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ENERGY BALANCE IN 40—50 DAY PERIODIC OSCILLATION OVER THE ASIAN SUMMER MONSOON REGION DURING THE 1979 SUMMER

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ABSTRACT

Based on calculations of data from FGGE Level III b, a discussion is made of the energy balance in the 40—50 day periodic oscillation over the Asian monsoon region during the 1979 summer. It is found that the main source of 40—50 day periodic perturbation is the monsoon region extending from central South Asia to Southeast Asia. In the upper layer over the North Pacific subtropical area (10—20°N, 150°E—150°W) pressure work turns into kinetic energy that maintains 40—50 day periodic perturbation associated with the variation in position and intensity of the mid-Pacific trough. The mean energy budget in the three-dimensional space (0—30°N, 30°E—150°W, 100—1000 hPa) indicates that the 40—50 day periodic perturbation transports kinetic energy to a seasonal mean and a transient perturbation wind field.

I. INTRODUCTION

Ahlguist (1981) shows that 40—50 day periodic oscillation (PO) manifests itself most considerably in the summer of 1979, and the evolution of its circulation, the change in the vapor-transporting field, its vertical structure and phase propogation have been investigated by He et al. (1984) and Murakami et al. (1983). However, it is worth studying how this oscillation is maintained——the problem of its energy source. Zhu and Miao (1984) treat the kinetic energy budget during the northward advance of summer monsoon in China, indicating that pressure work is the main source of average kinetic energy. Yet, no studies have been performed of the energy balance during the 40—50 day PO up to now. The paper is devoted to this problem on the basis of results obtained from the authors' previous work.

II. DATA AND METHOD USED

The 1979 FGGE Level III b data employed cover the time period of May 1 to September 30 (daily data), the levels of 100, 200, 300, 500, 700, 850 and 1000 hPa, and the region of 30° N—30°S, 30°E—150°W with a 3.75° latitudinal-longitudinal grid for calculation.

In order to deal with the time-dependent evolution of element fields in 40—50 day PO, a composite method is proposed for examining the phase-dependent evolution of the elements in an idealized cycle of this oscillation (He et al. 1984; Murakami et al. 1983). Now, a 40—50 day band pass-filtered zonal wind averaged over the region between 60—150°E along 11.25°N at 850 hPa $\tilde{u}$ is taken as a reference variable and composited cycle of 40—50 day PO is divided into 9 phases. For the composite method, see He et al. (1984) and Murakami et al. (1983). According to the program proposed by Murakami and Sumi (1982), from the ith phase motion equation of 40—50 day PO, we get the equation of its kinetic energy balance which takes the form

$$\frac{\partial[K_i]}{\partial t}=[F(K_i)]+[I(\langle K\rangle,K_i)]+[I(K^*,K_i)]+[F(\Phi_i)]$$
$$+[I(P_i,K_i)]+[R(K_i)],$$

where

$$K_i=(u_i^2+v_i^2)/2,$$

$$[F(K_i)]=-\left(\frac{\partial\langle u\rangle[K_i]}{\partial x}+\frac{\partial\langle v\rangle[K_i]\cos\varphi}{\cos\varphi\partial y}+\frac{\partial\langle\omega\rangle[K_i]}{\partial P}\right),$$

$$[I(\langle K\rangle,K_i)]=-\left([u_iu_i]\frac{\partial\langle u\rangle}{\partial x}+[u_iv_i]\frac{\partial\langle u\rangle}{\partial y}+[u_i\omega_i]\frac{\partial\langle u\rangle}{\partial P}-\frac{\tan\varphi}{a}[u_iu_i]\langle v\rangle\right)$$
$$-\left([u_iv_i]\frac{\partial\langle v\rangle}{\partial x}+[v_iv_i]\frac{\partial\langle v\rangle}{\partial y}+[v_i\omega_i]\frac{\partial\langle v\rangle}{\partial P}+\frac{\tan\varphi}{a}[u_iv_i]\langle u\rangle\right),$$

$$[I(K^*,K_i)]=-\left[u_i\left(\frac{\partial u^*u^*}{\partial x}+\frac{\partial u^*v^*\cos^2\varphi}{\cos^2\varphi\partial y}+\frac{\partial u^*\omega^*}{\partial P}\right)_i+v_i\left(\frac{\partial u^*v^*}{\partial x}+\frac{\partial v^*v^*\cos\varphi}{\cos\varphi\partial y}\right.\right.$$
$$\left.\left.+\frac{\partial v^*\omega^*}{\partial P}+\frac{\tan\varphi}{a}u^*u^*\right)_i\right],$$

$$[F(\Phi_i)]=-\left[\frac{\partial u_i\Phi_i}{\partial x}+\frac{\partial v_i\Phi_i\cos\varphi}{\cos\varphi\partial y}+\frac{\partial\omega_i\Phi_i}{\partial P}\right],$$

$$[I(P_i,K_i)]=-\left[\frac{R}{P}\omega_iT_i\right].$$

Also, $\left[W(\Phi_i)\right]\equiv-\left[u_i\frac{\partial\Phi_i}{\partial x}+v_i\frac{\partial\Phi_i}{\partial y}\right]=[F(\Phi_i)]+[I(P_i,K_i)],$

where [ ] represents an average of phases 1—8; ⟨ ⟩ a May—September mean; the quantity with asterisk the deviation from its seasonal mean; $F(K_i)$ 40—50 day periodic perturbation (PP) kinetic energy advected by the seasonal average wind field; $[I(\langle K\rangle,K_i)]$ the barotropical interaction between a seasonal mean wind field and 40—50 day PP; $[I(K^*,K_i)]$ the nonlinear interplay between the PP and transient perturbation; $[W(\Phi_i)]$ a pressure work term composed of $[F(\Phi_i)]$ and $[I(P_i,K_i)]$, the former denoting horizontal and vertical divergence/convergence of gravitational potential energy (which will be termed potential energy only hereafter) fluxes due to 40—50 day PP and the latter the conversion of perturbation available potential into perturbation kinetic energy; $[R(K_i)]$ a residual term of the kinetic energy balance equation, including in itself mainly the factor of friction.

III. HORIZONTAL DISTRIBUTION OF TERMS IN THE KINETIC ENERGY BALANCE EQUATION

Figs. 1—2 illustrate the 850-hPa distribution of the terms of the equation. It is apparent that a high-value region of $[K_i]$ stretches from the eastern Arabic Sea via the Indian and the Indo-China Peninsula to the western North Pacific east of Taiwan, with three high centers of $[K_i]$ in excess of 6 m^2/s^2 located in the eastern Arabic Sea (14°N, 65°E), the Indo-China—

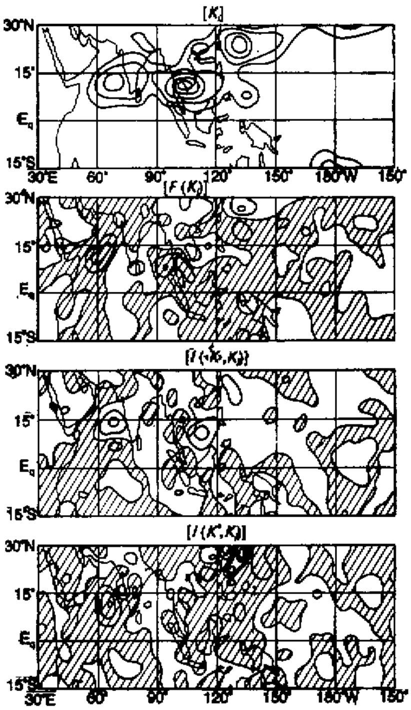

Fig. 1. Calculations of the relevant terms of the kinetic energy balance equation for 850 hPa. The interval of $[K_l]$ is 2 m^2/s^2 and those of $[F(K_l)]$, $[I(\langle K\rangle, K_l)]$ and $[I(K^*, K_l)]$ are all 2×10^{-5} m^2/s^3. The hatched area denotes a negative-value region.

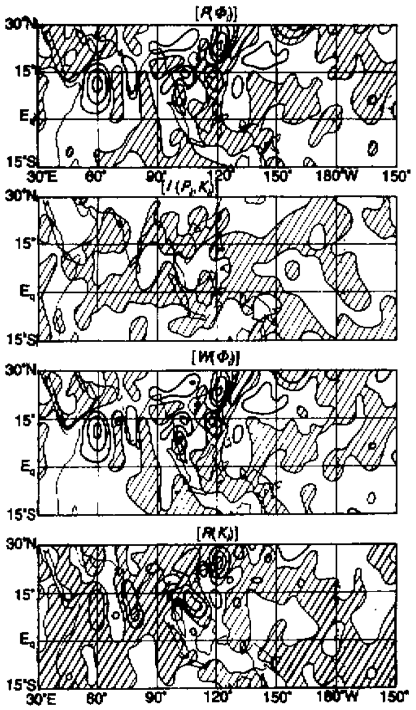

Fig. 2. The same as in Fig.1. The unit is 10^{-5} m^2/s^3. The interval of $[F(\Phi_l)]$, $[W(\Phi_l)]$ and $[R(K_l)]$ is 4 and that of $[I(P_l, K_l)]$ is 2 units. The hatched area is a negative-value region.

the South China Sea (10°N, 100°E) and the western Pacific east of Taiwan (25°N, 130°E), respectively. This indicates that the low-level 40—50 day PO is far more considerable over the summer monsoon region in central South Asia—Southeast Asia than in other areas. We can also find that three maxima of $[I(\langle K\rangle, K_l)]$ and almost in entire agreement with the above mentioned centers of $[K_l]$. It is obtained that the momentum transfer of 40—50 day PP in these regions ($[u_l u_l]$, $[u_l v_l]$) takes place along the gradient of the seasonal mean wind field, from which the PP acquires kinetic energy, that is, the barotropical conversion $[I(\langle K\rangle, K_l)]$ happening in these areas contributes to intensifying low-level 40—50 day PP of the Asian summer monsoon region.

A significant negative-value region of $[I(K^*, K_l)]$ (<-6 m^2/s^3) shows up in the eastern Arabic Sea (12°N, 65°E), and hence in this vicinity the kinetic energy $[K_l]$ is converted into the transient perturbation kinetic energy K^* via $[I(K^*, K_l)]$. Similarly, for the western North Pacific east of the South China Sea and Philippines transient perturbation is strengthened by virtue of kinetic energy from 40—50 day PP.

The pressure work term $[W(\Phi_i)]$ shows 7 maxima situated at 12°N, 60°E; 14°N, 75°E; 15°N, 102°E; 10°N, 130°E; 20°N, 140°E; 22°N, 120°E; 25°N, 107°E, respectively, which are, in the main, within the high-value regions of $[K_i]$. Although negative-value regions exist between these 7 areas, the integrations give greater positive values, as will be shown in Section III. We also find that $[F(\Phi_i)]$ plays a significant part and the conversion term $[I(P_i, K_i)]$ a tiny role in the net pressure work term, and that the order of $[F(\Phi_i)]$ is much higher than those of $[I(\langle K\rangle, K_i)]$ and $[I(K^*, K_i)]$. As will be seen later, the convergence of potential energy fluxes is brought about chiefly by the downward transfer of mid-tropospheric potential energy over the monsoon region. Besides, there is an approximately corresponding relationship between the high-value region of $[K_i]$ and the negative-value region of $[R(K_i)]$, which indicates the weakening effect of surface friction on the kinetic energy for 40—50 day PP.

Figs. 3—4 illustrate the calculations of the terms of kinetic energy balance equation for the 200-hPa level. It can be seen that a distinct high-value band of $[K_i]$ extends from the SH subtropical Indian Ocean (15°S, 65°E) across the equator around 90°E to the subtropical North Pacific, with a maximum at (20°N, 175°W) exceeding 40 m^2/s^2. The high values of $[K_i]$ reflects a considerable 40—50 day PO of the upper tropospheric trough over the Pacific, known as the mid-Pacific trough. To the west (east) is a high negative-value (positive-value) region of $[F(K_i)]$ which is due to the advection by seasonal mean westerlies. It is of much interest that the negative (positive) values of $[F(K_i)]$ are almost compensated or even overcompensated by the positive (negative) values of $[I(K^*, K_i)]$. Located in the North Pacific subtropical area (15—22°N, 160°E—180) is a distinct negative-value region (< -1 unit) of $[I(\langle K\rangle, K_i)]$ which implies that the 40—50 day PP provides, at least partially, kinetic energy for the maintenance of the seasonal mean wind field in the mid-Pacific trough and its neighborhood and that the 40—50 day PP momentum transfer is accomplished against the direction of the gradient of the wind field mentioned above. In the vicinity of the subtropical Pacific region (10—20°N, 150°E—150°W), the pressure work term $[W(\Phi_i)]$ has a considerably high value, which sustains the high value of $[K_i]$ over this area, and therefore appreciable 40—50 day PO. It is well-known that, as a rule, the summertime convection over the subtropical North Pacific is weak, which leads to the fact that the conversion term of availabe potential to kinetic energy $[I(P_i, K_i)]$ is not significant at both upper and low levels, as shown in Figs. 2 and 4. Hence, the high value of $[K_i]$ at 200 hPa for the subtropical region is sustained mainly by the convergence of horizontal fluxes of potential energy. And in this region, upper ageostrophic wind always blows in the direction of the gradient of geopotential height, meaning that the pressure work produces kinetic energy that makes possible the development of the mid-Pacific trough and the nearby 40—50 day PP.

Unlike the situation in the subtropical region, a distinct positive-value band with some centers of $[I(P_i, K_i)]$ is observed which extends approximately along 15°N from India via the Bay of Bengal to the South China Sea. However, $[K_i]$ is relatively small for this monsoon region. The fact that $[F(\Phi_i)]$ for this region are negative-valued for the most part means that the 200-hPa kinetic energy given by $[I(P_i, K_i)]$ is not used mainly to intensify the 40—50 day PP but to transport potential energy by virtue of the divergence of its fluxes to other regions, particularly to the south, where $[I(P_i, K_i)]$ is negative and $[F(\Phi_i)]$ positive. In a similar way, kinetic energy generated in the upper and mid-troposphere (about

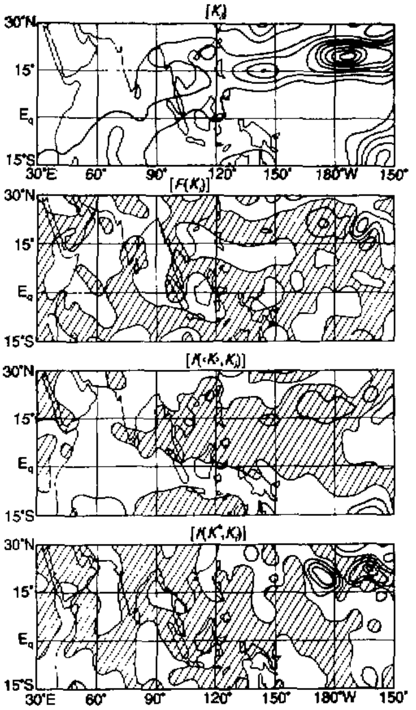

Fig. 3. Calculations of the relevant terms of the kinetic energy balance equation for 200 hPa. The interval of [K_i] is 5 m^2/s^2 and those of [$F(K_i)$], [$I(\langle K\rangle, K_i)$] and [$I(K^*, K_i)$] are all 1×10^{-4} m^2/s^3. The hatched area is a negative-value region.

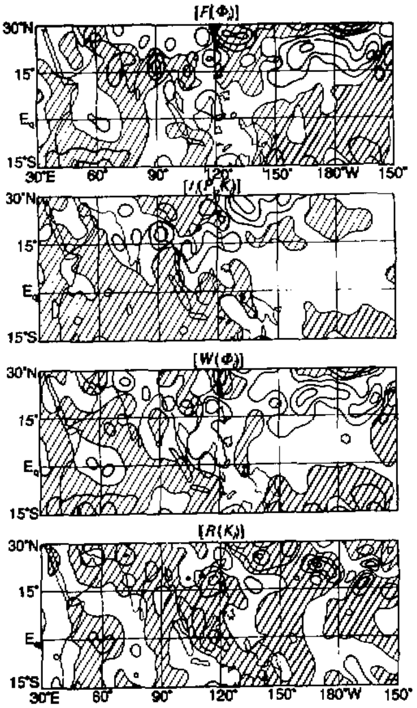

Fig. 4. Same as in Fig. 3, except that the intervals are all 1×10^{-4} m^2/s^3.

200 hPa) is transported downward as potential energy fluxes to facilitate the development of low-level perturbation in the monsoon region, which will be treated further in the subsequent section.

IV. VERTICAL PROFILES OF THE TERMS OF THE KINETIC ENERGY BALANCE EQUATION

The vertical profiles of the interaction terms averaged over the region of 0—30°N, 30°E—150°W are shown in Fig. 5. It is apparent that below 500 hPa, the 40—50 day PP acquires kinetic energy from a seasonal mean wind field via [$I(\langle K\rangle,K_i)$] but loses it to transient perturbation via [$I(K^*,K_i)$] which is opposite to that of the upper troposphere above 500 hPa, where, however, the sum of the two terms is negative, which indicates that the 40—50 day PP loses kinetic energy by means of barotropical interplay.

Between 300 and 700 hPa $[I(P_i, K_i)]$ has a greater positive value, that is almost compensated by the negative of $[F(\Phi_i)]$. This shows that the kinetic energy obtained from the baroclinic process of the conversion of available potential to kinetic energy is not used chiefly to reinforce the 40—50 day PP in the upper and mid-troposphere but transported downwards and upwards. In the lower troposphere below 850 hPa, $[W(\Phi_i)]$ is almost equal to $[F(\Phi_i)]$ both greater in magnitude, with a maximum of $+4\times10^{-5}$ m²/s² at 1000 hPa. The greater positive value of $[F(\Phi_i)]$ comes principally from the convergence of the downward transfer of potential energy, and at 1000 hPa, plays a role mainly in balancing the negative value of $[R(K_i)]$ caused by frictional dissipation. In the neighborhood of 200 hPa and the upper troposphere above $[I(P_i, K_i)]$ and $[F(\Phi_i)]$ both have greater positive values, whose sum, i.e., the pressure work term $[W(\Phi_i)]$, offsets the negative $[R(K_i)]$ to maintain the 40—50 day PP. In view of the fact that below 850 hPa and above 300 hPa, $[R(K_i)]$ has considerable negative values, frictional effect is indicated. On the other hand, in the layer adjacent to 500 hPa $[R(K_i)]$ have quite large positive values, which are perhaps due to the kinetic energy conversion from a subgrid to grid scale (Zhu and Miao, 1984) and various errors.

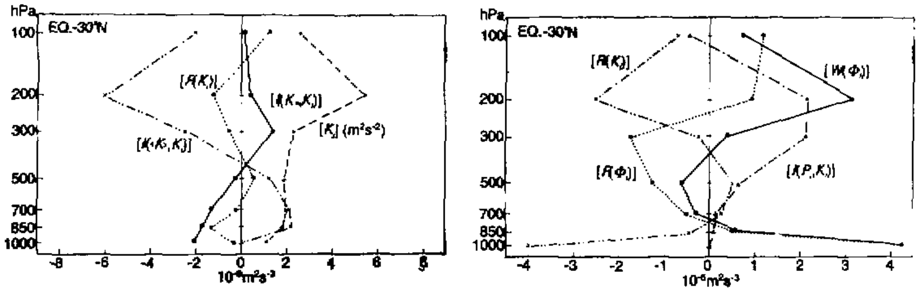

Fig. 5. Vertical profiles of the terms of the kinetic energy balance equation averaged over the region of 0—30°N, 30°—150°W, Units: m^2/s^2 for $[K_i]$; 10^{-4} m^2/s^3 for $[F(K_i)]$, $[I(\langle K\rangle, K_i)]$ and $[I(K^*, K_i)]$; 10^{-5} m^2/s^3 for $[F(\Phi_i)]$, $[I(P_i, K_i)]$, $[W(\Phi_i)]$ and $[R(K_i)]$.

Figs. 6—7 display the meridional vertical sections of $\overline{[\omega_i T_i]}$ and ($\overline{[v_i\Phi_i]}$, $\overline{[\omega_i\Phi_i]}$) averaged between 30°E—150°W, respectively. It is apparent by referring Fig. 6 that $\overline{[\omega_i T_i]}$ has a minimum (meaning that $[I(P_i, K_i)]$ has maximum) between 200 and 500 hPa in the vicinity of 15°N where perturbation available potential energy is converted into perturbation kinetic energy most intensely, indicating that the upper- and mid-troposphere over the South- and Southeast-Asian monsoon region is the energy source of the 40—50 day PP. Fig. 7 depicts an appreciable upward and downward transport of potential energy above 300 and below 500 hPa and a significant southward transfer of this energy at 200 hPa. This clearly shows that the kinetic energy in the upper and mid-troposphere due to convective activity over the monsoon region around 15°N is transported as potential energy fluxes downward, upward and southward to maintain the 40—50 day PP in the upper and low troposphere and the upper layer over the equatorial area.

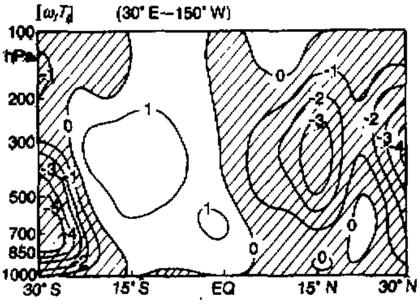

Fig. 6. The meridional vertical section of $[\overline{\omega_i T_i}]$ averaged between 30°E—150°W. Units: 10^{-5} deg hPa/s. The hatched area represents a negative-value region.

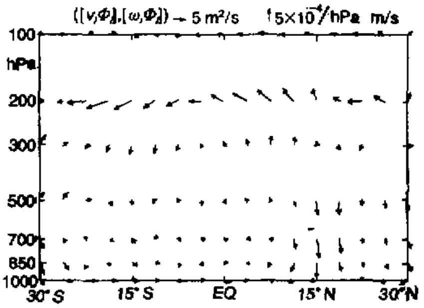

Fig. 7. The meridional vertical section of the potential energy transport $([\overline{v_i\Phi_i}], [\overline{\omega_i\Phi_i}])$ averaged between 30°E—150°W. Units: m³/s for $[\overline{v_i\Phi_i}]$ and 10^{-4}hPa m/s for $[\overline{\omega_i T_i}]$.

V. CONCLUSIONS

Based on the above analyses, we arrive at the following conclusions:

(1) The main energy source for the 40—50 day PP of the summer monsoon region is the conversion of perturbation available potential to perturbation kinetic energy occurring in the upper and mid-troposphere (500—200 hPa in the vicinity of 15°N), where the downward transfer of potential energy can maintain the low-level considerable 40—50 day PP by offseting frictional dissipation and its upward and southward transport the PP at 200 hPa over the equatorial region (5°N—15°S).

(2) For the subtropical North Pacific (10—20°N, 150°E—150°W) the 200-hPa ageostrophic wind always blows in the direction of the gradient of geopotential height, implying that kinetic energy is made via pressure work. Since convective activity in this region is generally quite weak, the conversion term $[I(P_i, K_i)]$ is not significant in the upper and low layers. This indicates that the maintenance of the 200-hPa appreciable 40—50 day PO over this monsoon area is accomplished mainly by virtue of the convergence of the horizontal fluxes of potential energy and such oscillation is associated with the change in position and intensity of the mid-Pacific trough.

(3) The 40—50 day PP below 500 hPa obtains kinetic energy from the seasonal mean wind field via $[I(\langle K\rangle, K_i)]$ but supplies transient perturbation with it via $[I(K^*, K_i)]$ and the reverse is true for the upper level above 500 hPa. Yet the integration results of both the layers show that the 40—50 day PP provides kinetic energy for the seasonal mean and the transient perturbation wind field. The residual term $[R(K_i)]$ represents a principal sink of energy, where friction is a main factor.

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