Vol. 5 No. 1 **Advances in Atmospheric Sciences** February 1988

THE TRANSFER OF PHYSICAL QUANTITIES IN QDPO AND ITS RELATION TO THE INTERACTION BETWEEN THE NH AND SH CIRCULATIONS

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Received December 18, 1986

ABSTRACT

Based on the 1979 FGGE Level III b data, calculation is made of the transfer of sensible and latent heat and momentum due to a quasi-40-day periodic oscillation (QDPO) on a cross-equatorial meridional vertical cross-section, and analysis is done of the characteristics of the transfer at all phases of QDPO, with the following results obtained:

1) During the monsoon's QDPO activation and break phases, a strong transfer of sensible heat to the SH is felt in the upper troposphere over the Asian monsoon region; the conversion of perturbation effective potential into its kinetic energy attains its maximum at 500–300 hPa (15°N), serving as the source of kinetic energy for the quasi-40-day periodic perturbation; an intense transfer of potential energy is found above 200 hPa from the monsoon area to the SH to maintain the QDPO at the tropical latitudes;

2) During the QDPO activation-break (and reverse) transitional phase the conversion of perturbation effective potential into kinetic energy reaches its maximum in the middle and lower troposphere over the SH middle latitudes and an appreciable lower transfer of potential energy occurs towards the SH tropical latitudes and the NH.

3) The upper-tropospheric powerful transfer of westerly momentum caused by QDPO is discovered from the SH tropical latitudes to the NH, and the resulting momentum divergence and convergence are unfavorable for the maintenance of the seasonal mean fields of the NH tropical easterly and SH subtropical westerly winds.

Finally, possible synoptical processes responsible for QDPO are discussed together with its relation to the interaction between the circulations of both the hemispheres. It is found that QDPO is both the result of and medium for the interaction.

I. INTRODUCTION

Atmospheric motion is global, not bounded by the equator. For instance, the asymmetrical land-sea distribution on the semispheres, great difference in the size between land and sea and the location of the Asian intertropical convergence zone (ITCZ) far away from the equator are responsible for the powerful monsoon region in the continent. Such a monsoon circulation is marked by low-level cross-equatorial flow originating from the SH and upper northeasterly flow to the SH, thus integrating two hemispheric circulations into one in favor of the intense exchange of atmospheric mass, latent/sensible heat, angular momentum, and kinetic/potential energy between them. This is an important mode in which the hemispheric circulations act one upon another. On the other hand, the meridional cross-equatorial propagation of low-frequency oscillation induces a quasi-periodic oscillation in the transfer of all the physical quantities, thus exerting mighty influence on the medium-range variation of the NH and SH circulations.

In the study of the transfer between the circulations, special emphasis is put on the role of the transfer passage, or the intense exchange band. As indicated as early as 1963 by S.Y. Tao et al. in the study of the exchange of summer atmospheric mass in a tropical meridional circulation, such a band is present around 150°E, with the lower transfer from the SH to NH. Later the Somalian jet stream was discovered and the interhemispheric transfer is calculated of lower atmospheric mass in West India (35°-75°E) (Findlater, 1969), and some other cross-equatorial passages have been found out in recent years. For example, Huang et al. (1979) shows six major passages within 40°-170°E for the particular summer, with the one around 45°E (which corresponds to the Somalian jet) being most intense and stable, and next to it another one about 105°E, based on the grid-point wind data of the 1979 MONEX.

All the works mentioned above deal with the properties of the mean transfer for an interval of time. In the investigation of the intraseasonal variation, however, the meridional propagation of low-frequency oscillation plays an important role, with the QDPO examined intensively. By use of the cross- and phase-spectrum techniques in their work, Chen and Jin (1982), indicates that the interhemispheric interaction relies on the QDPO of the component U. And the 10°S departure circulation due to the northward incursion of the SH cold air and the cross-equatorial northward displacement of the departure disturbance vortex at the corresponding upper and lower levels have effect on the NH monsoon area and the intensity of the ITCZ (Ke et al., 1982). Tao et al. (1979) shows that the development of the mid-latitude baroclinicity over 40°-160°E in the SH leads to a large-scale outbreak of cold air, hence the formation of an associated high-pressure belt, with southeasterly flow on the north side as the source of cross-equatorial current. The establishment of the current over India, the Indo-China Peninsula to the South China Sea and the northwestern Pacific results in the onset and building-up of summer monsoon in these regions, separately. The development of the SH mid-latitude, large-scale baroclinicity after the establishment of the monsoon in the NH causes the northward advance and intensification of the wind. Using the 1979 FGGE Level III b data, Murakami *T.* and He et al. (1984, 1985) show a systematic study of the evolution of the circulation due to the QDPO with its northward propagation and the associated transfer of moisture, indicating that the northward propagation of QDPO is related to the phases of monsoon's activation and break and to the seasonal northward movement of the monsoon rainband over China. The present paper aims at analysing the features of the transfer of the physical quantities for different phases of QDPO in order to examine the associated synoptical processes and its relation to the interaction between the circulations in both hemispheres.

II. DATA AND SPECIFICATION

The once-daily data used are taken from the 1979 FGGE Level III b base between May 1 and September 30, including the levels of 100, 200, 300, 500, 700, 850 and 1000 hPa covering 30°S-30°N and 30°E-150°W, with the grid length of 3.75° longitudinally and latitudinally.

In order to investigate the time-dependent evolution of the element fields due to a 40-50 day periodic oscillation, a corresponding band-pass filtering scheme is adopted for the quantities with a prime meaning the deviation from the seasonal trend or anomaly. As a result, a set of 40-50 day oscillations are retained in the filtered data and a composite technique is employed to examine the phase-dependent evolution of the meteorological elements in an ideal cycle of the oscillation (refer to He et al., 1984).

The composite procedures are described as follows. The mean anomalous value of the 850-hPa zonal wind obtained by 40-50 day filtering $\tilde{\bar{U}}'$ over 60°-150°E at 11.25°N is used as the reference variable for the definition of phases. The time-dependent evolution of $\tilde{\tilde{U}}'$ shows a systematic 40–50 day periodic oscillation, as illustrated in Fig. 1. The dots denote the unfiltered time sequence of $\bar{U}'$, which equally shows a systematic periodic oscillation. It can be seen that three cycles of $\tilde{\tilde{U}}'$ come to pass from 18 May to the end of September, with the period of 40–50 days. Then the three cycles are composited and divided into 25 intervals of time, i.e., $\tilde{\tilde{U}}'_n$ $n=1,2,3,\ldots,25$ (refer to figure 1), which is the day-to-day average of the 850-hPa $\tilde{\tilde{U}}'$ for the period of 5–6 days.

In addition, the composite method involves the assumption of an appropriate phase, or category, to each $\tilde{\tilde{U}}'_n$, with 1–9 phases in all, where phase 1 represents three intervals for the maxima of $\tilde{\tilde{U}}'$, namely $\tilde{\tilde{U}}'_1$, $\tilde{\tilde{U}}'_9$ and $\tilde{\tilde{U}}'_{17}$; phase 5 for its minima; phase 9 $\tilde{\tilde{U}}'_9$, $\tilde{\tilde{U}}'_{17}$ and $\tilde{\tilde{U}}'_{25}$, with phases 2–4 and 6–8 being of transitional nature. Therefore, the average for each phase is obtained through the calculation of the three cycles of $\tilde{\tilde{U}}'_n$, that is,

$$\bar{U}_K=(\tilde{\tilde{U}}'_K+\tilde{\tilde{U}}'_{8+K}+\tilde{\tilde{U}}'_{16+K})/3, \quad K=1,2,\cdots,9$$

where K is assumed to be $\bar{U}_1=\bar{U}_9=(\bar{U}_1+\bar{U}_9)/2$.

Methods of this type apply to other meteorological variables. The composited chart of the variables for each phase can be prepared by means of averages for the phases at each grid point. For any variable with a 40–50 day periodic oscillation, the pattern of its phases 5–8 on the composited chart should be, on the whole, analogous to that of the phases 1–4, respectively, with the difference in the sign (minus) only.

Then the difference in the composited quantities U_K is found in terms of $\Delta\bar{U}_K=(\bar{U}_K-\bar{U}_{K+4})/2$, $K=1,2,3,4$. Evidently the statistical significance of $\Delta\bar{U}_K$ is verified with ease.

Suppose that all these variables have pure periods of oscillation, and then we have

$$\begin{aligned}&A_i=\Delta A_i=(A_i-A_{i+4})/2, \quad i=1,2,3,4\\&A_i=-A_{i-4}, \quad i=5,6,7,8\\&A_1=A_9,\end{aligned} \tag{1}$$

where A denotes an variable; A_i the composited value at the ith phase, with $i=1,2,3,\ldots,8$ as indicated above.

For the examination of the transfer of the physical quantities at each phase, it is necessary to calculate the product term in the form of A_iB_i. From (1) we have

$$\begin{aligned}&A_iB_i=A_{i-4}B_{i-4}, \quad i=5,6,7,8\\&A_1B_1=A_9B_9,\end{aligned} \tag{2}$$

where A_iB_i denotes the transfer of such quantities as sensible heat, potential energy and momentum, respectively, at the ith phase. It can be seen from (2) that as far as the transfer is concerned, only 4 patterns are found for the phases.

He et al. (1987) indicates that the 8th phase corresponds to the phase of South- and Southeast-Asian monsoon in activation and the 4th in break, the others in between being transitional phases for monsoon's activities. For simplification, the 8th and 1st phases are classified as the phases of monsoon's activation; the 4th and 5th of break; the 2nd and 3rd as the transition from activation to break; and the 6th and 7th as the reverse transitional phases. According to (2), the transfer value of the activation phase is identical with that of the break and the values of the two transitional phases are the same as well. In the following, such terms as "activation and break phases" (ABP) and "transitional phases" (TP) will be adopted in describing the features of the transfer of physical quantities. It is particularly noted here that any set of the two phases, although of the same transfer value, represent entirely different synoptical processes, a problem which is to be treated later.

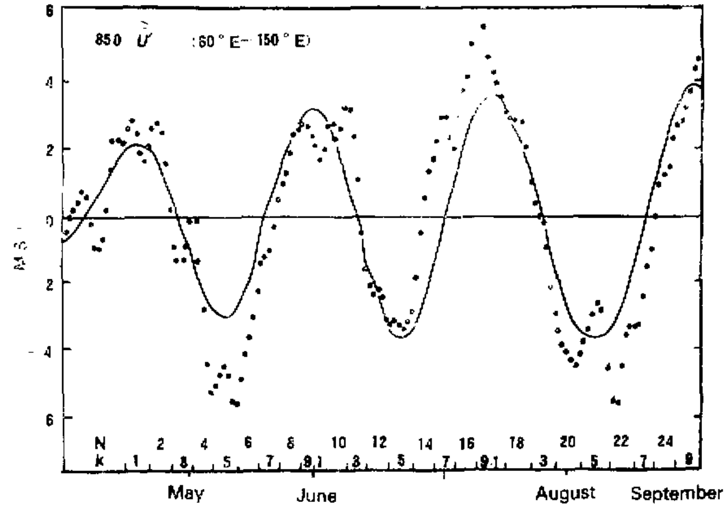

Fig. 1. The time sequence of mean anomaly of 850-hPa zonal wind obtained by the 40–50-day filtering $\tilde{\bar{U}}'$ between 60°–150°E along 11.25°N. The unfiltered day-to-day values of $\bar{U}'$ are represented by dots. The number of time intervals N and of phases K is as indicated in text.

III. ANALYSES OF FEATURES OF THE PHASE TRANSFER

1. *Transfer of Sensible Heat*

Meridional vertical cross-sections for the transfer of sensible heat caused by a quasi-40-day periodic disturbance averaged over 30°E–150°W are shown in Fig. 2a–d, indicating the conditions of phases 1–4, respectively, which, as denoted before, are also the transfer of phases 5–8, separately.

Figure 2d, a depicts the features of sensible heat transfer at the 8th and 1st phases (or the 4th and 5th), that is, of the monsoon in activation and break, respectively, the most appreciable being the strong transfer of sensible heat above 300 hPa in the troposphere from the NH to SH with the high-value region generally between 15°N–15°S. This is due to the fact that, when the monsoon is in the phase of activation (break), its circulation is intensified (weakened) and rising air is strengthened (declined) in the Asian region, thus leading to positive (negative) temperature perturbation due to the increase (decrease) in latent heat released through condensation, with the result of $V_i<0$ ($V_i>0$), $T_i>0$ ($T_i<0$). It brings about $T_iV_i<0$, suggesting that sensible heat is transported from the Asian monsoon region to the SH, which causes a considerable exchange of heat between both hemispheres. It can be seen that, at the ABP of the monsoon, the upper-tropospheric transfer of sensible heat is accomplished from the NH to SH, but the synoptical processes responsible for it differ completely.

The TP shows the features of such transfer in striking contrast to the ABP. As delineated in Fig. 2b, c, the upper-tropospheric transfer of sensible heat from the NH to SH is greatly reduced, while its southward transfer in the whole troposphere is much stronger at TP than at

ABP south of 20°S of the SH, with the negative-value area moving a little farther northwards. This implies that, at the break-activation TP (i.e., the 6th and 7th phases), strong cold air operates in the entire troposphere between 30°E–150°W at middle latitudes of the SH, that is, $T_i<0$, $V_i>0$, $T_iV_i<0$ brings about the intense southward transfer of sensible heat: at the activation-break TP (i.e. the 2nd and 3rd phases) strong warming occurs there, with $T_i>0$, $V_i<0$, $T_iV_i<0$, responsible for the transfer of sensible heat, too.

Figure 3 is a cross-section of sensible heat transfer averaged over a single period. Two negative high-value regions are shown in the figure: one stretching from the monsoon area to the SH in the upper troposphere in association with the ABP of the wind; the other situated at middle latitudes of the SH extending to the monsoon area at lower levels in relation to the activity of intense cold air or strong warming at these latitudes. A small positive-value region is found between the two negative areas in the upper and lower troposphere, with the eventual consequence that sensible heat transfer by the QDPO from NH to SH happens largely in the upper troposphere and below 700 hPa as well. The weaker transfer in the lower troposphere may be accounted for by the rapid transformation, hence the warming of the cold air during its northward course.

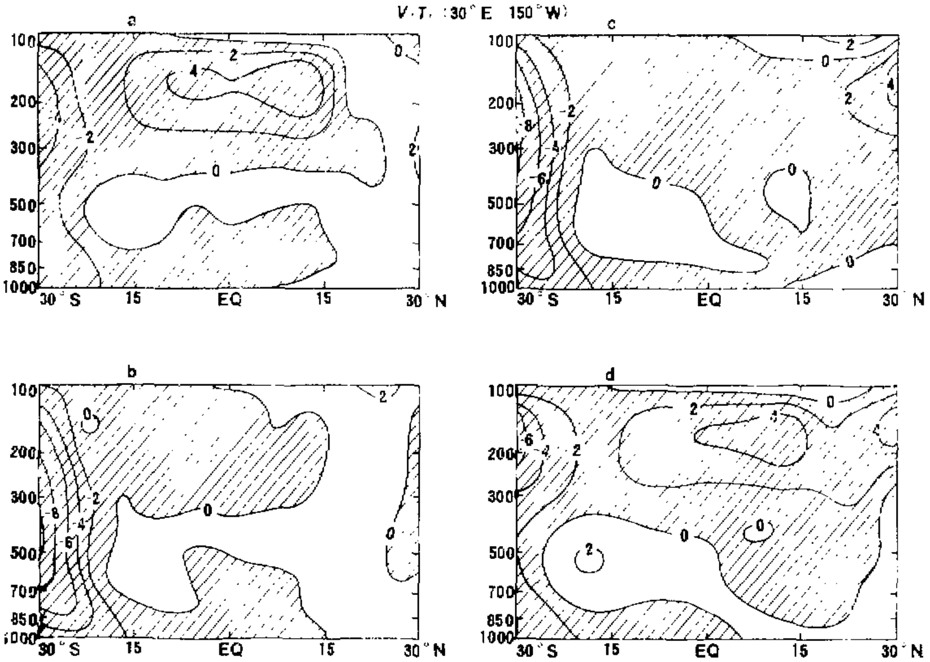

Fig. 2. Cross-sections of averaged transfer over 30°E–150°W at each phase. The interval is m s^{-1}°C. The shaded is the negative region of $\overline{V_iT_i}$, with the bar denoting spatial mean,

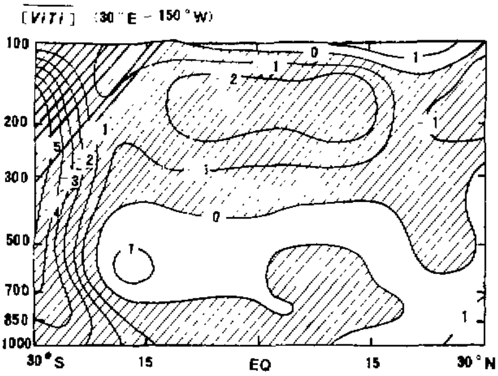

Fig. 3. The cross-section of the sensible-heat transfer averaged over a single period. "[ ]" denotes the average, the other illustrations being the same as in Fig. 2.

2. *Transfer of Potential Energy*

Figure 4a–d shows the potential energy fluxes for phases 1–4 on the meridional vertical cross-sections, respectively, where the broken line denotes the isoline of $\omega_i T_i$.

It is evident from Fig. 4d, a that at the 8th and 1st phases for the activation (or the 4th and 5th for the break), a considerable transfer of potential energy takes place towards SH at 200 hPa along 15°N and it is directed downward north of 20°S of the hemisphere after crossing the equator, and that at the two phases a minimum, or a negative maximum, of $\overline{\omega_i T_i}$ is present within 500–200 hPa over the Asian monsoon area (around 15°N) and a significant positive value region of $\overline{\omega_i T_i}$ north of 20°S of the SH. This suggests that at ABP the conversion of disturbance effective potential into its kinetic energy reaches its maximum, serving as the energy source for the quasi-40-day periodic perturbation (QDPP) for the Asian monsoon area, with the SH tropical latitudes as the sink. The above facts show that at the activation (break) phase the vertical motion is strengthened (weakened) over the monsoon area and the latent heat released through condensation is increased (decreased), thus leading to an extraordinarily large positive (negative) value of temperature disturbance and finally to a considerably negative value of $\overline{\omega_i T_i}$ and the maximum conversion of disturbance effective potential into its kinetic energy.

Figure 4b, c shows that such conversion is slight at TP and so is the transfer of potential energy towards SH. Yet, on the other hand, a strong negative-value area of $\overline{\omega_i T_i}$ is formed in the middle and lower troposphere between 500 and 850 hPa over 30°S, with an appreciable lower transfer of potential energy to the SH tropical latitudes, even across the equator. This indicates that at the break-activation TP (the 6th and 7th phases) there happens outbreak of cold air at middle latitudes of SH and it moves northward, favoring the conversion of effective potential into kinetic energy during the subsidence of the air, and the reinforced lower southerly flow accompanied by an anomalously positive value of its geopotential height brings about the northward transfer of potential energy of perturbation, while at the activation–break TP (the 2nd and 3rd phases) intense warming takes place at middle latitudes of SH, causing perturbation potential energy to be transformed into the kinetic energy and to be carried northward.

In addition, it can be seen that at the 7th, or the 3rd, phase (see Fig. 4c) there is a considerable negative-value center of $\overline{\omega_i T_i}$ between 500 and 200 hPa at the NH middle latitudes (30°N) and a significant transfer of potential energy to the monsoon area (15°N) at 200 hPa. A similar negative center of the sensible heat flux is shown in Fig. 2c. These mid-latitude centers may be associated with the local baroclinic disturbance, particularly with the disturbance in the subtropical monsoon region stretching from China's mainland to Japan. Probably, this fact indicates that the interaction between the circulations at the NH middle and low latitudes has some effect on the transition between the activation and break of the monsoon in South and Southeast Asia (15°N).

Figures 5, 6 show the meridional vertical cross-sections of $[\overline{\omega_i T_i}]$ and $([\overline{V_i \Phi_i}],[\overline{\omega_i \Phi_i}])$ averaged in a single period between 30°E and 150°W, respectively. It is apparent from Fig. 5 that a region of high conversion of perturbation effective potential into the kinetic energy between 200 and 500 hPa around 15°N serves as the energy source for QDPP, from which the energy is transported as potential downward to compensate for frictional dissipation for maintaining QDPP at lower levels and upward and southward across the equator to maintain QDPP over the SH tropical latitudes where perturbation kinetic energy is changed into the potential energy (see Figs. 5, 6). Also, a region of high conversion of perturbation effective potential into the kinetic energy is found in the middle and lower troposphere over the SH middle latitudes, from which energy is carried as potential northward to the tropical latitudes and across

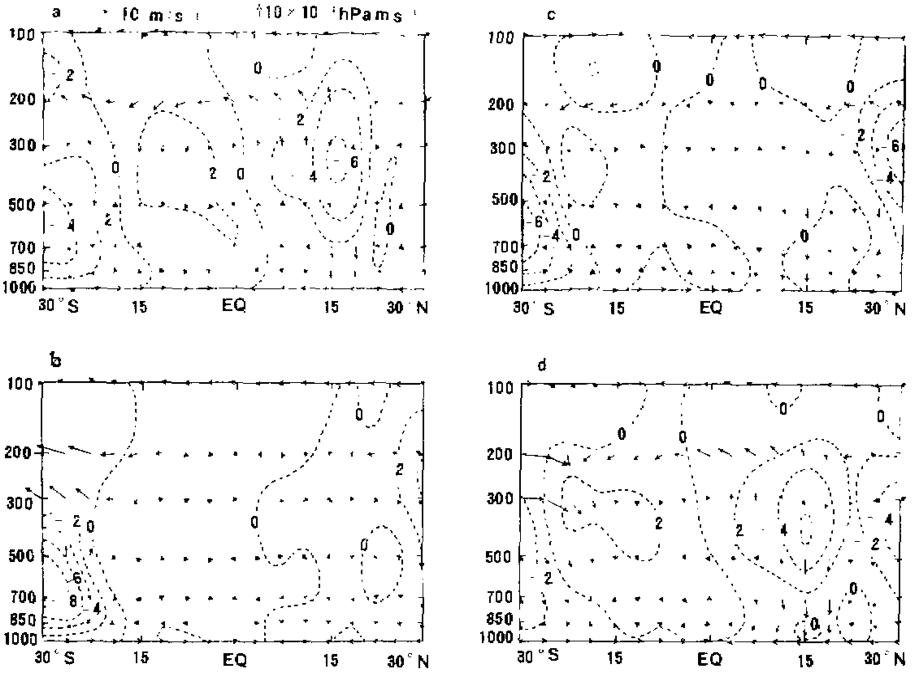

Fig. 4. Cross-sections of potential energy transfer averaged over 30°E-150°W. Arrows denote the flux of potential energy, and broken lines the isolines of $\overline{\omega_i T_i}$ with the spacing of 2×10^{-3} hPa s^{-1}°C.

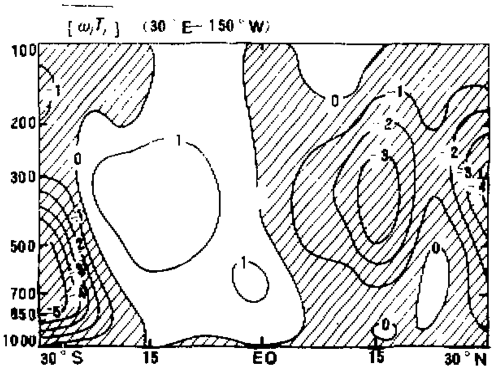

Fig. 5. The cross-section of $\overline{\omega_i T_i}$ averaged over a single period. The shaded area represents a negative-value region, the other illustrations being the same as in Fig. 4.

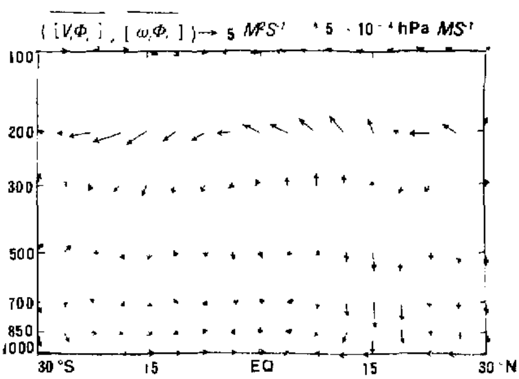

Fig. 6. The cross-section of potential energy flux averaged over a single period. The illustrations are identical with those in Fig. 4.

the equator. It is worth noting that the energy sources mentioned for QDPP have different properties. On the one hand, the former located in the upper and middle troposphere is related to positive (negative) temperature perturbation due to intensified (weakened) updraft, hence the great (small) release of latent heat over the monsoon area; the latter to the outbreak of cold air or strong warming at the SH middle latitudes. On the other hand, the former generates perturbation kinetic energy at the monsoon's activation or break phase, while the latter at the TP. Both the sources for QDPP, each situated in one hemisphere, operate alternately. Whether such disposition is favorable for the maintenance of the QDPO remains a problem to be studied.

3. *Transfer of Momentum*

Fig. 7 depicts the cross-section of the transfer of westerly momentum averaged over a single period. It can be seen that a high-value region of the northward transfer is formed above 200 hPa between 5°N and 20°S, which results from the periodic disturbance of upper northeasterly monsoon circulation and appears at the activation or break phase, that a high-value area of the southward transfer is found around 200 hPa at 30°S, which is associated with the activity of the mid-latitude baroclinic trough in the NW–SE direction and that a small-value region of the southward transfer appears at 500 hPa and below it at the SH tropical latitudes which is related to the strengthened lower southeasterly trade ($U_i<0, V_i>0, U_iV_i<0$) and the weakened ($U_i>0, V_i<0, U_iV_i<0$) over the SH.

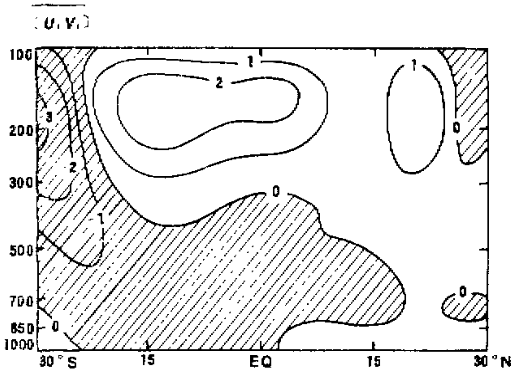

Fig. 7. The cross-section of the westerly momentum transfer averaged over a single period. The isoline interval is 1 $m^2 s^{-2}$. The shaded is the negative-value region.

On the other hand, it is noticeable that the transfer of westerly momentum by the QDPP is responsible for the convergence of the transferred momentum at the NH tropical latitudes with the divergence in SH, that is, the transfer caused by the QDPP does not facilitate the maintenance of the seasonally-averaged fields of the winds, i.e., the NH tropical upper easterly and SH subtropical westerly.

V. DISCUSSION OF RESULTS

i) The foregoing analyses indicate that within its single period QDPP brings about the considerable transfer of sensible heat and potential energy from the NH monsoon area to the SH and of momentum in an opposite direction. These processes are accomplished in the upper troposphere largely at the activation and break phases in association with the strengthening and weakening of the monsoon circulation. There occurs the lower transfer of sensible heat and momentum due to the SH mid-latitude QDPP from north (even the NH) to south and of potential energy towards NH, in relation to the quasi-periodic activities of cold air happening at the TP in the SH middle latitudes. Therefore, the cross-equatorial transfer of physical quantities induced by QDPP shows the interaction between the circulations over both the hemispheres.

ii) From the viewpoint of energetics, the kinetic energy responsible for QDPP originates from the conversion of perturbation effective potential energy (see He et al., 1987), with two sources: one situated in the upper and middle troposphere over the Asian monsoon area and the other in the middle and lower troposphere at the SH middle latitudes. The former appears on account of the periodic perturbation of convective activities in the monsoon region leading to the relation of ω_i to T_i and the latter by the quasi-periodic baroclinic activities at the SH middle latitudes. The two energy sources (the former one in particular) transport energy as potential to the south and north at upper and lower levels, respectively, to maintain the QDPP in the area under study. It is worth noting that these sources, each located in one hemisphere, operate for the particular phases of the QDPO, showing for different synoptical processes. Their disposition reflects the interaction between the SH mid-latitude cold air and Asian monsoon circulation, which may be a mechanism for maintaining the QDPO.

iii) From the previous discussions it is evident that the outbreak of cold air at the SH middle latitudes causes lower southeasterly and cross-equatorial flow to be intensified, thus strengthening the convergence and convection in the Asian monsoon region, and the reinforced upper divergent flow, in turn, intensifies southward cross-equatorial current with the result that sensible heat and potential energy are carried to SH and westerly momentum to NH. Afterwards, as cold air at the SH middle latitudes is weakened, southeasterly trade and cross-equatorial flow get weak accordingly, thus declining the convergence and convection, making the Asian monsoon transit to the break from activation. And then the upper northeasterly flow, although weakened, transfers sensible heat and potential energy to SH, westerly momentum being carried to NH.

According to the results obtained, we may well assume that QDPO represents a mode of interaction between the NH and SH circulations (forming the monsoon circulation system) caused by incessant impetus on the Asian monsoon circulation of the quasi-periodic outbreak of the SH cold air. Also, the QDPO meridional propagation results in the periodic change in the interhemispheric transport of physical quantities and the oscillation itself acts as the medium for the interaction between the hemispheric circulations.

The author is grateful to Prof. Zhu Qiangen for his valuable comments and suggestions on this article and to Prof. T. Murakami for his beneficial help with the research.

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