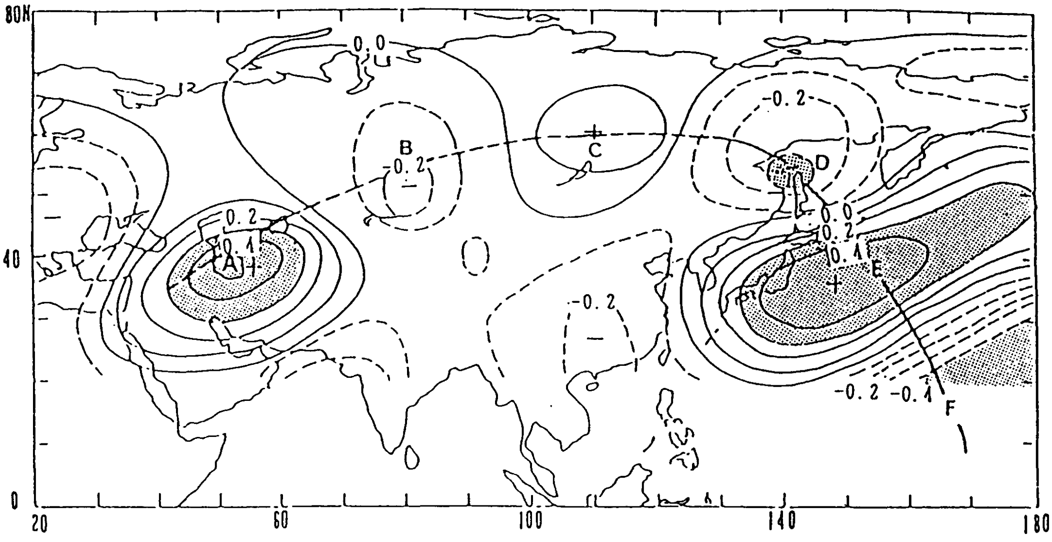

Fig. 1. Distribution of correlation coefficients between OLR at a key point (30°N/150°E) and the 500 hPa level height at all points in June, 1979–1984. Shaded areas show absolute values over 0.3 (over 90 % confidence level) and the thick (solid/dashed) line (A–F) links the positive and negative anomaly centers (after Wang, 1992).

sition from the climatological Baiu frontal zone in June and July) and height pentad-mean-values of all points at the 500 hPa level, for June in the area of 20–80°N/20–180°E, 1979–1984 (after Wang, 1992). It is seen that areas with a relatively large correlation coefficient are organized along a great arc going from the Caspian Sea, to the sea southeast of Japan, through Lake Baikal (marked by letters A–F in this figure). This pattern suggests the existence of a ray path of a stationary Rossby wave train from Point A to F, as proposed by Hoskins and Karoly (1981). However, the 90 % confidence level contours pertaining to the Okhotsk Sea (Point D), are separated from those near the Caspian Sea (Point A). Wang (1992) further pointed out that the wave-train-like propagation, associated with the Okhotsk blocking anticyclone, causes the Baiu front around Japan to shift southward. He also hypothesized that it might originate in the area between East Siberia and the Okhotsk Sea, based on the fact that the wave amplified there.

Since Hoskins and Karoly (1981) have pointed out that the atmospheric teleconnection pattern may be related to energy propagation of a Rossby wave, it has been speculated that the weather changes along the great-circle path of the wave could be the result of a Rossby wave propagation. However, the problem is now, how and by what means to assess that propagation. Edmon *et al.* (1980) studied the Eliassen-Palm flux (E-P flux) and proved that its vector is directly proportional to the Rossby wave's group velocity. Hoskins *et al.* (1983) developed a three dimensional E-P flux that emphasizes the feedback of the transient eddies onto the time mean flow. This vector is a good index only for describing transient wave phenomena. Then, Plumb (1985) extended that E-P flux vector into a diagnostic for the propagation of stationary 3-D waves and called it stationary wave activity flux (hereafter referred to as SWAF). It has been confirmed that this vector, especially its horizontal component, is a useful diagnostic of quasi-stationary waves, as seen by Kanaya (1986) and Berbery *et al.* (1992). In addition, Karoly *et al.* (1989) presented a very convincing result by using the horizontal components of SWAF in a simple model of the atmospheric response to thermal forcing in the tropics. Therefore, in spite of the quasi-geostrophic theory used, SWAF can still be a useful diagnostic of stationary wave propagation, even in the case of thermal forcing in the tropics.

Although Wang (1992) has shown the wave-train-like pattern to be a result of Rossby wave propagation by statistical methods and a case study, his arguments still call for a diagnostic tool. In view of that, the present study aims to clearly diagnose Rossby waves from high latitudes to the tropics, by means of the SWAF method, in order to support this analysis. In addition, the present study analyzes the SWAF vertical component and its divergence distribution, in order to diagnose the quasi-stationary Rossby wave source.

2. Method employed in the analysis

In order to reduce the amplification of noise by successive differentiation, the SWAF vector was developed by assuming geostrophic and thermal wind. According to Plumb (1985), an eddy flux of stationary waves in spherical geometry can be expressed as follows:

$$F = \begin{pmatrix} F_\lambda \\ F_\phi \\ F_z \end{pmatrix} = \frac{p}{p_s}\cos\phi \times \begin{pmatrix} v'^2 - \dfrac{1}{2\Omega a \sin 2\phi}\dfrac{\partial(v'\Phi')}{\partial\lambda} \\ -u'v' + \dfrac{1}{2\Omega a \sin 2\phi}\dfrac{\partial(u'\Phi')}{\partial\lambda} \\ \dfrac{2\Omega\sin\phi}{S}\left[v'T' - \dfrac{1}{2\Omega a \sin 2\phi}\dfrac{\partial(T'\Phi')}{\partial\lambda}\right] \end{pmatrix} \quad (1)$$

where

$$S = \frac{\partial\bar{T}}{\partial z} + \frac{\kappa\bar{T}}{H} \quad (2)$$

is the static stability and where wind fields were approximated geostrophically:

$$u = -\frac{1}{fa}\frac{\partial\Phi}{\partial\phi} \quad (3a)$$

$$v = \frac{1}{fa\cos\phi}\frac{\partial\Phi}{\partial\lambda} \quad (3b)$$

The divergence of the wave activity flux is generally defined as

$$\nabla\cdot F = \frac{1}{a\cos\phi}\frac{\partial F_\lambda}{\partial\lambda} + \frac{1}{a\cos\phi}\frac{\partial(F_\phi\cos\phi)}{\partial\phi} + \frac{\partial F_z}{\partial z} \quad (4)$$

Because the order of the third term in the right-hand side of (4) is much smaller, as well as difficult to be estimated exactly, it is neglected here.[2] The notations used are as follows:

$\overline{(\ )}$: zonal average
$(\ )'$: deviation from zonal mean
λ : longitude
ϕ : latitude
H : scale height (= 8 km)
$z = -Hln\left(\frac{p}{p_s}\right)$: log-pressure vertical coordinate
p : pressure
p_s : 1000 hPa
Φ : geopotential
T : temperature
Ω : rate of the earth's rotation
θ : potential temperature
a : radius of the earth
κ : ratio of the gas constant to the specific heat at constant pressure (about 2/7).

The properties of F are:

1) it is non-divergent for steady and conservative waves;

2) it is a phase-independent quantity, which is parallel to the group velocity for almost plane waves;

3) it has non-zero divergence for steady waves, indicating the existence of wave sources and sinks, as pointed out by Plumb (1985).

The twice-daily (00 and 12 GMT) geopotential height and temperature at grid points of 2.5° × 2.5° that were produced by the U.S. National Meteorological Center (NMC) for the month of June in the years 1979–1984, are used in the calculation of SWAF.

3. Horizontal wave activity flux for a circulation régime associated with the Okhotsk blocking anticyclone

According to Wang (1992), the wave train from high-latitudes to low-latitudes in June, is often related with a blocking anticyclone/strong ridge around the Okhotsk Sea (around Point D in Fig. 1). In this section, for the sake of simplicity, we discuss it only by using a composite map associated with the Okhotsk blocking anticyclone (500 hPa level). Then, we will analyze it in detail, with a case, in Section 4.

Figure 2a presents the composite distribution of geopotential height (solid lines) and its anomaly (dashed lines) at 500 hPa level (Z500 and Z'500 respectively) for those pentads that refer to the established Okhotsk blocking anticyclones. Pentads were collected so that the Okhotsk blocking anticyclone was at least 3 days in one pentad and its high center was limited to 50–70°N/131–150°E from daily weather map (same as the definition in Section 3 of Wang (1992)). Figure 2b shows the horizontal components of SWAF for the circulation régime at the 500 hPa level. Eight pentads in Fig. 2 were used from the period of June, 1979–1984. The anomalies are calculated as the deviations from mean values in June (1979–1984).

It is seen that the positive centers of Z'500 are located at 62.5°N/67.5°E (beyond 80 gpm) and near the Okhotsk Sea (beyond 70 gpm), and negative centers exist at 40°N/155°E (the sea east of Japan) (below 70 gpm) and near Lake Baikal (below 70 gpm). The ridges/troughs are located at the regions associated with the positive/negative centers of Z'500. The positive and negative centers of Z'500, closely arranged, roughly coincide with the correlation centers in Fig. 1. The Okhotsk blocking anticyclone and the trough around Lake Baikal have well developed. On the other hand, the ridge on the western side and

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[2] In fact, the three terms on the right-hand side of the Eq. (4) have been calculated in order to compare them with the first two terms in the case analyzed in Sub-section 4.1 below. However, no apparent difference between them was found. The distribution of the latter shows noiselessness.

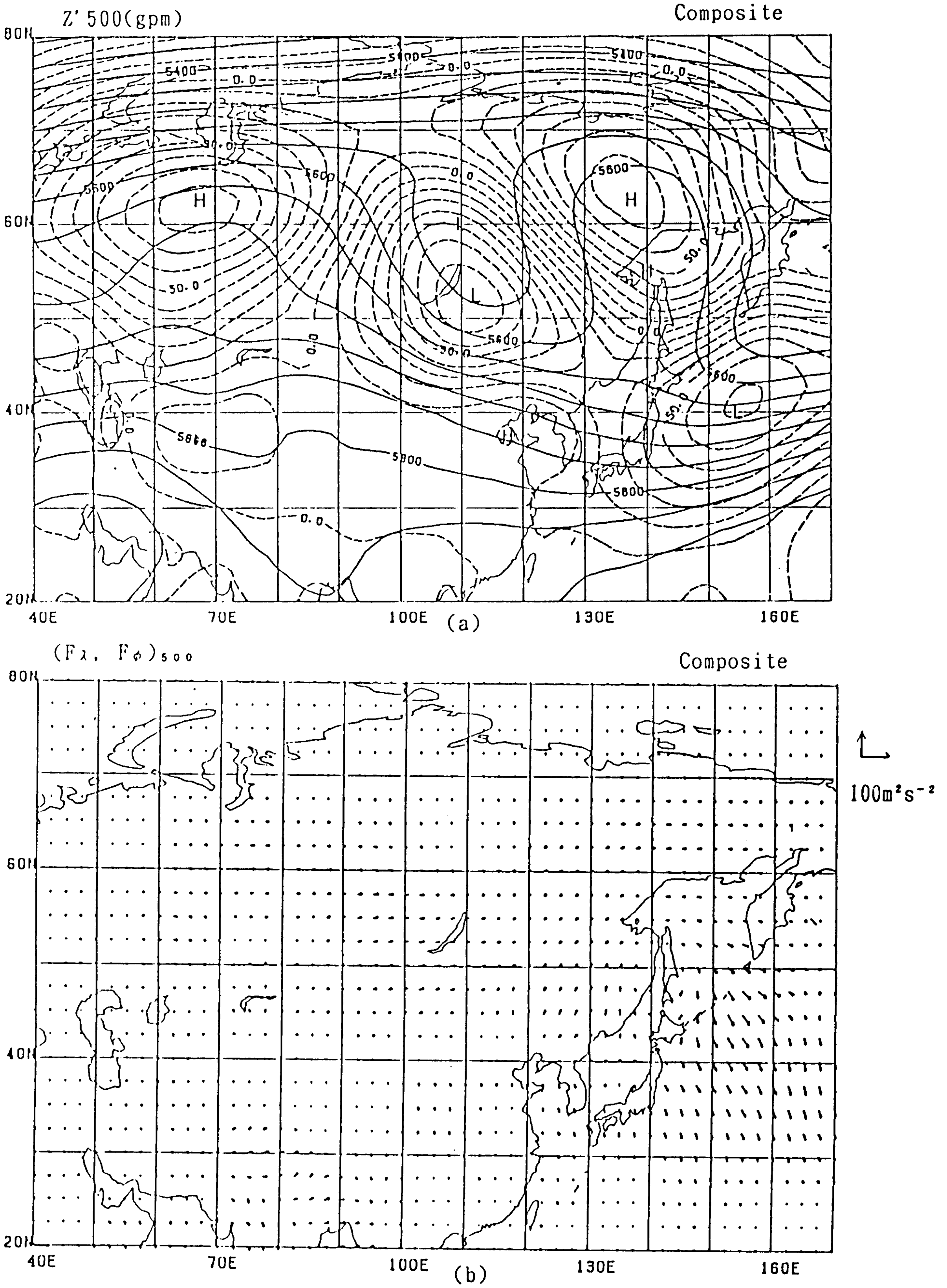

Fig. 2. Composite map of pentad 500 hPa height (solid lines) and anomalies (dashed lines) in June of 1979–1984 (a) and its horizontal component of SWAF (b) for the pentads when the Okhotsk blocking anticyclone is established.

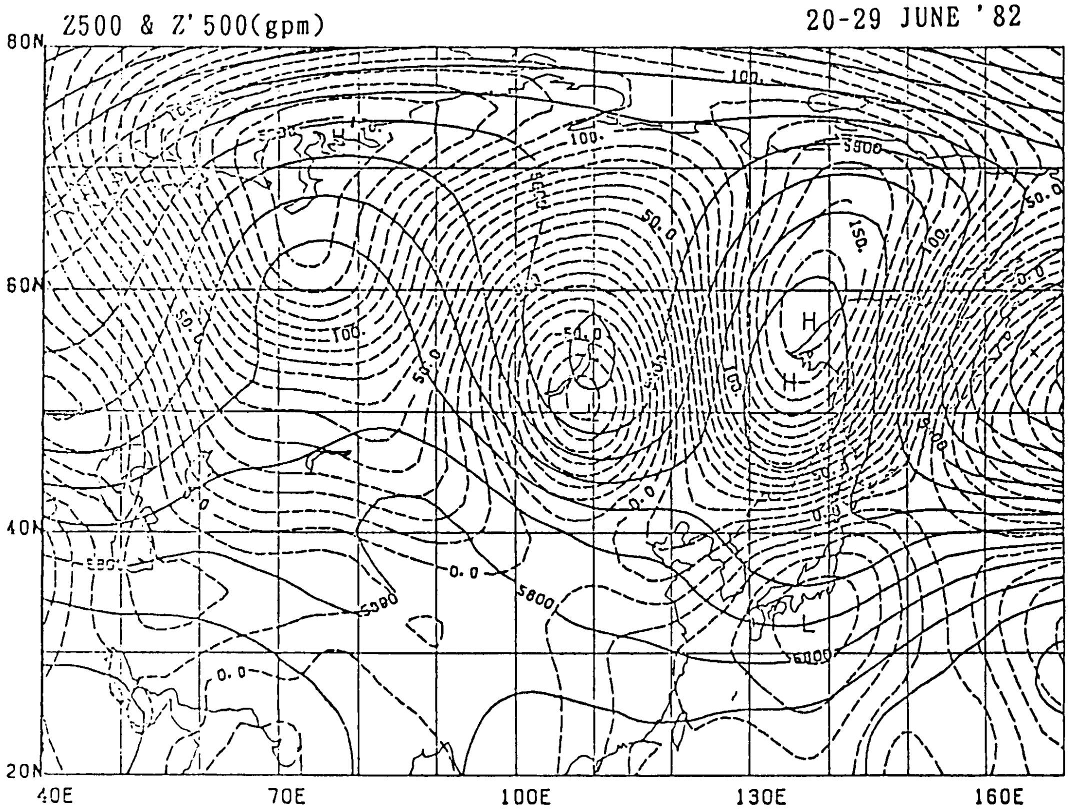

Fig. 3. 500 hPa height (solid lines) with its anomalies (dashed lines) for 20–29 June of 1982.

the trough around the sea east of Japan, looks relatively weak. The low OLR axis was located along the southern edge of the trough from 40°N/160°E to 30°N/140°E (not shown here, but see Fig. 4b of Wang, 1992).

The larger wave activity flux (about 45 $m^2 s^{-2}$ in Fig. 2b, suggests a stationary Rossby wave propagating equatorward, eastward away from the positive height anomalies in the Okhotsk Sea, and towards the negative height anomalies in the ocean southeast of Japan (see also in Fig. 2a). The direction of the activity flux, from the Okhotsk Sea to lower latitudes, roughly overlaps with the great circle (Point D to near F) shown in Fig. 1. Although the wave-train-like pattern is found from Points A to F, it looks like a Rossby wave only from Points D to F, whose 90 % confidence level correlations can be seen in Fig. 1.

4. A case study for June 1982

Wang (1992) has already presented a case study for the relationship between the Okhotsk blocking anticyclone and the Baiu front in June, 1982. In this section, we will use the SWAF diagnostic method to analyze this relationship in more detail.

4.1 Wave activity in the 500 hPa field

According to Plumb (1985), the SWAF conservation relation has the form:

$$\frac{\partial A}{\partial t} + \nabla \cdot F = C \tag{5}$$

where A is the wave activity density and C represents wave sources and sinks. It is only for steady waves ($\frac{\partial A}{\partial t} = 0$), that $\nabla \cdot F$ can be expressed by their sinks or sources absolutely. In fact, there is a lot of noise in the observational data. We have to exclude it roughly by prolonging the time mean as long as possible. In order to introduce the wave activity flux in this case, the longer-average fields (10 days) are prepared specially for the quasi-geostrophic stationary waves. This differs from the case study by Wang (1992) in which he treated data with a 5-day average value.

The 500 hPa height (solid lines) with its anomalies (dashed lines) are shown in Fig. 3 for the period of June 20–29 in 1982. As shown in Fig. 3, two ridges have developed well at about 75°E and 135°E. The east ridge is so strong that it has developed into a perfect blocking anticyclone (the Okhotsk blocking anticyclone). A strong trough around 107.5°E and a weaker trough to the southeast of Japan with a negative anomaly are established.

Figure 4 shows the distribution of the horizontal wave activity flux and its divergence for the régimes in Fig. 3. Two striking Rossby waves propagate during that period. The west one propagates from 60°N/60°E to about 55°N/102.5°E but does not

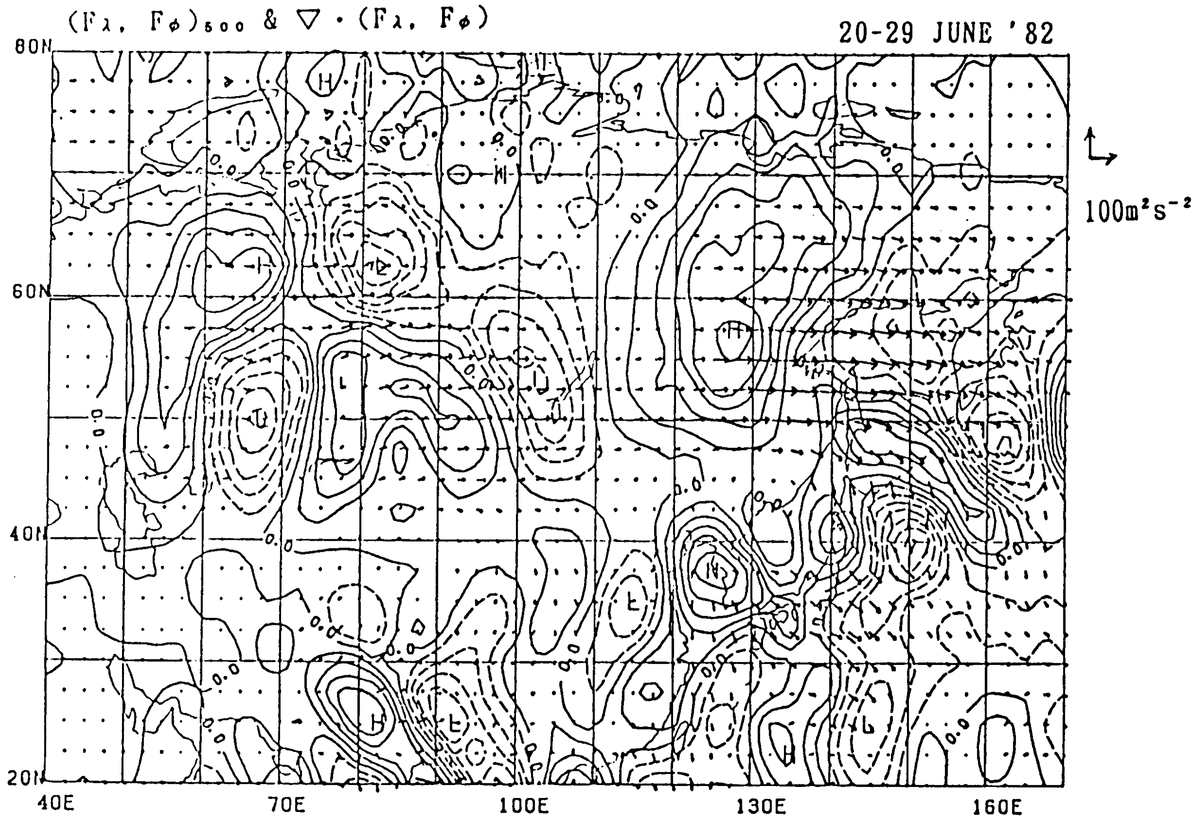

Fig. 4. Distribution of the horizontal component of wave activity flux and its divergence for 20–29 June of 1982. The contour interval of the divergence is 2×10^{-5}/s.

reach around East Siberia. The east wave (about 70 $m^2\,s^{-2}$) tends to concentrate on the great circle from about Point D (somewhere upstream of the flux in Fig. 2a) to Point F shown in Fig. 1 during the period. It is noteworthy that a large scope of divergence of the flux (with a maximum over 10×10^{-5}/sec) centers at 57.5°N/127.5°E, *i.e.*, the rear of the Okhotsk blocking anticyclone. Some positive and negative centers of divergence around the west propagation show horizontal wave divergence and convergence. Although the divergence of the horizontal flux approximately matches the divergence of the three dimensional wave flux as explained before, the positive divergence not always corresponds to the forcing source of quasi-stationary waves when we analyze the flux from the observational data. The precision in the value of the divergence is influenced by the noise caused by the weather systems of smaller scale, in spite of having used the ten-day-average data. Therefore, other divergence centers, especially smaller ones in middle and low latitudes, which may be the result of weather system of smaller scale, have uncertain significance. We will discuss the forcing source in detail in Section 5, by means of the vertical component of the flux and its divergence.

4.2 Evolution of waves in the 500 hPa anomaly field

Figure 5 shows the time evolution of twice-daily 500 hPa height deviations from the zonal mean ($Z''500$) along the great circle A–F in Fig. 1, during 15–29 June, 1982 (after the Fig. 14 of Wang (1992)). There are some large positive and negative anomaly centers arranged closely in Fig. 5. Two wave-train-like propagations (marked with thick straight lines) during the above period are found. The first one is from 50°N/80°E (Point B) to lower latitudes, around 37.5°N/150°E (Point E) along the great circle, from 20 to 23 June. The second one, which originated in the area from the Okhotsk Sea (Point D) towards Point F along the great circle, is also seen from 26 to 28 June. The two propagations might result from the east part of the flux in Fig. 4. The common features of the two propagations are the pair of the positive $Z''500$ at Point D and the negative anomaly at Point E. This just suggests that the propagations could bring about a positive anomaly from East Siberia to the Okhotsk Sea and a negative anomaly around the east of Japan.

4.3 Vertical structure of the wave flux

Although a Rossby wave generally propagates quasi-horizontally, sometimes the vertical component of its flux can not be ignored for a large upward-wave-activity flux from low layers, in which its forcing source may lie (Plumb, 1985).

Figure 6 is the distribution of the vertical compo-

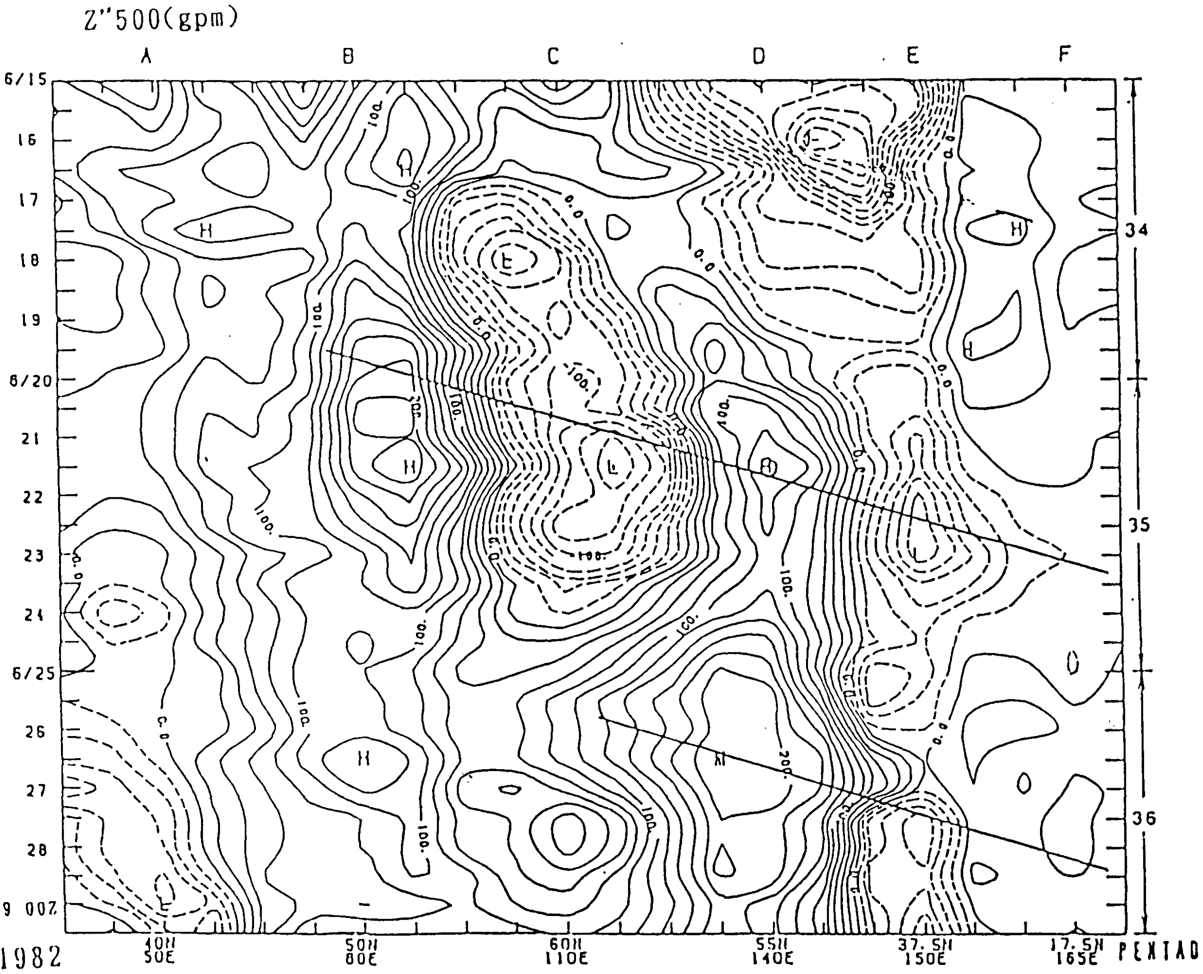

Fig. 5. Time evolution of the twice-daily 500 hPa height deviations (gpm) along the great circle A–F in Fig. 1 for the period of June 15–29 1982. Each value is a deviation from the daily zonal mean. The contour interval is 20 gpm, with the negative ones dashed. Thick solid lines are subjectively defined courses of wave propagations (after Wang, 1992).

nent of the wave activity flux at the 500 hPa level during that period (note a positive value represents ascending flux here). A wide scope and a strong upward flux centered at 57.5°N/130°E can also be found. There are two more small negative-center areas and one positive at 65°N/62.5°E, 32.5°N/85°E and 62.5°N/85°E, respectively. Since the smaller areas of upward flux on the west side and on the low latitude side are not related to the wave propagation along the great circle shown in Fig. 1, we only focus on the largest value around East Siberia. Fig. 7a and 7b show the latitude-height projection of F along 140°E and longitude-height projection along 55°N during the same period. The strong upward flux occurred from the 1000 hPa level to the 300 hPa level around 60°N, as shown in Fig. 7a. Most ascending flux propagates southward, especially that at 500 hPa level extending to 30°N. Fig. 7b shows an ascending flux area around 115–140°E. It is also seen that the most striking upward area is around 130°E.

5. Discussion

It has been identified by the above diagnostic analysis that a large horizontal-wave activity flux originates in the area from East Siberia to the Okhotsk Sea and propagates southeastward. In addition, a wide area of horizontal flux divergence closely overlaps with an area of the upward flux around East Siberia during 20–29 June, 1982 in Fig. 6b and 4. A strong ascending flux from 1000 hPa to 300 hPa is also found around East Siberia, as shown in Fig. 7. Therefore, the region from East Siberia to the Okhotsk Sea can be thought of as one of the important sources of Rossby waves in June. Okawa (1973, 1976) pointed out that there is even a very large thermal contrast between the continental area of East Siberia and the Bering sea in early summer. The rapid increase of temperature to the north of Huabei in China in June, has also been described

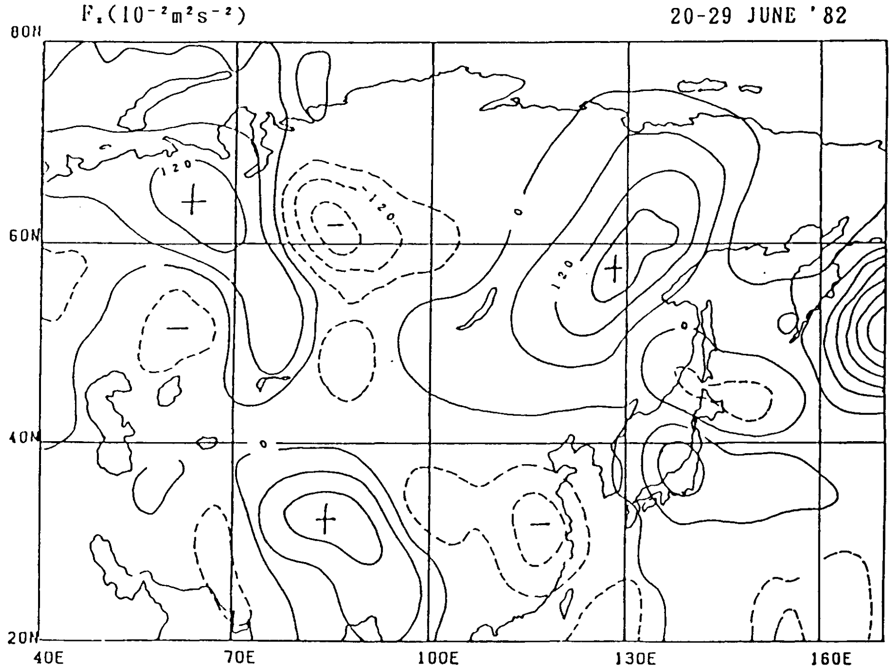

Fig. 6. Distribution of the vertical component of wave activity flux at 500 hPa level for 20–29 June, 1982. The contour interval is $60 \times 10^{-2}\mathrm{m}^2\,\mathrm{s}^{-2}$ and positive values indicate the upward flux.

by Kato (1985). Plumb (1985) has shown that the most obvious alternative forcing mechanism for the quasi-stationary wave propagation is diabatic heating. Therefore, the diabatic heating there might be considered as one of the important factors that cause the wave propagation. Wang (1992) made an investigation of blocking anticyclones in Eurasia in Meiyu/Baiu season (see Fig. 2 of Wang, 1992) and found that they occur most frequently at 50–70°N/131–150°E (this area includes the Okhotsk Sea) in early summer. These facts suggest that a wave related to a ridge (or a blocking anticyclone) can often be generated in the area from East Siberia to the Okhotsk Sea in June.

It is noteworthy that, though a 10-days average analysis reveals a propagation that originates in the area from East Siberia to the Okhotsk Sea, twice daily analysis reveals a propagation coming from upstream (*e.g.*, the first propagation in Fig. 5). Wang (1992) has already pointed out that such a propagation (from Point B, via Point D, to the sub-tropics) occurred and was amplified around the Okhotsk Sea (about Point D in Fig. 5). We also notice from the Fig. 16 in Wang (1992) that the Okhotsk blocking anticyclone was established after some synoptic scale baroclinic disturbance had developed actively over East Asia during 17–21 June, 1982. This agrees with Hoskins *et al.* (1983) who pointed out that synoptic scale systems with baroclinic instability could positively feedback the development of a blocking anticyclone. However, the generation of the wave arising from the transient eddies can not be detected by using Plumb's diagnostic tool.

Although there are some highlands near the Okhotsk Sea, they can not compare with Tibet or the Rockies. Therefore, the rôle of orography there seems to be less important than diabatic heating. It is highly probable that diabatic heating including the interaction among transient eddies together result in the propagation from the Okhotsk Sea to the sub-tropics.

In summary, the present study proposed a possible source region (from East Siberia to the Okhotsk Sea) of Rossby waves. However, because there is no perfect theory describing the establishment of blocking events, the relationship among the wave propagation over East Asia, the baroclinic waves and the Okhotsk blocking anticyclone, is still not understood clearly. Their forcing or enhancement process needs to be analyzed further.

6. Summary

The present study has examined the distribution of the horizontal wave activity flux component (Plumb, 1985) for the circulation régime associated with the Okhotsk blocking anticyclone and made a detailed case study for the period of 20–29 June, 1982, by using the three-dimensional flux vector and its horizontal divergence.

The following results were obtained.

(1) Pronoonced quasi-stationary wave activity flux across the Okhotsk Sea via Japan to the sub-tropics was identified in early summer, corresponding to the train of the Okhotsk blocking

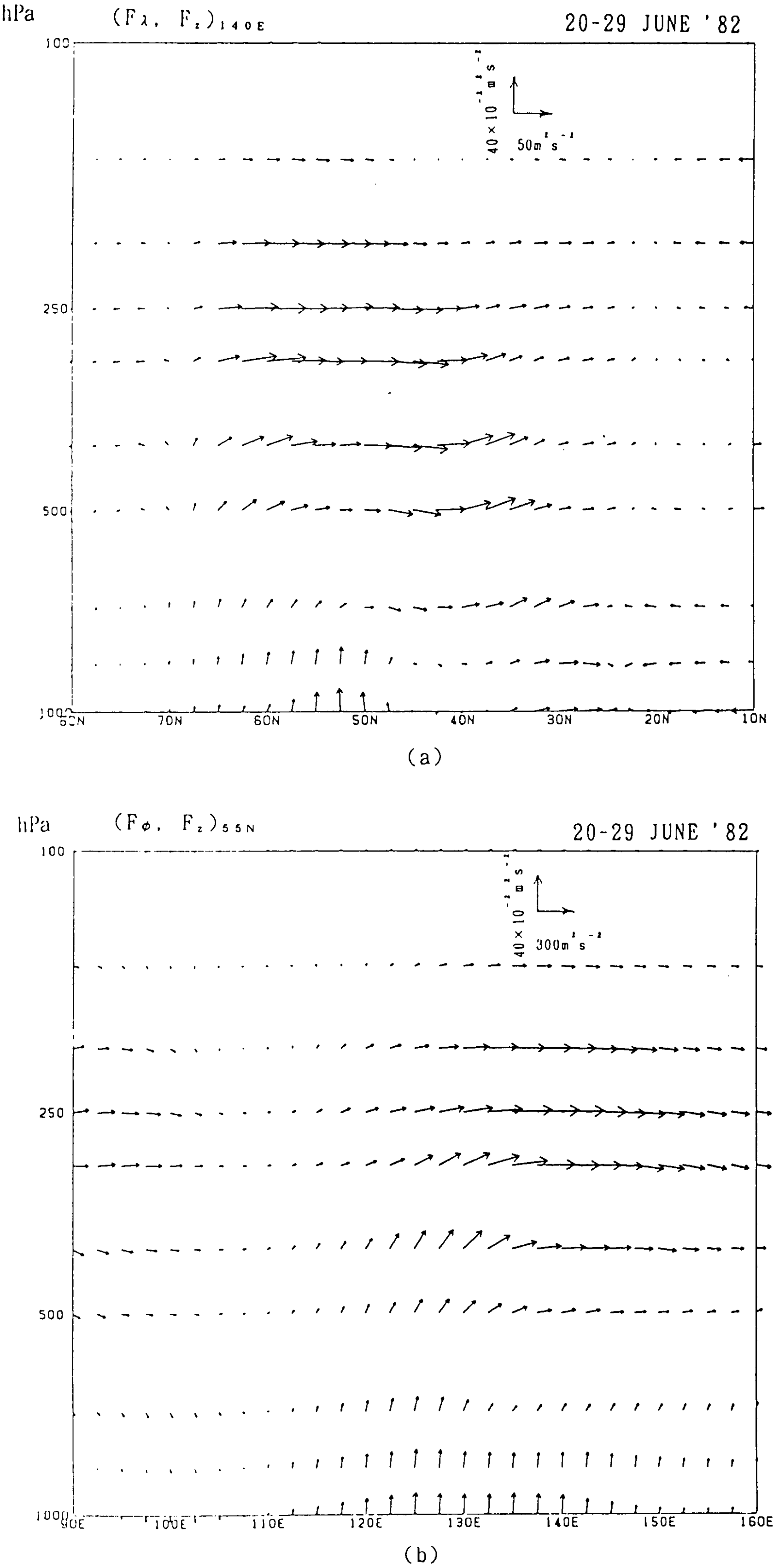

Fig. 7. Latitude-height projection of F at 140°E (a) and longitude-height projection of F at 55°N (b) for 20–29 June, 1982.

anticyclone and two troughs around Lake Baikal and near Japan, respectively. These features are found by using both composite and case analyses. This result complies with Wang's suggestion. Especially, the case study shows that large horizontal flux (50–80 $\mathrm{m^2\,s^{-2}}$) originating from East Siberia (about 57.5°N/137.5°E) propagates to about 25°N/142.5°E.

(2) A wide area of horizontal flux divergence almost overlapped with an upward flux area around East Siberia during 20–29 June, 1982. The divergence center is located slightly westward from the center of the Okhotsk blocking anticyclone (by about 10° longitude). Therefore, the area around East Siberia (slightly westward from the Okhotsk blocking anticyclone at the 500 hPa level) is considered as one of the important candidates for the forcing source of the waves.

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初夏、高緯度から低緯度に至る波列についての診断解析

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本文はPlumb (1985) が開発した定常波のアクティビティ・フラックスを用いて初夏の高緯度から低緯度に至る波列について診断解析を行った。

オホーツク海付近におけるブロッキング高気圧に伴い、顕著なフラックスの水平成分がオホーツク海から日本付近を経由して亜熱帯 (25–27.5° N) へ伝播することが合成図と事例 (1982年6月20–29日) により示唆された。

一方、1982年6月20日–29日の事例解析で相当的に広範囲での上向きのフラックス及び水平フラックスの発散域が東シベリア付近に存在することが発見された。従って、励起するメカニズムがまだ分かっていないが、そこはロスビー波の重要なforcing source地域の一つであることが考えられる。