Vol. 2 No. 1 JOURNAL OF TROPICAL METEOROLOGY June 1996

INTERHEMISPHERIC EFFECT OF DIABATICALLY INDUCED LINEAR STATIONARY WAVES

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Received 31 August 1995

ABSTRACT

A numerical investigation of diabatically induced stationary waves in northern winter season was carried out by using a linear steady state spectral model with primitive equations in global domain. It was focused on inter-hemispheric connections of stationary wave behaviour in response to several cases of idealized thermal forcings centred in different latitudes. The results showed that the thermally forced stationary waves in one hemisphere might propagate across the equator into the other hemisphere, and thus contribute substantially to the maintenance and variation of the stationary waves in both hemispheres.

Key words: stationary waves, inter-hemispheric connection, wavetrain propagation

I. INTRODUCTION

There have been a lot of studies on stationary waves, which are of essence in maintaining climate in a season, for the previous 15 years (e.g. Hoskins et al, 1981; Simmons, 1982; Navarra, 1990; et al). These studies mainly investigated maintainence and behaviour of atmospheric stationary waves in response to three major forcings, i. e. orography, diabatic heating and transient eddies, in addition to some model aspects such as impact of model resolution, imposition of damping rates and many others.

Interhemispheric connection of stationary waves induced by diabatic heating has still been of much speculation. There are difficulties in simulating stationary waves in one hemisphere in response to diabatic heating forcing situated in other hemisphere by a linear model due to the presence of critical latitudes in the tropical area where the longitudinal component of zonal mean velocity vanishes. However, observational evidence (see Webster, 1983; Figure not shown) displayed that kinetic energy does propagate from the northern hemisphere into the southern hemisphere in the presence of westerly at a level in the tropical region. Therefore an attempt was made in this article to explore interhemispheric propagation of diabatially induced stationary waves by using a linear steady-state model defined over the globe. In the next section, we will describe the model used and the diagnostic methods for analysing the model results, followed by two sections on experimental results thereof. And some conclusions will be drawn in the final section.

II. MODEL DESCRIPTION AND DIAGNOSTIC METHODS

The numerical model used for this study is a linear steady state spectral model in global domain. It is derived from the primitive equations as described by Machenhauer and Daley (1972), and lately used by Lei (1986). It was obtained by linearizing the primitive equations with respect to the symmetric component of the monthly averaged zonal velocity $[U]$ and temperature $[T]$, which will be described later, according to the perturbation theory (e.g. Holton, 1979). The main features of the model are that it is formulated under a terrain -following σ coordinate which is defined as $\sigma = 2\frac{P}{P_s} - 1$ in which P denotes pressure at a model level and P_s the pressure at the earth surface. This vertical coordinate has an advantage of easiness to incorporate the representation of dependent variables in vertical by orthogonal polynomials such that the surface geopotential could be incorporated into the model without difficulty. Actually the dependent variables of the model are represented by spherical harmonics in horizontal and associated Legendre polynomials in vertical. Therefore the model is very flexible in terms of its resolution in both vertical and horizontal. We use triangular truncation at maximum wavenumber 9 in horizontal and maximum order 4 of the Legendre polynomials in vertical. Furthermore, some simple forms of Newtonian cooling and Rayleigh friction with spatially varying decay rate, similar to those of Simmons (1982) and Nigam et al (1986), as well as bi-harmonic horizontal diffusion are included into the model in order to facilitate reasonable mechanistic modelling. The detailed formulation of the linear model can be referred to e.g. Peng (1992).

The monthly-averaged symmetric component of zonal velocity $[U]$ and temperature $[T]$, used in this model as basic state, are derived from the monthly mean climatology in January 1979. No attempt is made to adjust the basic state $[U]$ and $[T]$ into balancing requirement since the original data were very well balanced, although we noticed that the original balancing relationship between them may be violated after zonal averaging is taken. Instead, some sensitivity tests of the model results to the basic state (see e.g. Zimmerman, 1989; Peng, 1992) were carried out and showed that the influence of the basic state, with minor modification, to the model output is insignificant for the cases of studying the diabatically induced stationary waves, though Kang (1990) found significant influence of zonal mean flow change on stationary wave fluctuations. The detailed structure and distribution of the $[U]$ and $[T]$ are displayed in Fig. 1. It is worth noting that there is a channel of westerly in the upper troposphere in the tropics, which links the two westerly jets in the middle latitudes of both hemispheres.

The diagnostic methods used to illustrate the stationary wave behaviour are three-dimensional wave activity flux noted as Plumb flux (Plumb, 1985) and EP flux (see e.g. Andrews, et al, 1976; Edmon, et al, 1980). The Plumb flux describes waves propagation, and generation (dissipation) of wave activity through its convergence (divergence). Furthermore, the zonal average of the Plumb flux can be reduced to the EP flux which can be used directly to visualize the direction of wave propagation in meridional direction. The detailed description of both fluxs has been well published and may be referred to relevant papers.

Ⅲ. EXPERIMENTAL RESULTS

Numerical experiments were carried out for the model response to idealized diabatic heating forcing. The diabatic heating, apart from Newtonian cooling, is collectively incorporated into the model. The idealized diabatic heating in a horizontal plan may be prescribed by the following function,

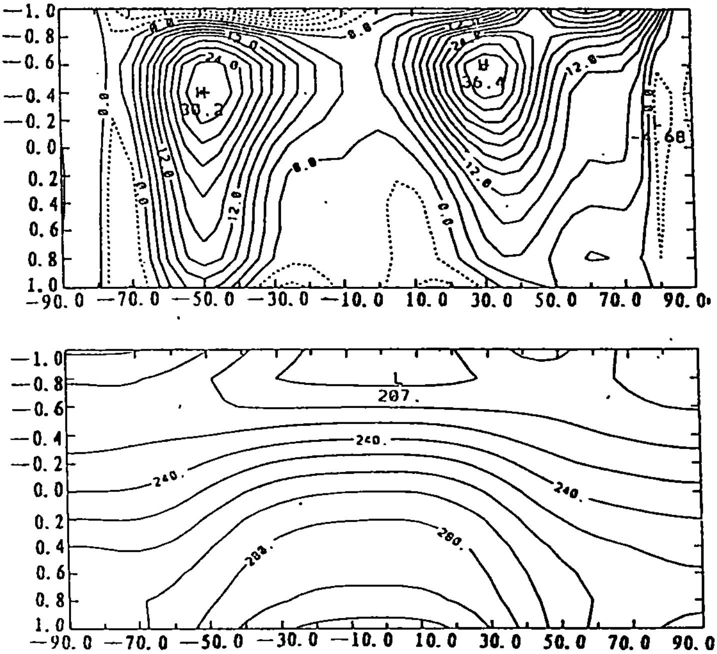

Fig. 1. Zonal mean state [U] (left) and [T] (right), derived from FGGE III-b formated climatology in January 1979, and directly interpolated into Gaussian latitudes and Gaussian levels. It is plotted through transformation from spectal coefficients.

$$\frac{Q}{C_p}=\begin{cases} A_{\max}\left[\sin\frac{\pi(\lambda-\lambda_1)}{(\lambda_2-\lambda_1)}\sin\frac{\pi(\varphi-\varphi_1)}{(\varphi_2-\varphi_1)}\right]^2, & \lambda_1\leqslant\lambda\leqslant\lambda_2,\ \varphi_1\leqslant\varphi\leqslant\varphi_2. \\ 0 & \text{Otherwise.}\end{cases} \qquad (1)$$

where λ is longitude and φ latitude ; Q the heating rate ; C_p specific heat at constant pressure; and $A_{\max}$ the maximum amplitude of temperature increase due to heating. We consider two cases of idealized diabatic heating specified and centred at 45°N in latitude, 135°E in longitude and 15°N, 135°E respectively. The maximum heating rate ($A_{\max}$) at the centres of both cases is prescribed as 5 K per day which could imply a precipitation rate of the order of 10 mm per day, a value appropriate for the wettest regions in the tropics (Simmons, 1982; Robertson et al, 1990). The vertical distribution of the heating is the same for both cases and profiled in such a way that the maximum heating occurs at about 500 hPa so as to parameterize the net effect of localized regions of intense mean latent heating peaked in the middle to upper troposphere (e.g. Hartmann et al, 1984).

1. *Response to an isolated mid-latitude heating*

Assuming that no orography exists at the Earth surface, an experiment is conducted for the model response to an idealized diabatic heating in mid-latitudes, which is the only external forcing to induce the stationary waves.

This isolated heating is illustrated in Fig. 2 for the values $\varphi_1=30°$N, $\varphi_2=60°$N, $\lambda_1=90°$, $\lambda_2=180°$, with the maximum amplitude $A_{\max}=5$ Kd^{-1} (A is dependent of σ).

The vertical distribution of the heating is profiled by the function in formula (2) to parameterize the net effect of localized regions of intense mean latent heating peaked in the middle to upper troposphere (e.g. Hartmann et al, 1984)

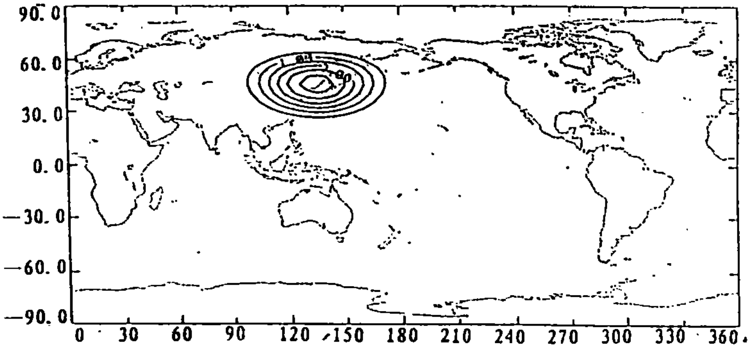

Fig. 2. Idealized diabatic heating in mid-latitude, centred at 45°N, 135°E. The contour interval is 0.5 Kd^{-1}. The zero contour is suppressed.

$$\frac{A(\sigma)}{A_{\max}} = \begin{cases} \left[\sin \dfrac{\pi(\sigma-\sigma_1)}{(\sigma_2-\sigma_1)}\right]^2 , & \sigma_1 < \sigma < \sigma_2 \quad ; \\ 0 & \text{Otherwise.} \end{cases} \qquad (2)$$

where $\sigma = - 0.86$, $\sigma = 1.0$ for this experiment and later calculations.

The perturbation streamfunction fields of the response to the isolated heating in mid-latitudes are illustrated in Figs. 3 and 4 at 700 hPa and 200 hPa respectively.

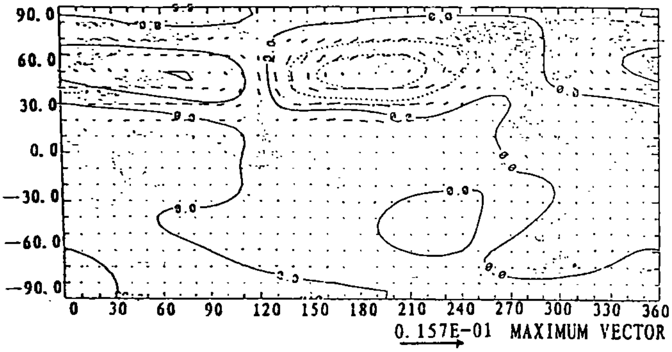

Fig. 3. 700 hPa pertubation stream field for the model response to an isolated heating in middle latitudes. Contours are the pertubation streamfunction ($\times 10^5 \mathrm{m}^2\mathrm{s}^{-1}$) with an interval of 10 units. The negative contours are dashed. Vectors denote the horizontal velocity on isobaric surface, and an arrow scale in units of ms^{-1} is indicated at the bottom right of the picture.

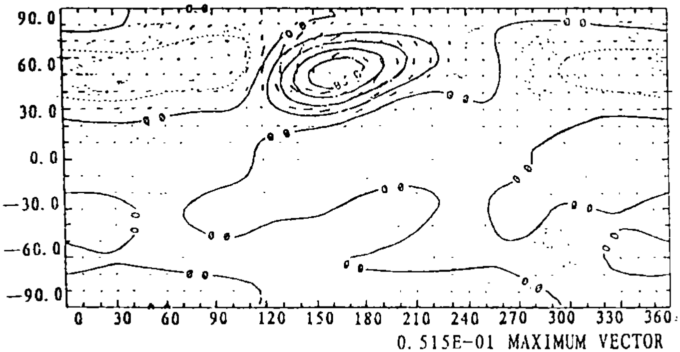

Fig. 4. Same as Fig. 3, but for 200 hPa. Contour interval is 20 units.

The overall patterns of circulation at both levels is relatively simple and constrained in mid-latitudes of the northern hemisphere. At 700 hPa, a cyclonic circulation is located to the east of the heating centre with an anti-cyclonic circulation in the west. At 200 hPa, however, the circulation patterns are roughly reversed, with an anti-cyclonic circulation in the east of the heating centre and a cyclonic circulation in the west. The baroclinity of the response is very obvious in northern mid-latitude belt. The result fully agrees with those obtained by others (e. g. Simmons, 1982; Lei, 1986) in mid-latitudes, but differs significantly in polar regions and the tropical areas, due to different imposition of damping rates enhancement. It is also of interest to point out that there is no pronounced response in the southern hemisphere to the heating centred in northern mid-latitudes.

The Plumb flux at both 800 hPa (Fig. 5) and 500 hPa (Fig. 6) highlights that the wave activity propagates predominantly eastward over, and downward downstream of the heating centre. At 200 hPa (not shown), however, it propagates eastward then turning to southeastward over the heating source, and upward to the east of the heating centre. Furthermore, from the EP cross-section (Fig. 7), it clearly denotes that the wave activity propagates both downward, and upward to the stratosphere, with the maximum divergence of the EP flux situated at about 400 hPa, the location of the maximum of the vertical distribution of diabatic heating. Also, both Plumb flux and EP cross-section illustrate that the isolated diabatic heating in northern middle latitudes has little effect in the southern hemisphere, and a very restricted effect in the northern hemisphere itself.

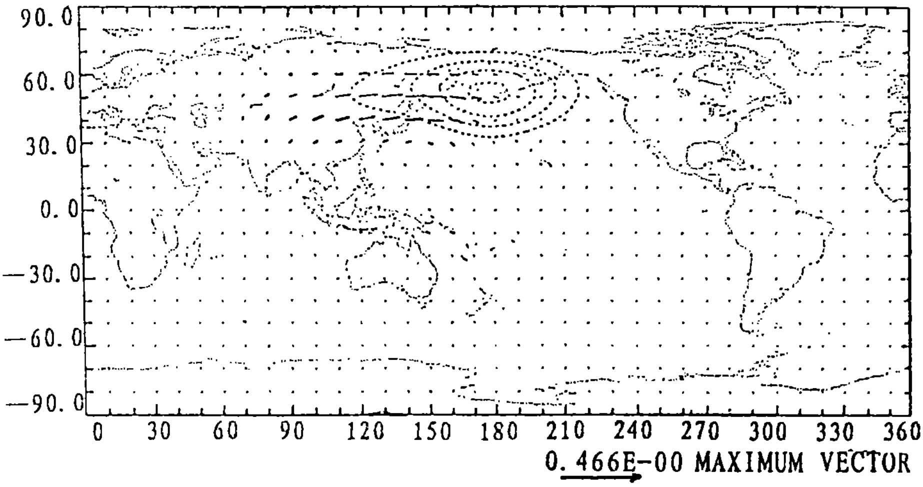

Fig. 5. Wave activity flux F at 800 hPa for the model response to an isolated diabatic heating in northern middle latitudes. Contours are the vertical component F_z ($10^{-3}m^2s^{-2}$) with an interval of 5 units (positive upward). The zero contour is excluded. An arrow with scale on at the bottom right represents the horizontal components (in units: m^2s^{-2}).

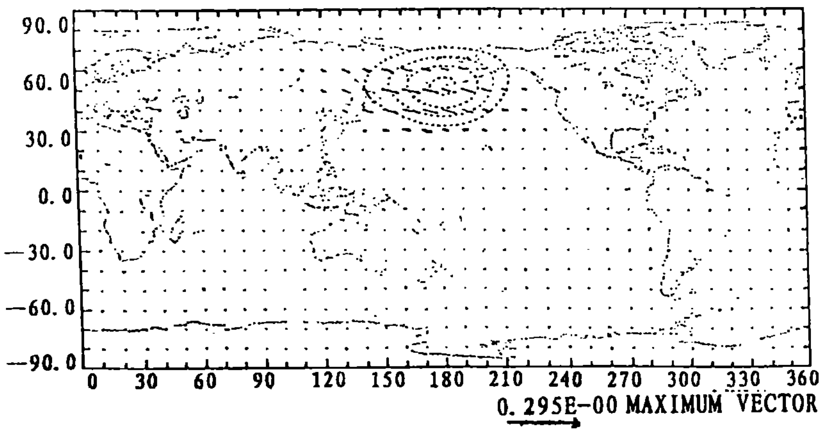

Fig. 6. Same as Fig. 5, but for 500 hPa. Contour interval is 5 units.

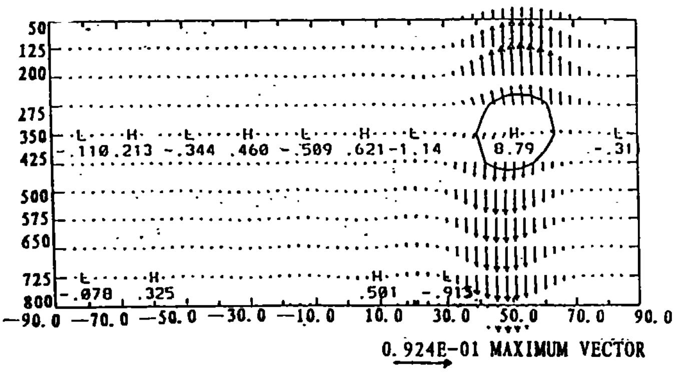

Fig. 7. EP cross-section for the model response to an isolated diabatic heating in northern mid-latitudes. An arrow scale is bottom right. The numerical value marked is to be multiplied by $2\pi a^2 p_0$ $\mathrm{m^2 s^{-2}}$ for $\hat{E}_\varphi$ and $2\pi a^3 p_0$ $\mathrm{m^2 s^{-2}}$ for $\hat{E}_z$ respectively. The contours represent the quantity $\triangle$ defined by expression in e.g. Peng (1992) ; the numerical values marked on the contours are to be mulitiplied by $2\pi a^3 p_0 \times 10^{-7}\mathrm{ms^2}$. The contour interval is 5 units. The zero contour is excluded.

2. *Response to tropical heating*

This experiment is virtually the same as the previous one, but with the heating shifed to low latitudes centred at 15°N, 135°E with the change of values to $\varphi_1 = 0°$, $\varphi_2 =$ 30°N of the function. The streamfunction and velocity field in response to this tropical heating are displayed in Fig. 8 and 9 at 700 hPa and 200 hPa respectively. In low latitudes, there is a cyclonic circulation at lower levels, with an anti-cyclonic circulation at upper levels, centred to northeast of the heating centre. Due to the imposition of a high damping rate in low latitudes, the tropical response away from the heating source at both levels is very weak. A weak cyclonic circulation at upper levels and an anti-cyclonic circulation at lower levels can be visualized from the velocity field far downstream of heating centre.

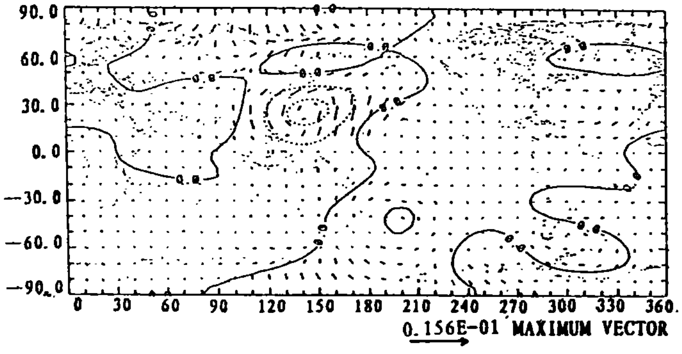

Fig. 8. 700 hPa as in Fig. 3 but for the model response to an isolated heating in northern tropics. Contour interval is 10 units.

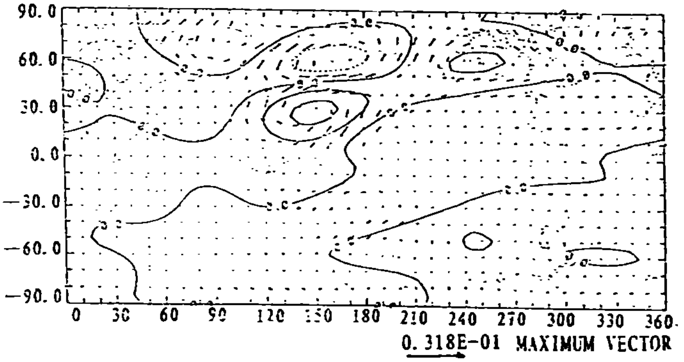

Fig. 9. Same as Fig. 8, but for 200 hPa. Contour interval is 20 units.

In addition, there is clear evidence that the northern tropical diabatic heating has a strong impact on mid-latitudes of both hemispheres. In northern mid-latitudes, a cyclonic circulation northeast of Japan and an anti-cyclonic circulation over north America can be found at 200 hPa, but only a relatively weak response can be seen at lower level. In southern mid-latitudes, a cyclonic system, though small, exists. However the model response in both of the polar regions and southern tropics is hardly seen.

Fig. 10 and 11 highlighted the wave activity flux at 800 hPa and 500 hPa respectively. At 800 hPa, the wave activity propagates predominantly upward and east-to-south-

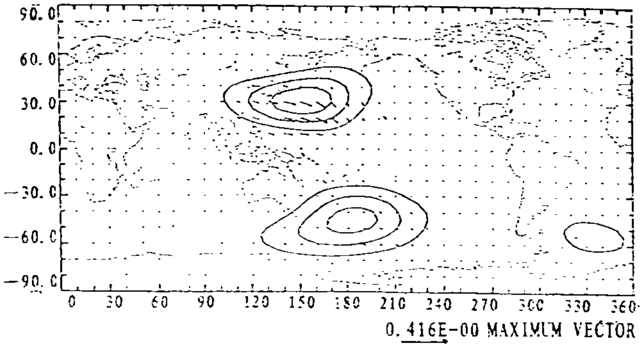

Fig. 10. Plumb flux: As in Fig. 5, but for model response to an isolated diabatic heating in northern tropics. The contour interval is 1 units.

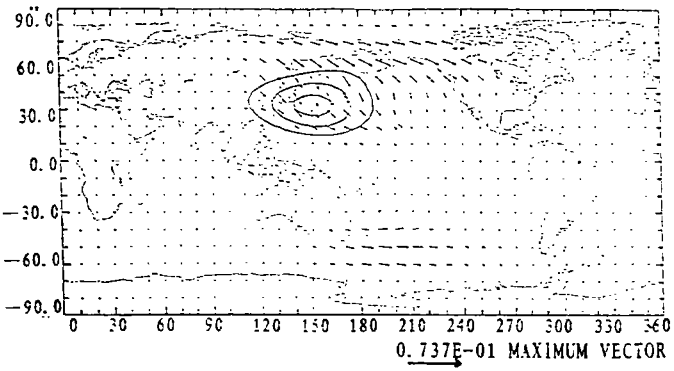

Fig. 11. As in Fig. 10, but for 500 hPa. The contour interval is 1 unit.

eastward to the north of the heating centre. It is of interest to note that the upward propagation of wave activity in southern mid-latitudes is quantitatively significant, while its horizontal progapation is negligible.

At 500 hPa, the main feature of the wave activity propagation in the northern hemisphere is an increased southeastward component to the north of the heating centre, extending to high latitudes. The upward propagation to the north of the heating centre is comparable to that at 800 hPa. In the southern hemisphere, however, the wave activity propagation is much weaker in the vertical, while stronger and more predominantly eastward in the horizontal, than that at 800 hPa. At further higher level (200 hPa, Figure not shown), the Plumb flux is much reduced in the vertical, but enhanced significantly in southeastward direction. This vertical structure of the wave activity flux implies that the wave activity flux over the heating source will be refracted towards the tropics in upper troposphere. This feature can be further illustrated by the EP cross-section in Fig. 12, which also showed that the strongest EP flux is located at lower levels over the north side of the heating centre. Moreover, by comparing the results in the previous subsection, the EP cross-section denoted that there was a significant effect of northern tropical heating on mid-latitude low-levels of the southern hemisphere, while no sign of the stationary waves in southern hemisphere can be visualized in response to the diabatic heating in the northern middle latitudes.

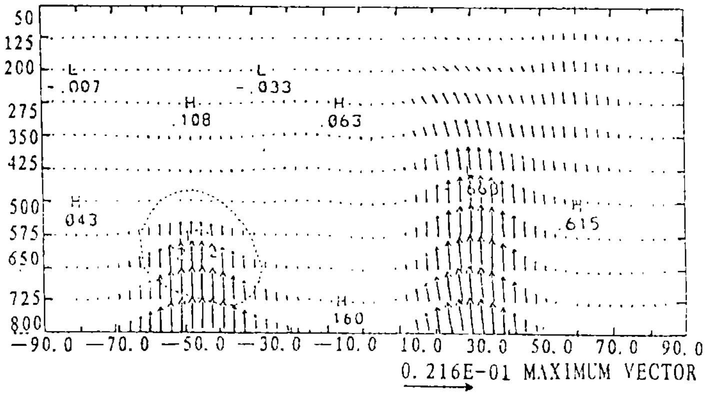

Fig. 12. EP cross-section: As in Fig. 7, but for model response to an isolated diabatic heating in northern tropics. The contour interval is 1 unit.

Ⅳ. CONCLUSION

The experimental results described above exhibited an evidence that may lead to the following conclusions to be drawn.

a. The model result for the response to an idealized diabatic heating in the tropical regions showed that an isolated tropical heating produced not only a strong response in the tropical region itself, but also a strong extratropical response in both hemispheres.

b. The effect of diabatic heating in tropics appeared as a wavetrain propagating poleward as well as longitudinally, and suggested that the tropics may have a significant influence on stationary waves in middle and high latitudes in the northern winter season. This speculation was also supported by intercomparsion with the model response to diabatic heating in northern middle latitudes.

c. And most importantly, the EP fluxes of the numerical results suggested that stationary waves diabatically induced in the northern tropics may be able to propagate into the middle latitudes of the southern hemisphere via a channel of westerly in the middle layers of the tropical atmosphere. However, the stationary waves induced by diabatic heating in northern middle latitudes can propagate only within the northern hemisphere.

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