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On the kinetic energy budget of the summer-mean flow at 200 mb in the tropics

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ABSTRACT

The 200-mb wind data of the 1967 summer in the tropics is used to analyze the kinetic energy budget of the tropical time-mean flow. The horizontal distributions of the kinetic energy variables in the tropics are investigated and compared with the midlatitude studies of Holopainen (1978) and Lau (1979).

The results reveal that the large-valued transient kinetic energy extends from the maximum core to the downstream of the tropical easterly jet. The maximum kinetic energy of the tropical time-mean flow goes hand in hand with this jet core. The relative locations of the maximum kinetic energy of the time-mean and transient flows in the tropics differ from those in the midlatitudes. The geographic distributions of horizontal fluxes of kinetic energy in the tropics shown in this study and the vertical circulations in the upstream and downstream sides of the tropical easterly jet shown by Krishnamurti (1971a, b) indicate that the kinetic energetics of the tropical easterly jet may be similar to that of the westerly jet in the midlatitudes.

1. Introduction

The time-mean state of atmospheric circulation for long time periods is one of the important aspects of climatology. Examination of how the time-mean atmospheric flow is energetically maintained would promote our understanding of the dynamics of climate. Recently, Holopainen (1978) examined the kinetic energy budget of two 5-year mean flows and Lau (1979) investigated that of eleven 3-month winter mean flows in the midlatitudes. It is found that the maximum kinetic energy of the time-mean flow, $\bar{k}$, occurs at the position of the climatological jet stream over the eastern coasts of the continents. The maximum kinetic energy of transient flow appears to the northeast from those of $\bar{k}$. The kinetic energies of the time-mean and transient flows are generated by the pressure gradient force upstream of the jet and are transported toward the ocean. The kinetic energy of the time-mean flow which converges over the ocean areas is destroyed by the pressure-gradient force.

The westerlies and westerly jet in the midlatitudes give way to the easterlies and easterly jet in the tropics. The tropical easterly jet obtains its maximum intensity in summer and extends from the South China Sea to western Africa. The energetics study of large-scale circulation in the tropics, e.g. Chen (1980), Krishnamurti et al. (1973), Kanamitsu et al. (1972), and Depradine (1980), shows that the atmospheric energetics in the tropics differs from that in the midlatitudes. The question is whether both Holopainen's and Lau's (hereafter referred to as H and L respectively in this paper) findings of the kinetic energetics of the time-mean atmospheric flow in the midlatitudes extend to the tropics. We report the preliminary examination of this problem using H's approach and the 200-mb wind fields of the 1967 summer in the tropics compiled by Professor Krishnamurti and his colleague (Krishnamurti and Rodgers, 1970) at Florida State University.

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2. Kinetic energy equations

Following Holopainen (1978), we can express the kinetic energy equations of the time-mean and transient flows as follows:

$$\frac{\partial \bar{k}}{\partial t} = -\nabla \cdot (H_0 + H_1) - \frac{\partial}{\partial p}\left[\bar{k}\bar{\omega} + \overline{(\bar{u}u' + \bar{v}v')\,\omega'}\right] - \bar{\mathbb{V}} \cdot \nabla\bar{\phi} + \bar{\mathbb{V}} \cdot \bar{\mathbb{F}} - C(\bar{k}, k'), \tag{1}$$

$$\frac{\partial k'}{\partial t} = -\nabla \cdot (H_2 + H_3) - \frac{\partial}{\partial p}\,\overline{(k'\,\omega')} - \overline{\mathbb{V}' \cdot \nabla\phi'} + \overline{\mathbb{V}' \cdot \mathbb{F}'} + C(\bar{k}, k'), \tag{2}$$

where

$\bar{k} = \frac{1}{2}(\bar{u}^2 + \bar{v}^2)$,
$k' = \frac{1}{2}(u'^2 + v'^2)$,
$H_0 = \bar{\mathbb{V}}\bar{k}$,
$H_1 = \overline{(\bar{u}u' + \bar{v}v')\,\mathbb{V}'}$,
$H_2 = \bar{\mathbb{V}}\,k'$,
$H_3 = \overline{\mathbb{V}'\,k'}$,

and

$$C(\bar{k}, k') = -\frac{\overline{u'\,u'}}{a\cos\phi}\frac{\partial \bar{u}}{\partial \lambda} - \frac{\overline{u'\,v'}\cos\phi}{a}\frac{\partial}{\partial \phi}\left(\frac{\bar{u}}{\cos\phi}\right) - \frac{\overline{u'\,v'}}{a\cos\phi}\frac{\partial \bar{v}}{\partial \lambda} - \frac{\overline{v'\,v'}}{a}\frac{\partial \bar{v}}{\partial \phi} + \overline{u'\,u'}\,\bar{v}'\,\frac{\tan\phi}{a} - \overline{u'\,\omega'}\frac{\partial \bar{u}}{\partial p} - \overline{v'\,\omega'}\frac{\partial \bar{v}}{\partial p}. \tag{3}$$

$\overline{(\ )}$ = time average and $(\ )' = (\ ) - \overline{(\ )}$. $\mathbb{F}$ is the frictional force.

The local changes of $\bar{k}$ and k' are caused by various physical processes displayed on the right-hand side of (1) and (2). The first two terms represent the horizontal and vertical divergence of kinetic energy flux respectively. The third term is the generation of kinetic energy due to the work done by the cross-contour flow. The fourth term is dissipation of kinetic energy which is generally difficult to evaluate. The last term, $C(\hat{k},k')$, denotes the conversion between the kinetic energies of time-mean and transient flows. Lau (1979) regards $\nabla \cdot H_1 + C(\bar{k}, k')$ as the contributions of transient-flow kinetic energy to the maintenance of the time-mean-flow kinetic energy in his $\bar{k}$ equations. $C(\bar{k},k')$ is the exchange of kinetic energy between the transient and time-mean flow to maintain the former.

Since the 200-mb wind fields are the only available observational data in this study, terms involving the vertical motion, height field and dissipation cannot be estimated. Therefore only a tentative picture of kinetic energy budget of the tropical flow, especially the kinetic energetics of the tropical easterly jet, can be reached based upon the horizontal fluxes.

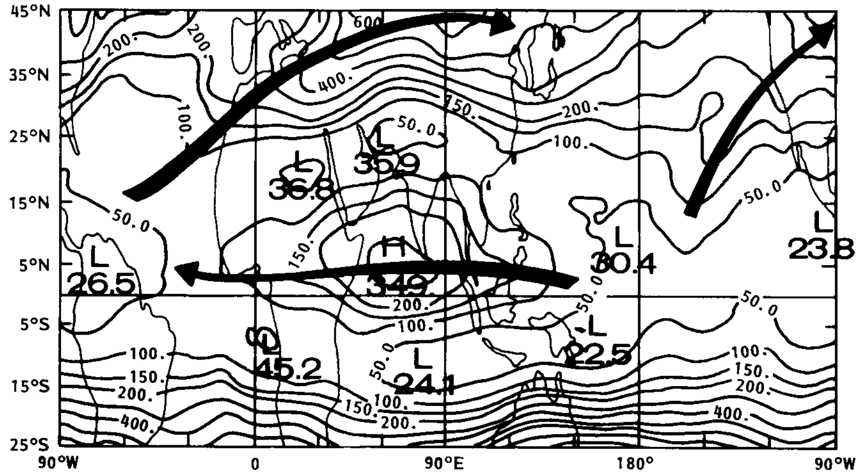
3. Results

3.1. *Horizontal distribution of kinetic energy*

The major features of the summer tropical circulation at 200 mb described by Krishnamurti (1971a) are two mid-oceanic troughs in the sub-tropics of the Northern Hemisphere, the tropical easterly jet across the Indian Ocean and the subtropical westerly jet in the Southern Hemisphere. The high-speed wind is expected to be associated with these circulation features.

The horizontal distribution of total kinetic energy, k, displayed in Fig. 1a, is very similar to the isotachs of the resultant wind at 200 mb of summer 1967 shown in Krishnamurti's (1971a) Fig. 2.2. The square root of $2k$ is equivalent to the magnitude of the resultant wind. The thick solid arrows designate the subtropical and tropical jet. A large-valued k between 5° S and 20° N extends from the western Pacific Ocean to western Africa with the maximum value appearing at the south-southwest of India. This k distribution corresponds to the existence of a tropical easterly jet. The k distribution in the subtropics of the Northern Hemisphere shows two areas of large-valued k which associate with the strong south-westerly flow ahead of the mid-oceanic troughs. This k distribution is somewhat different from H's results in which two major maxima of k exist over the oceans with the area of large k extending to the east coasts

Fig. 1. Horizontal distribution of (a) total kinetic energy, (b) kinetic energy of time-mean flow and (c) kinetic energy of transient flow for the summer of 1967. Unit: J kg^{-1}.


45°N
35°N
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5°S
15°S
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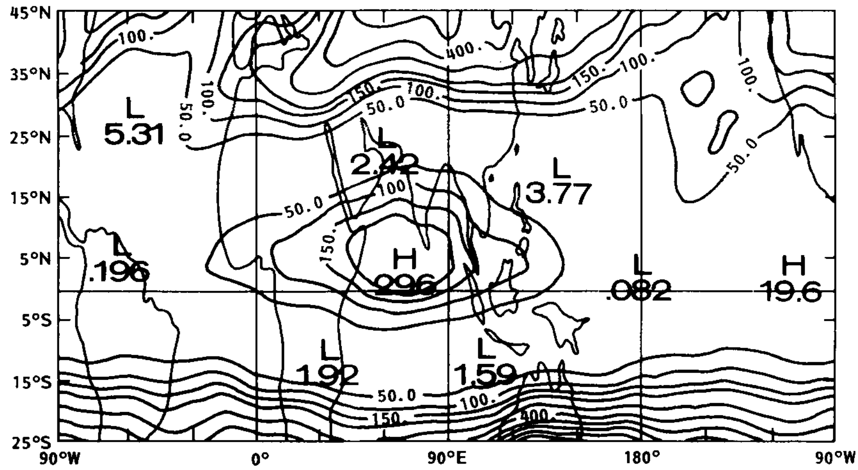
90°W
0
90°E
180°
90°W
L 35.9
L 36.8
H 349
L 26.5
L 30.4
L 23.8
L 45.2
L 24.1
L 22.5

(a)


45°N
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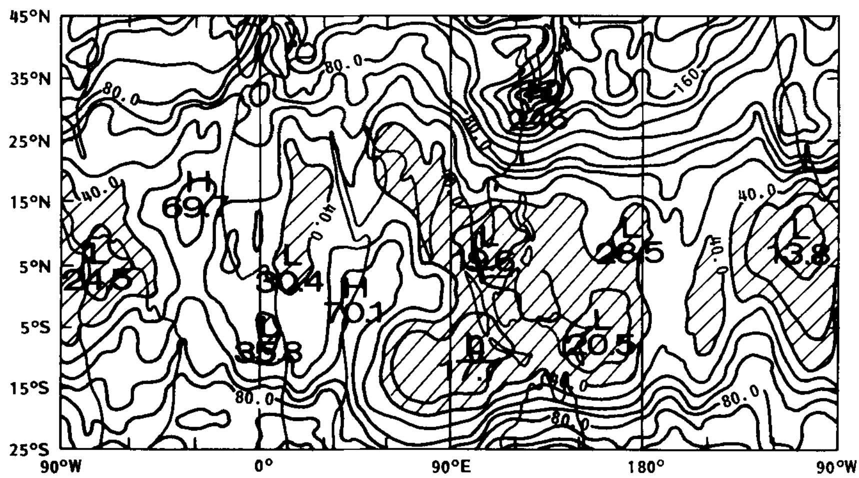
90°W
L 5.31
L 2.42
L 3.77
L .196
H 296
L .082
H 19.6
L 1.92
L 1.59

(b)


45°N
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5°S
15°S
25°S
90°W
0°
90°E
180°
90°W
H 69.7
L 24.5
L 30.4
H 70.1
L 28.5
L 13.8
L 20.5

(c)

of the continents. This discrepancy exists because H dealt with the annual mean flow and integrated k over the whole layer of atmosphere. The large-valued k in the subtropics of the Southern Hemisphere is due to the subtropical jet.

The horizontal distribution of mean-flow kinetic energy, $\bar{k}$, is depicted in Fig. 1b. Although the magnitude of $\bar{k}$ is smaller than that of k, the distribution of $\bar{k}$ is very similar to that of k. This similarity of the k and $\bar{k}$ distributions indicates that the major features of the tropical summer circulation at 200 mb mentioned above are standing-eddy phenomena. The distribution of transient-flow kinetic energy, k', Fig. 1c, is not as regular as that shown in H's study in midlatitudes. The hatched area represents the location where the k' value is smaller than 40 J kg^{-1}. k' in the subtropics displays large values in the downstream sides of westerly jets, especially near Japan. The k' distribution in the tropics has large values extending from the eastern Indian Ocean to the western Atlantic Ocean. In other words, the large-valued k' covers the area extending from the core of the tropical easterly jet to its downstream.

Chen (1980) showed that $\bar{k}$ was mainly associated with the zonal flow and wavenumber one and k' with waves of wavenumber larger than one in the tropics. The geographic distribution of $\bar{k}$ and k' shown in Fig. 1 illustrates this result on a horizontal plane. The k' maxima found in the midlatitudes of H's study are located on the northeast of the $\bar{k}$ maxima. H explains that this configuration of k' and $\bar{k}$ is likely because the baroclinic disturbances are generated in the area of maximum baroclinity which is roughly the areas of $\bar{k}$ maxima, and k' reaches its maximum values a long way downstream. The geographic locations of large-valued k' relative to the $\bar{k}$ maximum in the tropics do not show characteristics similar to those displayed in the midlatitudes. This manifests qualitatively that the mechanisms generating transient disturbances in the tropics differ from those in the midlatitudes.

The conversion between zonal (K_Z) and eddy (K_E) kinetic energy, $C(K_Z, K_E)$ is regarded as an indicator of the barotropic instability of the zonal flow. Krishnamurti (1971a) made a detailed calculation of $C(K_Z, K_E)$ at the 200-mb tropics of summer 1967 in space and time. He found a 3.5-day oscillation of this energy conversion which indicates the existence of this short-period barotropic instability. Kanamitsu et al. (1972) computed this energy conversion in the spectral domain for the time-mean and transient flows. They found that positive $C(K_Z, K_E)$ mainly appeared in the transient eddies with wavenumber larger than three. Based upon these findings, Krishnamurti et al. (1973) proposed a tropical energy diagram in which the tropical waves, except forced ultralong waves, were barotropically generated. The large-valued k' displayed in Fig. 1c may not only provide the geographic distribution of transient tropical wave activities, but may also indicate that the favorite location of barotropic instability in the tropics is possibly to the east of large-valued k' areas.

3.2. *Horizontal distribution of kinetic energy flux terms*

In his review for the research of atmospheric general circulation in the past three decades, Wallace (1979) pointed out that the transient eddies play a relatively important role in satisfying the balance requirements of the zonally averaged time-mean circulation. On the contrary, the transient eddies are not so vital to the balance requirements of the local time-mean circulation. According to the confluence theory of Namias and Clapp (1949), the local time-mean circulation is mainly maintained by the time-mean flow. The diagnostic analysis of the kinetic energy budget by H and L confirms this theory. This brief historical account of atmospheric circulation study deals with the midlatitudes. It was discussed in the last section that the time-mean flow dominates the large-scale tropical atmospheric circulation. Furthermore, the height field and friction are difficult to observe and estimate in the tropics. The horizontal distribution of kinetic energy flux terms in the kinetic energy budget equations may provide some alternative to examine how the tropical time-mean circulation is locally maintained.

All the divergences of kinetic energy flux terms and $C(\bar{k}, k')$ were computed in this study. It was found that $\nabla \cdot H_2$, $\nabla \cdot H_3$ and $C(\bar{k}, k')$ are small compared with $\nabla \cdot H_0$ and $\nabla \cdot H_1$. In addition, the horizontal distributions of the former three quantities, using the data of one summer, are noisy. We shall only highlight the result of $\nabla \cdot H_2$, $\nabla \cdot H_3$ and $C(\bar{k}, k')$, rather than show their distributions.

Horizontal distributions of $\nabla \cdot H_0$ and $\nabla \cdot H_1$ are displayed in Fig. 2. $\nabla \cdot H_1$ has been regarded as the

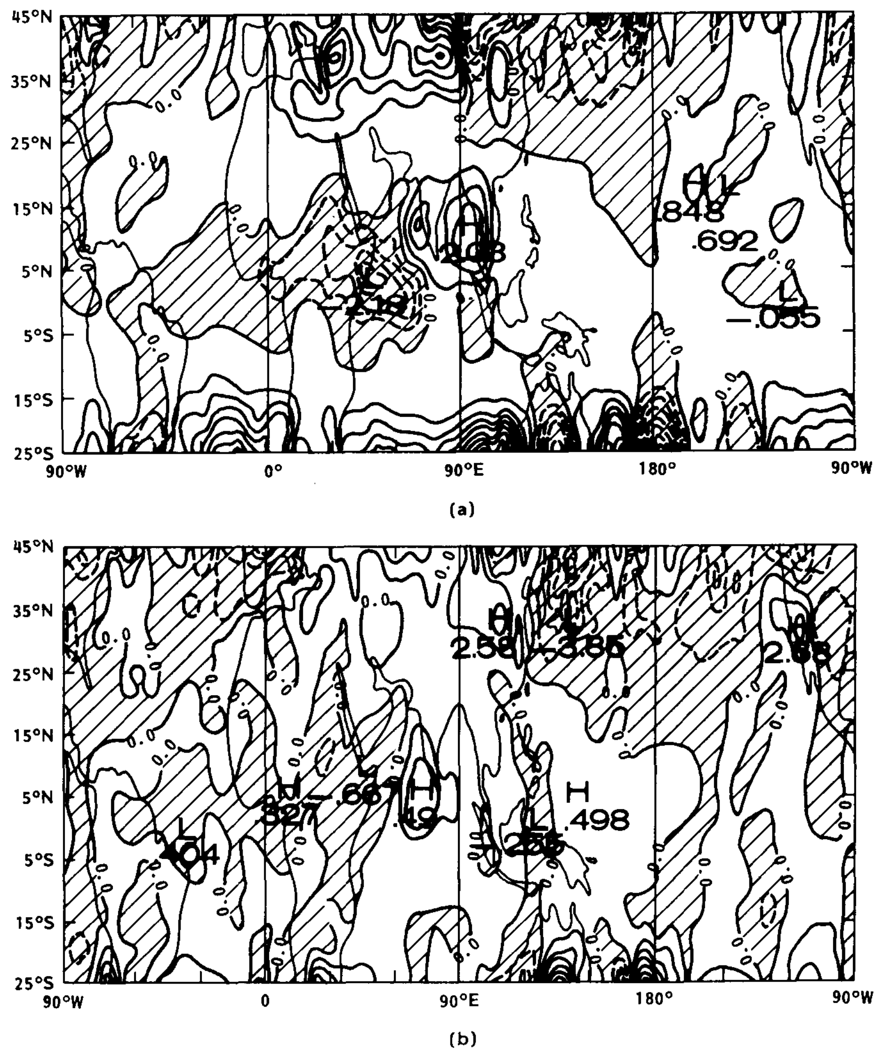

Fig. 2. Horizontal distributions of (a) $\nabla \cdot H_0$, and (b) $\nabla \cdot H_1$ for the summer of 1967. Note that the contour interval is 0.5×10^{-4} W kg^{-1} between 5° S and 20° N, and 1.0×10^{-4} W kg^{-1} outside this region. The negative-valued area is hatched. Unit: 10^{-4} W kg^{-1}.

maintenance of time-mean flow by the transient Reynold's stress by H. Comparison between Figs. 2a and b shows that $\nabla \cdot H_0$, the horizontal flux of time-mean kinetic energy by time-mean flow, is a dominant process. In other words, the magnitude of $\nabla \cdot H_0$ in the tropics is significantly larger than that of $\nabla \cdot H_1$, while the magnitude of these quantities in the midlatitudes are comparable in H and L.[1] This could be because the main dynamical role in the summer tropical circulation is played by the time-mean flow. It is also interesting to note that the horizontal distribution of $\nabla \cdot H_0$ and $\nabla \cdot H_1$ over the tropics are almost in phase. This indicates that both $\nabla \cdot H_0$ and $\nabla \cdot H_1$ contribute to the divergence of $\bar{k}$ upstream of the easterly jet and contribute to

[1] Lau (1979) computed $\nabla \cdot H_1 + C(\bar{k}, k')$, rather than $\nabla \cdot H_1$. Since $|\nabla \cdot H_1| \gg |C(\bar{k}, k')|$ (Halopainen, 1978) is true over most places in midlatitudes, $|\nabla \cdot H_1 + C(\bar{k}, k')| \simeq |\nabla \cdot H_1|$ may be an acceptable approximation. The present computation shows that $|\nabla \cdot H_1 + C(\bar{k}, k')| \simeq |\nabla \cdot H_1|$ in the tropics is a good approximation.

the convergence downstream of the easterly jet. According to H and L, this may imply that the generation of k due to the pressure gradient force is larger than dissipation on the upstream side to accelerate the easterly jet. The reverse occurs on the downstream side of the easterly jet.

The $\nabla \cdot H_2$ distribution is similar to those of $\nabla \cdot H_0$ and $\nabla \cdot H_1$ except the magnitude of $\nabla \cdot H_2$ is several factors smaller than $\nabla \cdot H_0$. This contrast between the magnitudes of $\nabla \cdot H_0$ and $\nabla \cdot H_2$ is consistent with L's study in the midlatitudes. $C(\bar{k}, k')$ is another means of depleting $\bar{k}$ and enhancing k' or vice versa. The magnitude of $C(\bar{k}, k')$ is comparable to $\nabla \cdot H_2$, but is still smaller than $\nabla \cdot H_0$. The horizontal distribution of $C(\bar{k}, k')$ shows that its sense is opposite to $\nabla \cdot H_0$, $\nabla \cdot H_1$ and $\nabla \cdot H_2$. $\nabla \cdot H_3$, which involves the triple product of transient eddies, and is very small in our computation, as found by H.

It was found in the study of H and L that $\bar{k}$ is transported from the eastern continents to the oceans in the midlatitudes. As a matter of fact, this trend can still be seen in the midlatitudes of the Northern Hemisphere in Fig. 2. The question remains as to whether the same physical process occurs in the tropics. Fig. 2 shows that $\nabla \cdot H_0$ and $\nabla \cdot H_1$ are positive, i.e. divergence of kinetic energy flux, from the western Pacific Ocean to the eastern Indian Ocean, and negative, i.e. convergence of kinetic energy flux, from the western Indian Ocean, across the African Continent, to the Atlantic Ocean. It seems that $\bar{k}$ is transported from ocean to continent in the tropics. In other words, the geographic distribution of $\bar{k}$ flux divergence and convergence relative to continent, say, Africa, does not exhibit similarity to those in the vicinity of the westerly jet in midlatitudes.

H and L point out that the divergence (convergence) of kinetic energy indicates that the generation of kinetic energy due to the work done by the cross-contour flow, i.e. ageostrophic flow, is larger (smaller) than the dissipation. Based upon the confluence theory of Namias and Clapp (1949), L also points out that the thermally direct circulation exists in the entrance region of the jet and accelerates it, while the thermally indirect circulation appears in the downstream of the jet and decelerates it. The distribution of horizontal fluxes of kinetic energy with respect to the continent in the tropics discussed above is different from the argument of H and L. Can the same physical processes occur for the energetic maintenance of the tropical easterly jet?

The conclusion of H and L on the energetic maintenance of the westerly jet in midlatitudes is based upon the assumption that the friction dissipates kinetic energy and the vertical transport is less significant than the horizontal transport. Since only one level data is available in the present study, we should be cautious in applying the residual method to interpret the generation of kinetic energy based upon the results of $\nabla \cdot H_0$ and $\nabla \cdot H_1$. The vertical transport term, which cannot be evaluated here, may be more significant in the tropics. In addition, Vincent and Schlatter (1979) found some evidence that deep cumulus clouds may act as a source of grid-scale kinetic energy. Since deep cumulus convections are so vital to drive large-scale circulation in the tropics, the possibility that the subgrid-scale friction turns out to be a source of kinetic energy of tropical flow may exist. Presumably the effect of friction and vertical transport on the tropical flow is similar to that on the midlatitude flow. $\nabla \cdot H_0$ and $\nabla \cdot H_1$ shown in Fig. 2 are positive in the upstream side and negative in the downstream side of the easterly jet. H and L's finding for the generation of kinetic energy of the jet due to the work done by the cross-contour flow in the entrance and exit regions may be applicable to the tropical easterly jet. In any event, the computations of the generation of kinetic energy using the height field is highly desirable as far as our study is concerned.

Based upon the synoptic analysis of the 200-mb wind field, 300-mb temperature field and gradient-level wind field in the tropics of summer 1967, Krishnamurti (1971a) proposed a three-dimensional circulation model. This schematic model shows that the southwest Asian monsoon circulation has an ascending branch near the Himalayas and returns equatorward around the Tibetan high. The convergence which causes a descending branch occurs over the Indian Ocean at the equator. This circulation is a thermally direct cell in the entrance of the tropical easterly jet. The northeast trade over the Atlantic Ocean converges near the ITCZ and causes the ascending air to move north poleward ahead of the mid-oceanic upper-level trough. The northward moving air converges and induces a descending branch off the west coast of the African continent. This circulation is a thermally indirect cell in the exit of the

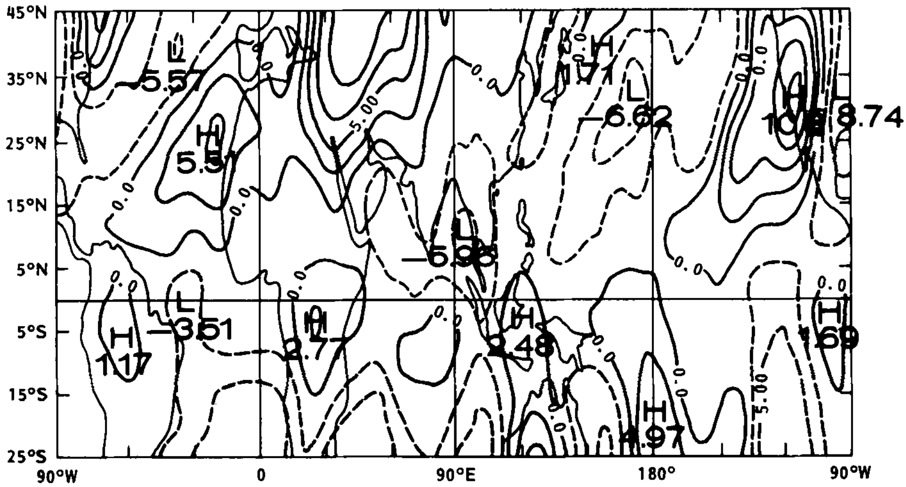

Fig. 3. Mean meridional wind (m s^{-1}) for the summer of 1967 at 200 mb.

tropical easterly jet. This three-dimensional schematic circulation model around the easterly jet was confirmed by Krishnamurti's (1971b) computation of mean divergent motions and isotachs for his study of the east–west circulation in the tropics. The mean meridional winds for summer 1967 at 200 mb, displayed in Fig. 3, show that the northward flow exists over equatorial Africa, downstream side of the tropical easterly jet, and the southward flow appears over the Bay of Bengal, upstream side of the tropical easterly jet. In other words, the distribution of meridional winds in the tropics also shows the evidence to support the existence of thermally direct (indirect) circulation in the entrance (exit) region of the tropical easterly jet. The average July rainfall of 1955, compiled by Koteswaram (1958), showed heavy precipitation north of the entrance of the easterly jet and south of the exit region of this jet. This indicates that large-scale ascent occurs north of the entrance and south of the exit region. Although Kanamitsu and Krishnamurti (1978) note that the significant year-to-year variations of the tropical flow patterns exist, Koteswaram's result seems to be consistent with Krishnamurti.

The three-dimensional circulations in the entrance and exit regions of the tropical easterly jet analyzed by Krishnamurti support the application of L's finding for the energetic maintenance of the midlatitude westerly jet to the tropical easterly jet. In other words, a thermally direct circulation exists in the entrance where $\nabla \cdot H_n$[1] are positive and the jet is accelerated, and thermally indirect circulation exists in the exit where $\nabla \cdot H_n$ are negative and the jet is decelerated.

4. Concluding remarks

The present study reports a preliminary result of the kinetic energy budget analysis along the lines of Holopainen (1978) and Lau (1979) using the 200-mb wind field of summer 1967 in the tropics. It is found that the large-valued transient kinetic energy extends from the core of the tropical easterly jet to the downstream of this jet. The maximum kinetic energy of the tropical time-mean flow goes hand in hand with this jet core. The relative locations of the maximum kinetic energy of the time-mean and transient flows in the tropics differ from those in the midlatitudes. This discrepancy manifests that the mechanisms which generate the transient disturbances in the tropics are different from those in midlatitudes.

According to Holopainen and Lau, the divergence (convergence) of kinetic energy indicates that the generation of kinetic energy due to the work done by the cross-contour flow is larger (smaller) than the dissipation. The geographic distribution of

[1] The subscript, n, can be 0, 1, 2, and 3.

kinetic energy flux in the current study displays divergence (convergence) in the upstream (downstream) region of the tropical easterly jet. It seems possible that Holopainen's and Lau's argument for the generation of kinetic energy due to cross-contour flow may be applicable to the kinetic energetics of the tropical easterly jet. Since only 200-mb wind data in the tropics is available in our study, a further study to examine the generation of kinetic energy using multilevel wind and height field is highly desirable.

Lau (1979) pointed out that divergence (convergence) of kinetic energy flux associates with a thermally direct (indirect) circulation in the entrance (exit) region of the jet and the jet is accelerated (decelerated). Krishnamurti's (1971a, b) synoptic analysis of the divergent motions and their isotachs for the tropical east–west circulation shows clearly the existence of a thermally direct (indirect) circulation in the upstream (downstream) side of the tropical easterly jet. The geographic distribution of kinetic energy flux divergence shown in our computation and Krishnamurti's vertical circulations with respect to the tropical easterly jet manifests that Lau's reasoning for the kinetic energetics of the midlatitude westerly jet may be applied to the tropical easterly jet.

Based upon computations using the 200-mb tropical wind fields, only a tentative conclusion was made concerning the kinetic energetics of the tropical circulation, especially the tropical easterly jet. It is our hope that an extensive analysis of the present study can be performed to shed more light on the climatology of the tropical circulation when the FGGE level III-b data become available.

5. Acknowledgments

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REFERENCES

Chen, T.-C. 1980. On the energy exchange between the divergent and rotational components of atmospheric flow over the tropics and sub-tropics at 200 mb during two northern summers. *Mon. Wea. Rev. 108*, 896–912.

Depradine, C. A. 1980. Energetics of large-scale motion in the tropics during GATE at 250 mb. *Mon. Wea. Rev. 108*, 886–895.

Holopainen, E. 1978. A diagnostic study of the kinetic energy balance of the long-term mean flow and the associated transient fluctuations in the atmosphere. *Geophisica 15*, 125–145.

Kanamitsu, M., Krishnamurti, T. N. and Depradine, C. A. 1972. On scale interactions in the tropics during the northern summer. *J. Atmos. Sci. 29*, 698–706.

Kanamitsu, M. and Krishnamurti, T. N. 1978. Northern summer tropical circulations during drought and normal rainfall months. *Mon. Wea. Rev. 106*, 331–347.

Koteswaram, P. 1958. The easterly jet stream in the tropics. *Tellus 10*, 43–57.

Krishnamurti, T. N. 1971a. Observational study of the tropical upper tropospheric motion field during the Northern Hemisphere summer. *J. Appl. Meteor. 10*, 1066–1096.

Krishnamurti, T. N. 1971b. Tropical east-west circulation during the northern summer. *J. Atmos. Sci. 28*, 1342–1347.

Krishnamurti, T. N. and Rodgers, E. B. 1970. 200 mb wind field June, July and August 1967. Rep. No. 70-2, Dept. of Meteorology, Florida State Univ., 114 pp.

Krishnamurti, T. N., Kanamitsu, M., Koss, W. J. and Lee, J. D. 1973. Tropical east-west circulations during the northern winter. *J. Atmos. Sci. 30*, 780–787.

Lau, N.-C. 1979. The structure and energetics of transient disturbances in the Northern Hemisphere winter circulation. *J. Atmos. Sci. 36*, 982–995.

Namias, J. and Clapp, P. F. 1949. Confluence theory of the high tropospheric jet stream. *J. Meteorol. 6*, 330–336.

Vincent, D. G. and Schlatter, T. W. 1979. Evidence of deep convection as a source of synoptic-scale kinetic energy. *Tellus 31*, 493–504.

Wallace, J. M. 1979. A historical introduction. In *The general circulation* (ed. M. L. Blackmon). National Center for Atmospheric Research, 1–14.