Diagnosis of the Medium–Range Variation of the Subtropical High over the Western Pacific during a Meiyu Process by Three–Dimensional E–P Flux①

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ABSTRACT

In this paper, using the daily grid data (2.5 × 2.5) of the ECMWF / WMO, we have computed respectively the three–dimensional wave activity flux in the stages of pre–onset, prevailing and post ending of Meiyu from 1 to 31 July 1982. The potential vorticity field is taken as the physical quantity relating the wave activity flux to the variation of the subtropical high over the Western Pacific. It is found that the three–dimensional wave activity flux is a powerful means for diagnosis of the variation of the subtropical high over the Western Pacific: The region of the subtropical high is just the confluence area of wave energy, whose changes in intensity and range decide the variation of the subtropical high. The confluence of wave energy comes from the monsoon flow in low latitudes, the Meiyu rain belts in middle latitudes and the heating fields on the eastern side of the Qinghai–Xizang Plateau. The relation between these sources and the subtropical high displays the self–adjusting mechanism among members of East–Asia summer monsoon.

I. INTRODUCTION

The E–P flux is the first form of wave activity flux in two –dimensional space and it was derived out under qausi–geostrophic conditions by Eliassen and Palm (1960). Due to its direction parallel to the group velocity of wave, the E–P flux usually is used in diagnosing the propagation of wave and the interaction between wave and zonal flow, and it is a useful tool to diagnose the transport of potential vorticity as well. Shiotani and Hirota (1985) discussed the stratospheric sudden warming by use of the time evolution of E–P cross sections. After wards, great developments have been gotten in this aspect. Taking account of the influence of non–geostrophic components on the transport of potential vorticity, Huang (1982) derived the two–dimensional wave activity flux under non–geostrophic conditions on a global atmosphere, thus extending E–P flux to the globe scale. Although the above advance is rapid and has success in application, the E–P flux is essentially a zonally–averaged component and can only state the zonally averaged wave–propagation on the meridional cross section. It is well known that if the zonally averaged data are used, which have lost their longitudinal differences, many significant phenomena and features would be lost in analysing the general circulation and diagnosing weather systems, especially the synoptic regime of subtropical high over the Western Pacific (SHOWP hereinafter) which is characterized by strong longitudinal variability. Therefore it is necessary to introduce three–dimensional E–P flux, which is not only of the feature of two–dimensional E–P flux but also avoids its deficiency

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in 2–D form and shows fully the longitudinal difference of synoptic regimes. Dickinson (1966) and Holton (1975) extended the nonacceleration theory to the three–dimensional geostrophic system, and Plumb (1985) also derived the three–dimensional E–P flux. In this paper, attempt is made to discuss synoptic regime based on this theory, and to diagnose the feature of SHOWP's oscillation during a Meiyu process.

II. DATA PROCESSING AND CALCULATION SCHEME

The data used in this paper are the ECMWF / WMO zonal data including six elements of $u, v, w, T, R, Z,$ with horizontal grids of 2.5×2.5 km, and seven standard isobaric surfaces of 1000, 850, 700, 500, 300, 200 and 100 hPa in the vertical. The time series is taken from 1 to 31 July 1982. In terms of the onset of Meiyu on 9 and the ending on 25, the time series is divided into three stages: the pre–onset of Meiyu (from 1 to 8), the period of Meiyu (from 9 to 25) and the post ending of Meiyu (from 26 to 31). In order to avoid the influence of synoptic systems on the Western Hemisphere, the day–to–day data on the Western Hemisphere are replaced by the data averaged for 31 days. The day–to–day data on the Eastern Hemisphere are used. Trismoothing operator is adopted on the border of both hemispheres. The above treatment is practicable because of the absence of incontinuity in the data. Then, make the data stage–average and analyse the features in the three stages.

What is adopted in this paper is the three–dimensional wave– activity flux theorem proposed by Plumb (1985). The wave activity flux F_s derived from the quasi–geostrophic vorticity equation can be expressed as:

$$F_s = p \cdot \cos\varphi \cdot \begin{bmatrix} v'^2 - \frac{1}{2\Omega a \sin 2\varphi} \cdot \frac{\partial (v'\Phi')}{\partial \lambda} \\ -u'v' + \frac{1}{2\Omega a \sin 2\varphi} \cdot \frac{\partial (u'\Phi')}{\partial \lambda} \\ \frac{2\Omega \sin\varphi}{s}[v'T' - \frac{1}{2\Omega a \sin 2\varphi}\frac{\partial}{\partial \lambda}(T'\Phi')] \end{bmatrix} \quad (1)$$

where F_s includes three components. Its two horizontal components represent the horizontal transport of momentum and the vertical one represents the meridional transport of heat. The value of F_s can be obtained in terms of Eq.(1) if u', v', t' and Φ' are known. Moreover, by assuming that perturbation stream function varies slowly, F_s can get the following relation

$$F_s \approx M \cdot \vec{c}_g \quad (2)$$

where M is a positive parameter ($M > 0$). The above relation states that wave activity flux F_s is parallel to group velocity, i.e., the direction of F_s represents that of the propagation of energy. It is not difficult to infer that on a two–dimensional cross section the above conclusions also hold. Further derivation may get the following relation

$$\nabla \cdot F_s \approx \overline{v'q'} \quad (3)$$

which states that the meridional transport of potential vorticity approximately represents the divergence of wave–activity flux. This conclusion is the basis of diagnosing the SHOWP's advancing and withdrawing.

III. THE BACKGROUND OF CIRCULATION AND THE ANALYSIS OF POTENTIAL VORTICITY FIELDS

The time series adopted in this paper underwent a Meiyu process which set in on 9 and ended on 25 July. During this period SHOWP underwent a pronounced process of westward extending and eastward withdrawing, as shown in Fig.1. In the pre-onset Meiyu stage, SHOWP located over the sea by south and east, the 500 hPa western ridge point (WRP) of 5880 gpm contour was near 125°E, and its ridge line lay south of 20°N. After the onset of

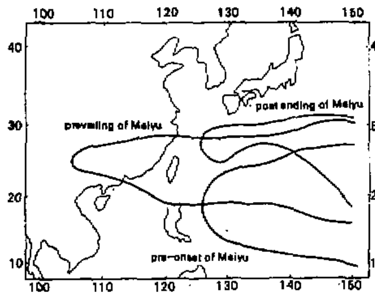

Fig.1. Averaged 5880 gpm lines at 500 hPa level for each stage. Thin full lines–the period of pre–onset of Meiyu, thick full lines–the Meiyu period, dashed lines–the period of post ending of Meiyu.

Meiyu, SHOWP extended westwards obviously, the WRP extended to 105°E, the ridge line of the main body advanced northwards to 25°N, so the East–Asia Continent was controlled by the high ridge area. The Meiyu rain belts over the basin of Changjiang and Huaihe Rivers became strong. After the ending of Meiyu, SHOWP became weaker and withdrew eastwards. At that time WRP returned to 125°E, but the main body continued advancing northwards and the ridge line was at about 27.5°N. It is obvious from Fig.1 that this Meiyu process had a close relationship with the variation of the synoptic system around the area.

In view of the absence of the relation between wave activity flux and synoptic system, it is necessary to select a suitable quantity acting as a medium to relate them. From Eq.(3), the latitudinal transport of a potential vorticity by perturbations has a direct relation with $\nabla \cdot F_s$. As for the potential vorticity itself, it displays the comprehensive effects of thermodynamic and dynamic factors. The SHOWP is also mainly characterized by the thermodynamic and dynamic features. Therefore, potential vorticity field is selected to act as the medium to show the features of SHOWP. Fig.2 depicts the distribution of 500 hPa mean potential vorticity for each stage. It can be seen from Fig.2 that there is a positive area of potential vorticity over the subtropic area all the time, and its zero isopleth has an evident rule of variation. At the first stage the positive area located on the sea, and the westernmost point of zero isopleth was at about 120°E with the center of the isopleth about 20°N. The distribution pattern was similar to the location of 5880 gpm line at 500 hPa in the corresponding period shown in Fig.1. In the second stage, the positive area expanded greatly. Especially it extended westwards to the East–Asia Continent with the westernmost point of zero isopleth extending to about 100°E and the central isopleth moving northwards to 25°N. This variation process is in accordance with the feature of SHOWP's westward–extending and northward–advancing during the Meiyu period. In the third stage, the center of the positive area moved northwards continuously to 27.5°N, with its range contracted eastwards and the westernmost point of zero isopleth returned to 120°E again, displaying the variation regularity similar to SHOWP's. The variation rule of potential vorticity at the middle levels over subtropics is not fortuitous, but the result of the northward transport of potential vorticity by disturbances. Fig.3 gives the distribution of $\nabla \cdot F_s$ on the cross section along 120°E in these three stages, displaying the northward transport of potential vorticity. According to Eq.(3), the positive area of wave activity flux at middle levels over subtropics in Fig.3 is just the area of northward–transport of potential vorticity, and the negative area which appears at high and low levels is the area of southward transport of potential vorticity. The region of maximum potential vorticity

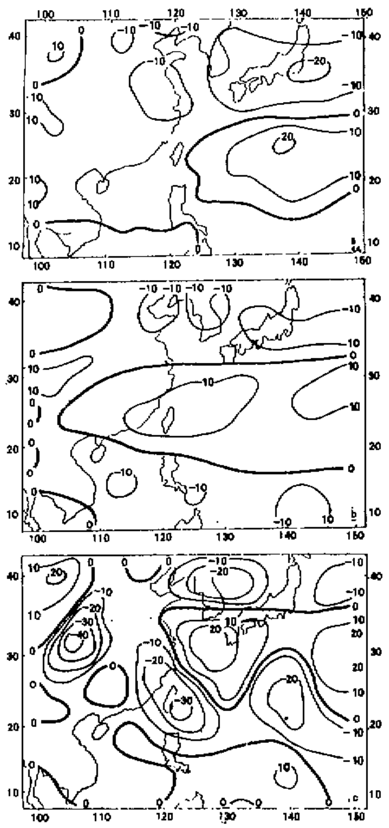

Fig. 2. 500 hPa mean potential vorticity fields for each stage. a. first stage, b. second stage, c. third stage.

northward–transporting is at about 25°N for the first stage, and at about 27.5°N and 30°N respectively for the latter two stages. The northward advance of maximum center corresponds to the northward jump of SHOWP twice. Fig.4 shows $\nabla \cdot F_s$ distribution along a meridional cross section at 27.5°N. Similarly, from the continent to the sea there is an area of northward–transport of potential vorticity in middle troposphere, while that of southward–transport at high and low levels. It is worth noticing that there exists a path of northward transport of potential vorticity at about 105°E on both continent and sea. The path over the sea is maintained throughout three stages with little change, but on the continent, the path changes greatly. The area of mid troposphere maximum of wave activity flux

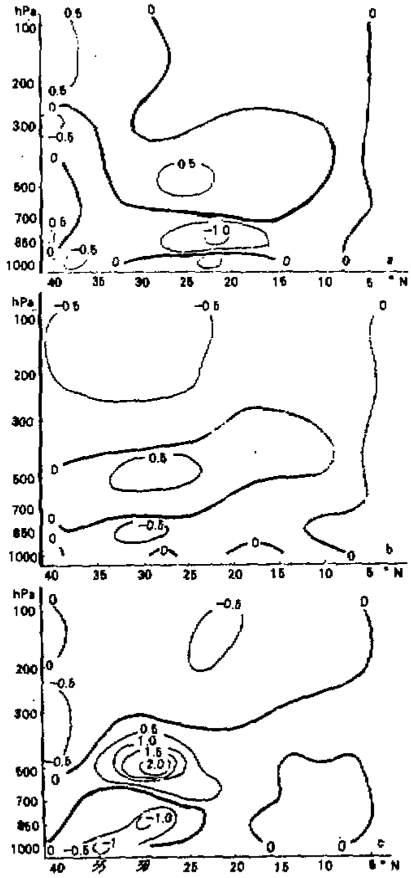

Fig.3. Meridional cross section of mean divergence of wave activity flux for each stage, along 120°E (unit: m^2s^{-2}).

over the region west of 105°E for the second stage was much larger than that for the first stage, and at the third stage this area weakened and broken off. Therefore, in the view of transport of potential vorticity, it is seen that the middle level over SHOWP is the area of potential vorticity's northward–transport and its maximum region obviously moved northwards twice corresponding to the twice northward jump of SHOWP's body. Besides, there exist paths for potential vorticity's northward–transport respectively on the continent and over the sea, the one over the sea corresponds to the main body of SHOWP and the one on the land varies, depending on the SHOWP's westward–extending and eastward–withdrawing. To sum up, the potential vorticity is available to diagnose the change of SHOWP, whose zero isopleth has a similar variation regularity to the characteristic line of 5880 gpm. The northward potential vorticity transport shows most strongly at mid troposphere, which corresponds to the fact that the SHOWP is most evident at levels of near 500 hPa.

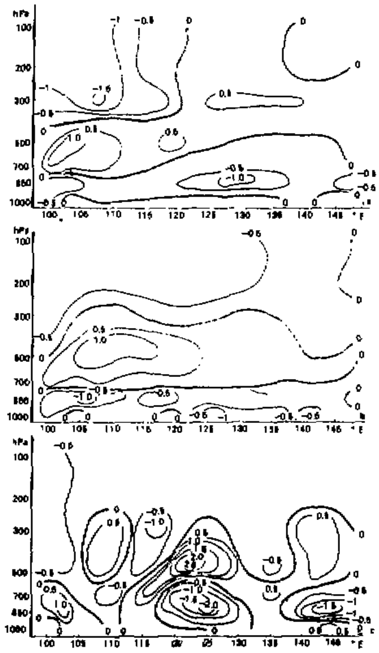

Fig.4. Averaged longitudinal cross–section of divergence of wave activity flux for each stage along 27.5°N (unit: m^2s^{-2}).

IV. WAVE–ACTIVITY FLUX FEATURES FOR THREE STAGES

1. *Features at 500 hPa*

In order to diagnose the distribution feature of wave–activity flux for SHOWP, we have selected the 500 hPa isobaric surface at middle levels, where the SHOWP is shown most evidently. At the horizontal plane, it is, according to Eq.(2), known that the projection of F_s on this cross section still indicates the propagating direction of wave energy in this plane. The distribution of F_s at 500 hPa for various stages is given in Fig.5. Before ending of the Meiyu, there exists a wide divergence belt of wave energy showing not only directional divergence, but also velocity divergence in the region of 35–37.5°N, 132.5–147.5°E over the Western Pacific. The easterly component of the divergence branch on the south side decreases gradually as it propagates southward. And the component becomes southward component in the region 27.5–32.5°N, then turns to the orientation of SE gradually. Meanwhile there also exists NE–orientated wave activity flux over a large area in lower latitudes. The two branches converge near 20–22.5°N over the sea and become a convergence belt of wave energy which just corresponds to the area of SHOWP's main body at the same stage. All this presented above states that the region of SHOWP is the convergence area of wave energy. Besides, on the East–Asia Continent there also exists a divergence belt of wave energy from NE to SW.

Its component on the east side converges toward the inner part of SHOWP and the convergence belt of wave energy is over the South–China Sea south of 15°N. Checking up daily weather data shows that these divergence and convergence of wave energy represent different synoptic regimes. The divergence belt of wave energy over the sea at middle latitudes shows the action of rain belts of shear line on SHOWP's north side and the tilting divergence belt on the East–Asia Continent displays the concurrent presence of the rain belt in South China. These two belts, together with the monsoon flow in low latitudes maintain the SHOWP over the sea. After onset of the Meiyu, there also exists a divergence belt of wave energy near 40°N over the Western Pacific, with its location further north than the former. And the convergence region of wave energy is equally maintained in the subtropics on the south side, corresponding to the SHOWP at the same stage. Great changes occur on the East–Asia Continent, and the former, SW–NE tilting divergence belt, disappears. Divergence belts of wave energy form near 35°N and 15°N and a new convergence belt occurs between them, extending from 110°E to 127.5°E and then extending northeastwards to 30°N, 137.5°E. On the land, this distribution pattern is the most obvious feature at this stage, representing the westward–extending of the SHOWP during the period. The divergence belts on both sides reflect the influence of both the continent rain belt and ITCZ over the South China Sea. In addition, it is worth noticing that, although the regions of SHOWP on continent and over the sea both correspond to the convergence areas of wave energy,the convergence belts of the two areas are separated each other, rather than linked up. In the viewpoint of source of wave energy, the convergence over the sea comes mainly from the northward wave activity flux in low latitudes and the southward wave activity flux in the northern rain belt of the SHOWP and, conversely the convergence on land is the result of both north and south rain belts' action. The discussions above show that the main body of SHOWP is greatly different from the westward extending ridge region in nature. The work by Yu et al. (1989a) showed that the main body of SHOWP is maintained by trade circulations and the extending ridge region on land is mainly maintained by subtropical monsoon circulations.

After ending of the Meiyu there still exists a convergence area of wave energy over the sea which is located by north near 30°N, displaying the northward jump of the SHOWP main body. The divergence belts on the northern and southern sides on the land becomes weak considerably and break off, and so does the convergence area in between. This makes westward–extending ridge region hard to maintain and forces it to withdraw eastwards, being in accordance with the varying character of SHOWP at the last stage.

To sum up, the generation, disappearance and variation of the convergence belt and divergence area of wave activity flux are correspondent to a SHOWP's variation process; while the convergence area plays an important role in maintaining SHOWP. Throughout the Meiyu process, a wave energy convergence belt is maintained over the Western Pacific area, with intensity and range relatively stable. However, the convergence belt on the land varies greatly, with the strongest at onset of Meiyu, and weakest at ending of Meiyu. Its energy comes mainly from the rain belt on the north side of SHOWP. In different stage, variations in intensity and range of energy transport are in accordance with features in the advance and withdrawal of SHOWP. Moreover, it is also verified from the view of wave energy that the main body of SHOWP is different in nature from its western ridge region, and the maintaining mechanisms are also different.

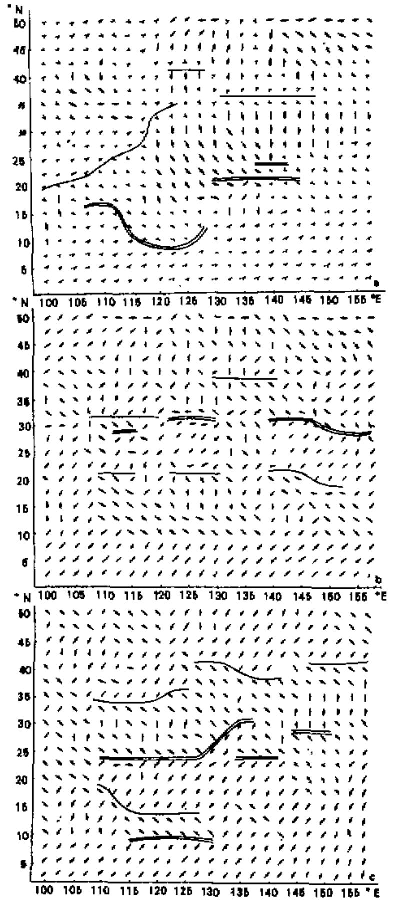

Fig.5. Averaged wave activity fluxes F_s at 500 hPa level for each stage (unit: m^3s^{-2}).

2. *Features on the meridional cross sections*

In order to further diagnose the variation of wave activity flux during the variation process of SHOWP, three meridional cross sections were taken at 100°E, 120°E and 150°E, respectively. The discussion below is mainly made on 120°E cross section(see Fig.6). It is seen from the figure that throughout the three stages, the northward transport of wave activity flux in low latitudes is only limited to about 10°N, but on the 100°E and 150°E cross sections (not shown), the northward transport of wave activity flux in low latitudes could reach 15°N further north (see Fig.5), and the wave activity flux is transported polewards and upwards under the 500 hPa surface, indicating the action of tropcial monsoon flow. At 120°E the wave activity flux in middle latitudes changes more regularly. After onset of Meiyu, a clear divergence center occurs at high levels from 200 to 100 hPa, and its poleward and downward wave activity flux converges with low–level southward and upward wave activity flux at middle troposhere levels near 22.5–32.5°N, becoming a convergence area of wave energy. At the earlier stage, the low level divergence feature is not obvious in middle latitudes. After ending of Meiyu, though the divergence center also exists at high levels, its intensity becomes weak and the divergence at lower levels is intensified greatly. The middle level convergence belt still exists with its range extending to about 25–35°N. This convergence belt is not obvious until its range extends in the onset of Meiyu. And it is maintained north of 25°N, corresponding to the twice poleward jumping of SHOWP for the later two stages. As a result, it turns into midsummer season.

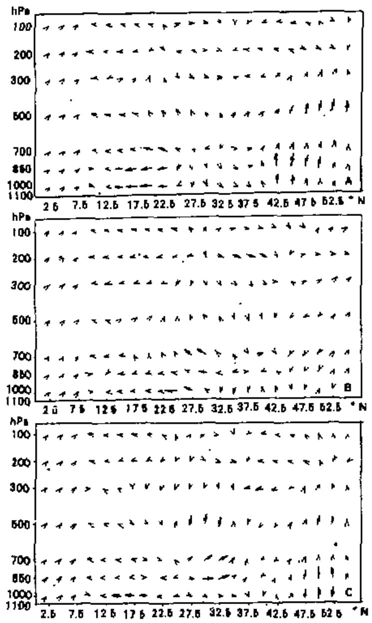

Fig.6. Averaged meridional cross section of wave activity fluxs for each stage along 120°E (m^3s^{-2}).

In addition, it was pointed out by Huang (1984) that the wave guide in the region of 40–50°N north of subtropics varies regularly. Before and after the Meiyu period this wave guide is apparent. Waves can propagate vertically from low levels upwards, and split into two branches poleward and equatorward respectively near 300 hPa. At the first stage, the equatorward wave guide having great influence on SHOWP joints with middle latitude poleward divergence component at 300 hPa near 32.5°N, thus strengthening the wave energy convergence there. After ending of Meiyu, this high latitude wave guide becomes more apparent, propagating southwards and converging downwards, finally merging into the lower–level middle–latitude northward divergence branch at 35°N. Consequently, this kind of upward propagration enhances the wave energy convergence at middle levels. This activity of wave guide in millde latitudes is closely associated with SHOWP. During Meiyu period, this wave guide disappears completely, and gives ways to the divergence component at high levels. It is seen through the whole process that there exist the energy transport disruption and retransport by westerly flow towards the subtropics, but its inherent mechanism and process still remain unclear yet.

On the meridional cross sections at 100°E and 150°E (not shown), there exist wave energy convergence areas at middle levels in subtropics which are shown most obviously at the second stage. In the viewpoint of wave guide, on the 100°E cross section there are two weve guides acting on the SHOWP: one is at low levels and propagates upwards from low latitudes then turns northwards and again downwards over the SHOWP. This guide acts on, only from lower levels, the SHOWP. The other one which is different from the former, is the southward and downword branch from the diveregerce center of wave energy at high levels in middle latitudes, acting on the SHOWP from high levels. Another kind of feature displayed on the cross section at 150°E is that, there exists a high level wave energy divergence center in midlatitudes, and its southward propagating branch converges with the northward wave activity flux coming from low latitudes at different levels and latitudes, thus forming a wave energy convergence belt which is southward–tilting with height, especially obvious in the first two stages and eventually almost vertical in the last stage. This distribution festure is in agreement with southward–tilting of the main body of SHOWP with height.

3. *Features on the longitudinal cross sections*

Three characteristic longitudinal cross sections are respectively taken at 22.5°N, 27.5°N and 32.5°N. Analysis is made mainly on the features of wave activity flux at 27.5°N. (Fig.7). It is shown from Fig.7. that east of 100°E there is a wave guide propagating upwards at 700 hPa over continent and then it turns eastwards, finally downwards penetrates to the inner main body of SHOWP over the sea area. This low level wave guide frequently exists in the whole process, becoming obvious at the second stage. Besides there also exists a high level wave energy divergence belt at 95°E, with its downward and eastward branch on the east side closely linked with the SHOWP. During the Meiyu period, it meets with the low level upward wave activity flux,forming a convergence belt at middle levels in the area of 107.5–132.5°E. The latter maintains the ridge area of the SHOWP on the land and its main body over the sea. Prior to the onset of Meiyu, no such cenvergence belt is formed. On ending of Meiyu, the convergence belt at middle levels weakens, and breaks up, in accordance with the feature of SHOWP at this stage. In connection with the synoptic regime, it is not difficult to see that the phenomenon at low levels is caused by the action of monsoon flow and at high levels reflects the effects of heating fields in the east side of Qinghai–Xizang Plateau.

The same feature may be seen from the zonal cross sections at 22.5°N and 32.5°N (not shown). In the sense of weather, what differs from the former is that the west high–level divergence center at 22.5°N represents the action of heating field over the Bay of Bengal.

V. CONCLUSIONS AND DISCUSSIONS

To sum up, some conclusions may be drawn as follows:

(1) The potential vorticity field, as a medium connecting the wave activity flux with the SHOWP, has its zero line at subtropics varying in accordance with the 5880 gpm line of the SHOWP. On the East–Asian Continent and over the sea of the subtropics there exist two paths of northward transport for potential vorticity.These northward transports change in value and range, and closely connect with the westward–extending and northward advancing of SHOWP. It also coincides with the most pronounced characteristics in mid troposphere.

(2) Analysis of wave action flux shows that region of SHOWP is just the region of convergence of wave energy, and its changes in intensity and range decide the intensity of SHOWP and its westward extending and northward advancing. This wave energy convergence comes mainly from tropical flow on the south side, the rain belts on the north side, ITCZ area in low latitudes and the heating field on the east side of Qinghai–Xizang Pla-

teau. It is worth noticing that on the land and over the sea there exist two convergence belts of wave energy during the Meiyu period, but they are separated each other and no link can be found. These manifest that they come from different sources, and the main body of SHOWP over the sea differs in nature from its westward–extending ridge on the East–Asia Continent.

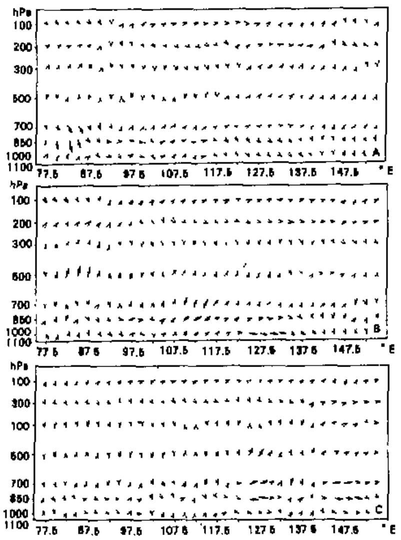

Fig.7. Averaged longitudinal cross section of wave activily fluxes for each stage along 27.5°N (unit: m^3s^{-2}).

(3) Energy source variations have a close relation with the medium–range oscillation of SHOWP. Prior to the onset of Meiyu, SHOWP lies over the sea by south and by east; there exists only a heating belt over the sea maintaining the main body. On the land, the southwesterly monsoon flow from the low latitudes drives straight into the Changjiang Valley, supplying the heating belt there with plentiful water vapor and forcing the subtropical monsoon cell to strengthen(see Yu et al., 1989b). Its subsidence on the continent induces the SHOWP to extend westwards and advance northwards. At the same time,a new rain belt on the land becomes the main source of wave energy in the westward extending ridge. Along with entering the Meiyu period, the SHOWP westward–extending reversely cuts the water transport of southwesterly monsoon flow off, and makes the rain belt on land weaken and break off. In addition ,the heating on the eastern side of Qinghai–Xizang Plateau weakens in pace with it. Finally, SHOWP withdraws eastwards and advances northwards and it goes into the period of Meiyu ending. As stated above, an intact process of medium–range oscillation is completed.

The deficiency in this paper lies in the following aspects.Firstly, all work done above is based on the assumption of quasi–geostrophy. Secondly, no filtering is taken, thus the wave guide obtained is less clear than that in two dimension for single wave. Nevertheless, the conclusions made indicate that wave activity flux is an effective tool to diagnose the variation in intensity of SHOWP and its advance and withdrawal.

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