The Diabatic Heating and the Generation of Available Potential Energy: Results from NCEP Reanalysis*

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ABSTRACT

In the existing studies on the atmospheric energy cycle, the attention to the generation of available potential energy (APE) is restricted to its global mean value. The geographical distributions of the generation of APE and its mechanism of formation are investigated by using the three-dimensional NCEP/NCAR diabatic heating reanalysis in this study. The results show that the contributions from sensible heating and net radiation to the generation of zonal and time-mean APE (G_Z) are mainly located in high and middle latitudes with an opposite sign, while the latent heating shows a dominant effect on G_Z mainly in the tropics and high latitudes where the contributions from the middle and upper tropospheres are also contrary to that from the low troposphere. In high latitudes, the G_Z is much stronger for the Winter Hemisphere than for the Summer Hemisphere, and this is consistent with the asymmetrical feature shown by the reservoir of zonal and time-mean APE in two hemispheres, which suggests that the generation of APE plays a fundamental role in maintaining the APE in the global atmospheric energy cycle. The same contributions to the generation of stationary eddy APE (G_{SE}) from the different regions related to the maintenance of longitudinal temperature contrast are likely arisen by different physics. Specifically, the positive contributions to G_{SE} from the latent heating in the western tropical Pacific and from the sensible heating over land are dominated by the heating at warm regions, whereas those from the latent heating in the eastern tropical Pacific and from the sensitive heating over the oceans are dominated by the cooling at cold regions. Thus, our findings provide an observational estimate of the generation of eddy APE to identify the regional contributions in the climate simulations because it might be correct for the wrong reasons in the general circulation model (GCM). The largest positive contributions to the generation of transient eddy APE (G_{TE}) are found to be at middle latitudes in the middle and upper tropospheres, where reside the strong local contributions to the baroclinic conversion from transient eddy APE to transient eddy kinetic energy and the resulting transient eddy kinetic energy.

Key words: diabatic heating, zonal and time-mean, stationary eddy, transient eddy, generation of available potential energy (APE)

1. Introduction

The generation of available potential energy (APE) is a fundamental component of the atmospheric energy cycle, because it describes the mechanism how the APE, which is continuously converted into kinetic energy in the atmosphere, is maintained by the diabatic heating process.

In the previous studies on the global atmospheric energy cycle, the generation of APE was usually obtained as a residual from other terms of the energy cycle through a balance requirement, rather than directly from the distributions of atmospheric heating and temperature (Oort, 1964; Oort and Peixoto, 1974; Oort and Peixoto, 1983; Arpe et al., 1986; Ulbrich and Speth, 1991). This residual method, however, gives no information about the contribution from different regions to the global generation of APE. Moreover, the errors in the other terms are accumulated in the residual. Since longitudinal and temporal temperature contrasts are maintained by the generation of eddy APE, this generation component is a main determinant of the climate on a regional scale. For an investigation of the generation of APE, the global three-dimensional distribution of diabatic heating is required. Due to the lack of better observations, realistic estimates of

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some important aspects of atmospheric energetics, such as the generation of eddy APE, are not well explored in the past. Therefore, its simulation with a GCM cannot be validated. Also, it is not clear for the contributions to the generation of APE from the various components of diabatic heating (latent heating, sensible heating, and net radiation) in different regions.

In terms of the diabatic heating data from NCEP/NCAR reanalysis (Kalnay et al., 1996), the generation of APE in the atmosphere according to Lorenz' (1955a, b) approximate equation, which is determined by the product of diabatic heating and temperature anomalies, is investigated in this study. Lorenz (1955a) showed that APE is generated if heating occurs at high, and cooling occurs at low temperatures. Here "high" and "low" mean relative to other latitudes, longitudes, and times. Therefore, the generation of APE in this paper is separated into three components: the generation of zonal and time-mean, of stationary eddy, and of transient eddy APE. These components are associated with the maintenance of latitudinal, longitudinal, and temporal temperature contrasts, respectively. The contributions to the generation of APE from the total diabatic heating and three components (latent heating, sensible heating, and net radiation), and their mechanism of formation are also investigated.

The paper is organized as follows. Section 2 provides a brief description of method and data for calculating the generation. Section 3 firstly gives the global integral values of generation of APE, then describes its geographic distribution and mechanism of formation, and performs a consistency analysis of the diabatic heating derived by using direct and indirect methods. Finally, Section 4 contains the summary and discussion in the study.

2. Method and data

2.1 *Method for calculating the generation*

Lorenz (1955b) has given the generation of APE, $G(p)$, an approximate expression in the form:

$$G(p)=\frac{1}{4\pi A^2}\int \gamma T''q''\mathrm{d}m, \qquad (1)$$

where A is the mean radius of the earth, $q''=q-\{q\}$, and $T''=T-\{T\}$. Here $\{q\}$ and $\{T\}$ are the global averages of the diabatic heating, q, and temperature, T, on an isobaric surface. The stability parameter γ can be expressed as

$$\gamma=-(\frac{K}{p})(\frac{\partial\{\bar{T}\}}{\partial p}-K\frac{\{\bar{T}\}}{p})^{-1}, \qquad (2)$$

where p is pressure, and $K=(c_\mathrm{p}-c_\mathrm{v})/c_\mathrm{p}$, where c_p and c_v are the specific heats of dry air at constant pressure and volume, respectively. The integral in Eq.(1) is taken over the entire mass of the atmosphere.

Assuming hydrostatic equilibrium, the time-mean of Eq.(1) can be written as

$$\bar{G}(p)=G_\mathrm{Z}+G_\mathrm{SE}+G_\mathrm{TE}, \qquad (3)$$

where

$$G_\mathrm{Z}=\frac{1}{2}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{0}^{p_\mathrm{s}}\frac{\gamma}{g}[\bar{T}]''[\bar{q}]''\cos\varphi\mathrm{d}\varphi\mathrm{d}p, \qquad (3a)$$

$$G_\mathrm{SE}=\frac{1}{2}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{0}^{p_\mathrm{s}}\frac{\gamma}{g}[\bar{T}^*\bar{q}^*]\cos\varphi\mathrm{d}\varphi\mathrm{d}p, \qquad (3b)$$

$$G_\mathrm{TE}=\frac{1}{2}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{0}^{p_\mathrm{s}}\frac{\gamma}{g}[\overline{T'q'}]\cos\varphi\mathrm{d}\varphi\mathrm{d}p. \qquad (3c)$$

Here g is the gravity acceleration, p_S is the zonal and time-mean surface pressure, φ is latitude, $[x]$ is the zonal-mean of x, $\overline{x}$ is the time-mean of x (in this paper the monthly mean), and x' and x^* are the deviation of x from $\overline{x}$ and $[x]$, respectively. Equations (3a), (3b), and (3c) are the approximate equations for the generation of zonal and time-mean, stationary eddy, and transient eddy APE, respectively. In Eq.(3) the G-symbols all denote globally averaged quantities.

Since the global three-dimensional daily diabatic heating data are not available, the field of diabatic heating (q) used for the calculation of generation of transient eddy APE is obtained as a residual in the thermodynamic energy equation, which can be written as

$$q=c_\mathrm{p}(\frac{\partial T}{\partial t}+\frac{u}{A\cos\varphi}\frac{\partial T}{\partial\lambda}+\frac{\nu}{A}\frac{\partial T}{\partial\varphi}+\omega(\frac{\partial T}{\partial p}-K\frac{T}{p})), \quad (4)$$

where λ is longitude, t is time, u is zonal wind, v is meridional wind, and $\omega = \mathrm{d}p/\mathrm{d}t$. The circulation data used in Eq.(4) ($u, v, \omega, and\, T$) are the global four-times daily (00, 06, 12, and 18 Z) NCEP/NCAR reanalysis data for the Januaries of 1990-1996 and Julies of 1990-1996.

2.2 *Data*

For the generation of zonal and time-mean, and stationary eddy APE, the monthly mean diabatic heating reanalysis is used in the calculation. These monthly mean diabatic heating data are obtained from NCEP/NCAR reanalysis including six heating rates that have 28 layers in the vertical direction with σ-coordinates: vertical diffusion, deep convection, shallow convection, large-scale condensation, shortwave radiation, and longwave radiation. These reanalysis data for seven Januaries of 1990-1996 and seven Julies of 1990-1996 are used in this study and interpolated in the vertical from σ-coordinates to 11 pressure levels (1000, 850, 700, 500, 300, 200, 150, 100, 50, 30, and 10 hPa). Thus, the total diabatic heating on an isobaric surface, $q(p)$, can be written as

$$q(p) = SH(p) + LH(p) + RD(p), \qquad (5)$$

where $SH(p)$ is the vertical diffusion heating rate on an isobaric surface induced by the conduction of sensible heating, $LH(p)$ is the total latent heating rate of large-scale condensation, deep convection, and shallow convection on an isobaric surface, and $RD(p)$ is the net radiation in the atmosphere on an isobaric surface, which is the sum of net shortwave radiation heating rate and net longwave radiation heating rate.

3. Results

3.1 *Globally averaged values*

Table 1 gives the globally averaged values of the generation of zonal and time-mean, stationary eddy, and transient eddy APE ($G_{\mathrm{Z}}, G_{\mathrm{SE}}$, and G_{TE}, respectively) in January and July which is a direct estimate of the generation of APE by using the fields of diabatic heating and temperature. The values of both G_{Z} and G_{SE} are positive while those of G_{TE} are negative. The value of G_{Z} is about 12% larger in January than that in July, but the value of G_{SE} is 35% less in January than that in July. In contrast to the results based on the residual method (Ulbrich and Speth, 1991), the computed values of G_{Z} in this study are well consistent with the corresponding values derived from the residual method that are 2.20 W m^{-2} in January and 1.94 W m^{-2} in July, while the values of G_{SE} are somewhat overestimated compared to the findings by Ulbrich and Speth (1991) (0.19 W m^{-2} in January and 0.30 W m^{-2} in July). Interestingly, the values of G_{TE} estimated by using two methods have the same sign (negative) and the comparative magnitude. The following discussion will further depict the local contribution to the generation of APE to gain a better understanding of its global mean value presented in this paper.

Table 1. Globally averaged values of the generation of zonal and time-mean, stationary eddy, and transient eddy APE (G_{Z}, G_{SE}, and G_{TE}, respectively) in January and July, in units of W m^{-2}

	G_{Z}	G_{SE}	G_{TE}
January	2.03	0.34	-0.15
July	1.81	0.52	-0.20

3.2 *The generation of zonal and time-mean available potential energy*

Figure 1 shows the local contribution to the generation of zonal and time-mean APE from the total diabatic heating and the corresponding three components in January. The positive contributions dominate in most of the tropospheres especially in high latitudes and tropical regions of both hemispheres (Fig.1a), which is consistent with the positive global mean value of G_{Z} (see Table 1). The large negative contributions occur mainly in southern high latitudes and northern middle latitudes of the low troposphere, and the small negative contributions are present at the tropical near-surface level and the middle troposphere of northern subtropics. By comparing the contributions from three components, it is found that the positive contribution to G_{Z} is dominated by the latent heating in the troposphere above 700 hPa, and the latent heating also leads to the strong negative contribution to G_{Z} in high latitudes of the low troposphere

(Fig.1b). The local contribution to G_Z from sensible heating is confined to the low troposphere where the strong positive contribution in high latitudes and the negative contribution in northern middle latitudes are available (Fig.1c). The net radiation almost shows a

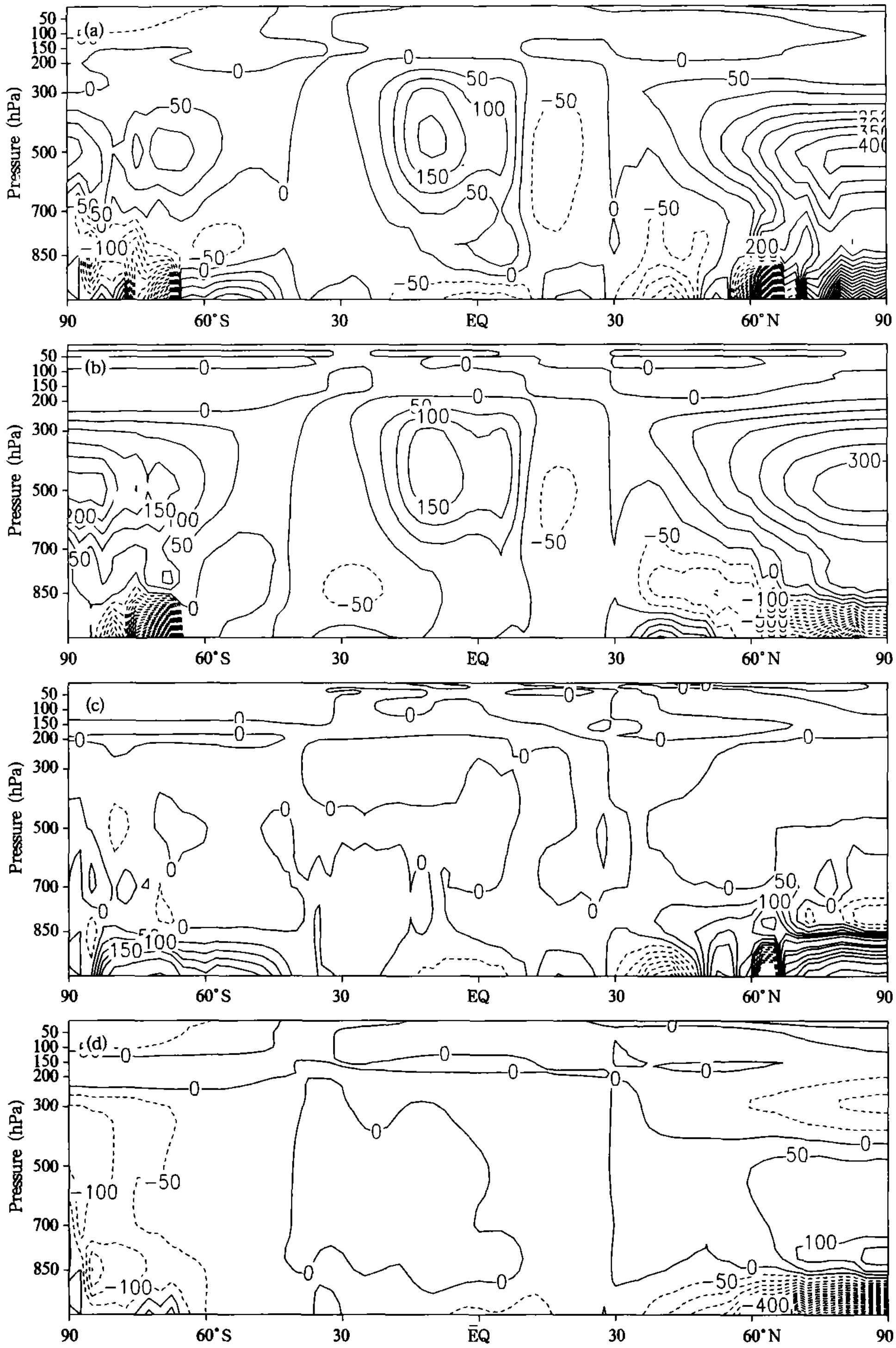

Fig.1. Local contributions to the generation of zonal and time-mean available potential energy (G_Z) from the total diabatic heating (a), latent heating (b), sensible heating (c), and net radiation (d) in January. Unit: 10^{-6}W m^{-2} Pa^{-1}

uniform negative contribution in middle and high latitudes except for a weaker positive contribution in the region poleward 60°N from 850 to 500 hPa (Fig.1d). It is also noted that in the tropics, the weak negative contribution to G_Z at near-surface level is attributed to the collective efforts of sensible heating and net radiation, although the dominant strong positive contribution is from the release of latent heat. In a word, the sensible heating and net radiation present the contributions to G_Z mainly in middle and high latitudes where the contributions between them are opposite, the latent heating shows a significant effect on G_Z mainly in tropics and high latitudes where the contribution from the middle and upper tropospheres is also opposite to that from the low troposphere.

In July (Fig.2), the local contribution to G_Z exhibits an obvious seasonal variation. In comparison with the pattern of G_Z in January, it can be seen that in high latitudes the local contribution to G_Z is much stronger for the Winter Hemisphere than for the Summer Hemisphere, whereas this case is reversed in the tropical region, that is, the contribution to G_Z is stronger for the Summer Hemisphere than for the Winter Hemisphere (Fig.2a). The contributions to G_Z from both the total diabatic heating and three components are subjected to the above same features of seasonal variation (Figs.1 and 2). Interestingly, the observed contribution from sensible heating in southern high latitudes is capable of reaching the troposphere around 500 hPa in July (Fig.2c), while it is restricted to the low troposphere below 850 hPa in January (Fig.1c). The effect of net radiation on G_Z for July is negligible in the northern high latitudes (Fig.2d).

To investigate the mechanism by which the contribution to G_Z in January and July is maintained (Figs.1a and 2a), an analysis of the fields of diabatic heating and temperature is thus highlighted. Figure 3 shows the distribution of meridional temperature contrast and total diabatic heating contrast in January and July. In the troposphere, the low latitudes are the relatively warm regions, and the middle and high latitudes are the relatively cold regions. However, in the stratosphere, the above case is reversed, i.e., the low latitudes are the relatively cold regions, and the middle and high latitudes are the relatively warm regions (Figs.3a and 3c). By associating with the temperature configuration, the distribution of diabatic heating directly determines the sign of the contribution to G_Z. The tropical region is dominated by the heating whose maximum is 0.015 W kg^{-1} centered at 10°S in January (Fig.3b) and 0.018 W kg^{-1} centered at 10°N in July (Fig.3d). Therefore the seasonal variation of tropical G_Z (Figs.1a and 2a) is largely attributed to the seasonal movement of the heating center. In high latitudes, most of the region is dominated by the cooling except that the low troposphere of Summer Hemisphere is dominated by the heating (Figs.3b and 3d). Lorenz (1955a) showed that APE is generated if heating occurs at high, and cooling occurs at low temperatures. The generation of APE is proportional to the covariance of diabatic heating and temperature. Therefore, it is understandable that in high latitudes most of the troposphere is dominated by the positive contribution to G_Z, whereas the low troposphere of Summer Hemisphere is dominated by negative contribution (Figs.1a and 2a). The similar interpretation is also applied to the negative contribution to G_Z over the subtropics of Winter Hemisphere, because it is relatively cooling and warming over that region (Fig.3), and this configuration of the fields of diabatic heating and temperature may result in the reduction of zonal and time-mean APE (negative G_Z) over there.

For the generation of G_Z, it should be noted that the "heating" or "cooling" here is a "relative" concept, which means the heating or cooling region relative to other latitudes, instead of the heating or cooling indicated by the positive or negative sign that the diabatic heating itself has. Furthermore, our findings show that in high latitudes the G_Z is much stronger for the Winter Hemisphere than for the Summer Hemisphere, which is consistent with the asymmetrical feature that the reservoir of zonal and time-mean APE shows in two hemispheres (Ulbrich, 1989). This implies that the generation of APE plays a fundamental role in the global atmospheric energy cycle, since the APE continuously converted into kinetic energy in the atmosphere is maintained by the generation term.

3.3 *The generation of stationary eddy available potential energy*

According to the definition of the generation of stationary eddy APE G_{SE} (see Eq.(3b)), the local contribution to G_{SE} is determined by the correlation of stationary eddy diabatic heating and stationary eddy temperature $(\overline{q}^{*}\overline{T}^{*})$ (a description of the symbols has

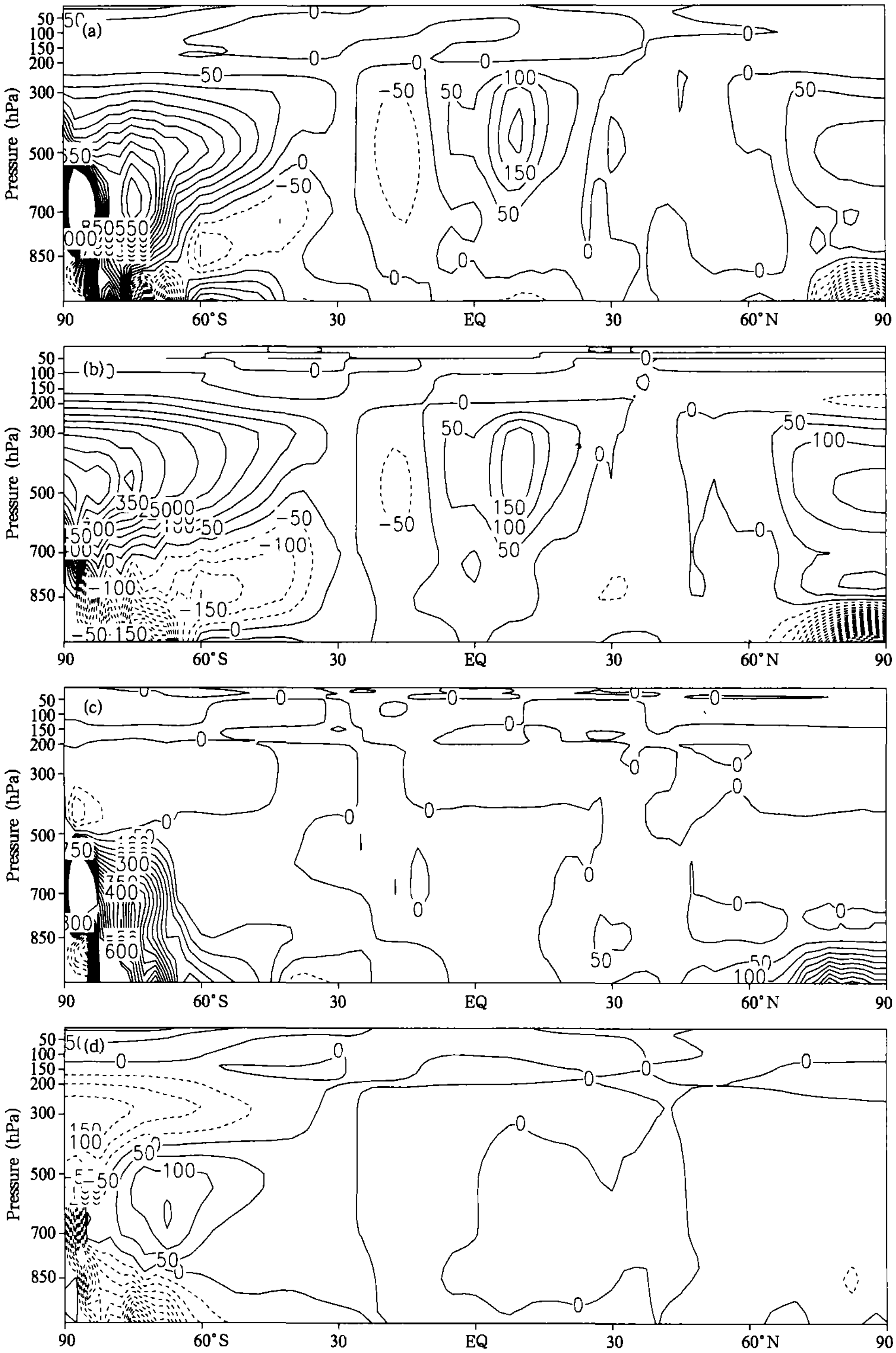

Fig.2. As in Fig.1, but for July.

been given in Section 2.1). Therefore, we use the pattern of $\overline{q}^{*}\overline{T}^{*}$ to indicate the horizontal distribution of G_{SE}, which may make a straightforward explanation of the contribution to G_{SE}.

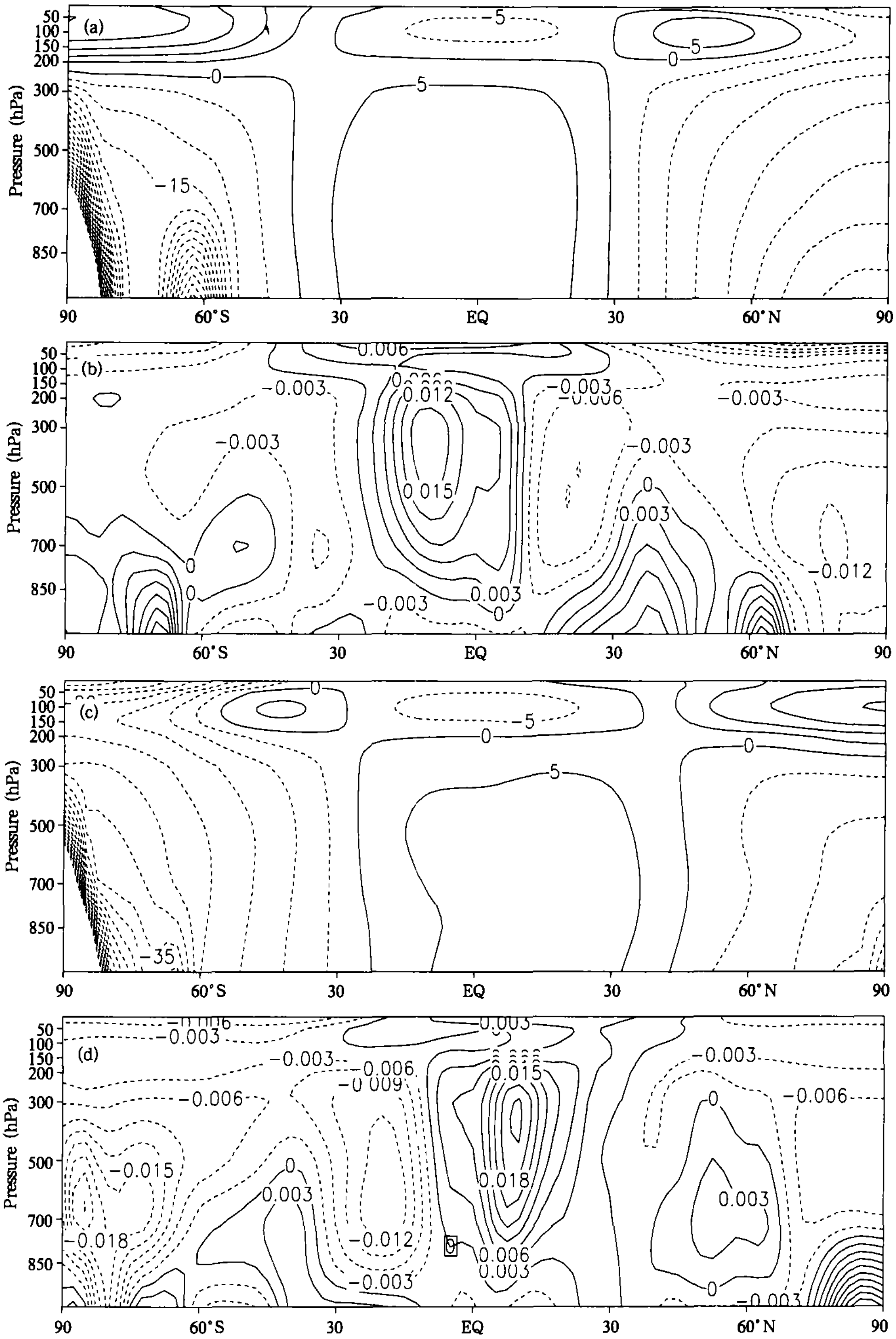

Fig.3. Distributions of meridional temperature contrast $[T]-\{T\}$ and total diabatic heating contrast $[q]-\{q\}$. Unit: K; W kg^{-1}. (a) $[T]-\{T\}$, January, (b) $[q]-\{q\}$, January, (c) $[T]-\{T\}$, July, and (d) $[q]-\{q\}$, July.

The geographical distribution of $\overline{q}^{*}\overline{T}^{*}$ in the upper troposphere (300 hPa) in January is shown in Fig.4. The local contribution to $G_{\rm SE}$ is mainly located in the region between 30°S and 30°N. The negative contribution over the area of Kuroshio (Fig.4a) is due to a united effort of the sensible heating (Fig.4c) and net radiation (Fig.4d) with comparative magnitude, and the negative contribution over the southeastern

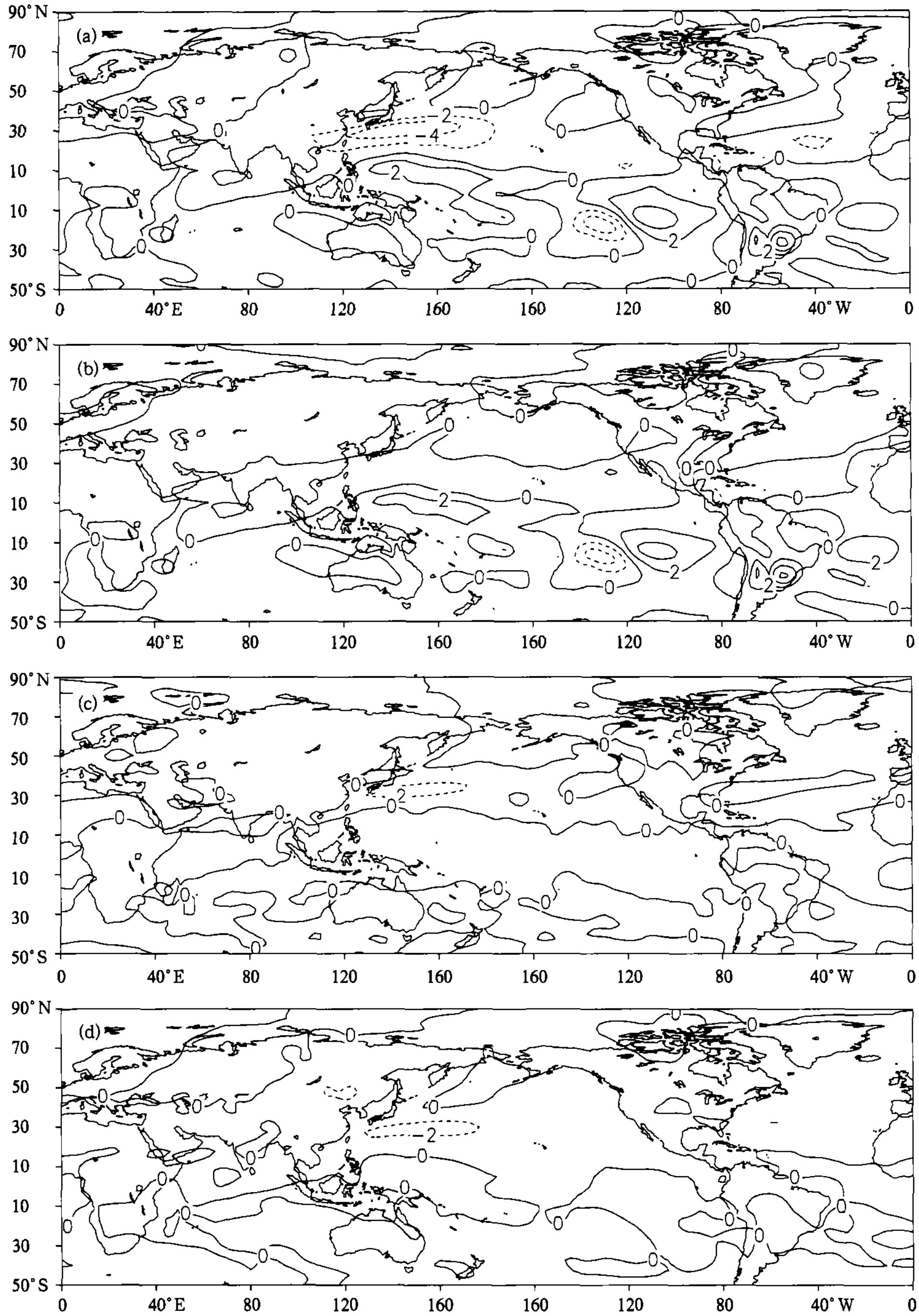

Fig.4. Geographical distributions at 300 hPa in January of $\overline{q}^{*}\overline{T}^{*}$ (in 10^{-2}K W kg^{-1}). (a) The contribution from the total diabatic heating, (b) the contribution from the latent heating ($\overline{LH}^{*}\overline{T}^{*}$), (c) the contribution from the sensible heating ($\overline{SH}^{*}\overline{T}^{*}$), and (d) the contribution from net radiation ($\overline{RD}^{*}\overline{T}^{*}$).

Pacific (Fig.4a) is mainly from the latent heating (Fig.4b). Also, a good consistency between the contribution to G_{SE} from the total diabatic heating and from the latent heating is shown over most of the regions including the tropical central and western Pacific, the tropical eastern Pacific, the southern Atlantic, South America, and the equatorial Africa, which suggests that the contribution to G_{SE} in the upper troposphere is dominated by the latent heating.

In January, the contribution to G_{SE} in the middle troposphere is also dominated by the latent heating and less affected by the sensible heating and net radiation (figure not shown). The major features of G_{SE} in the low troposphere are that the contribution from the latent heating is largely located in the east of Asia Continent and the northern Atlantic, and that the contribution from the sensible heating is found to be mainly around 30°S with three positive maxima centered at the south of Africa, Australia, and southern South America, respectively.

In July, the positive values of G_{SE} in the upper troposphere are mainly due to the release of latent heat in the monsoon region. In the middle troposphere, overall, they are also the results of latent heating, but the positive contribution induced by the sensible heating over the Tibetan Plateau is very strong (figure not shown). The low troposphere at 850 hPa is dominated by the positive contribution shown in Fig.5a. It can be seen that there are only weak positive contributions from the latent heating over South Asia and the subtropical eastern Pacific (Fig.5b), whereas there are significant contributions from the sensible heating over Asia-Africa Continent, southwest of North America, and the subtropical eastern Pacific with four maxima centered at the Iran Plateau, the Arab Peninsula, the Sahara of North Africa, and southern Africa (Fig.5c). Interestingly, the net radiation also shows a weak positive effect on the local contribution to G_{SE} over the Iran Plateau (Fig.5d).

The above analysis describes the geographical distributions of G_{SE} from the total diabatic heating and the associated three components. However, the positive local contribution to G_{SE} may be due to the heating ($\overline{q}^* > 0$) over the relatively warm region ($\overline{T}^* > 0$) at the same latitude, or the cooling ($\overline{q}^* < 0$) over the relatively cold region ($\overline{T}^* < 0$) at the same latitude. To figure out the physics how the local contribution to G_{SE} arises, it is essential for us to investigate the patterns of diabatic heating and temperature, respectively.

Figure 6 gives the geographical distributions of stationary eddy temperature $\overline{T}^*$ (the deviation of temperature from its zonal mean value) and stationary eddy diabatic heating $\overline{q}^*$ (the deviation of diabatic heating from its zonal mean value). In January, the cold regions ($\overline{T}^* < 0$) in the upper troposphere are over Eurasia Continent, most of Africa, and North America, while the warm regions ($\overline{T}^* > 0$) are over the area of Kuroshio, the northeastern Pacific, and the northern Atlantic (Fig.6a). The different patterns between heat source over the oceans and heat sink over land are owing to the fact that the oceans have the larger thermal capacity than land, and as a result, the oceans are warmer regions in contrast to land for the northern winter. Furthermore, the eastern Pacific between 45°S and 30°N is relatively cold region and the western Pacific is relatively warm region, which is consistent with the zonal SST distribution of warm pool and cold tongue. The corresponding stationary eddy latent heating in the upper troposphere at 300 hPa is shown in Fig.6b. It indicates that the heating regions ($\overline{q}^* > 0$) are primarily located in the area of Asian Monsoon, tropical western Pacific, and South America, and the cooling regions ($\overline{q}^* < 0$) are over the tropical eastern Pacific and the tropical Atlantic (shaded areas). Consequently, by comparing the pattern between heating (cooling) region and warm (cold) region in January, it is found that in the upper troposphere the positive contribution to G_{SE} from the latent heating over the tropical western Pacific (Fig.4b) is attributed to the heating (Fig.6b) at warm region (Fig.6a), but that over the tropical eastern Pacific (Fig.4b) is the result of the cooling (Fig.6b) at cold region (Fig.6a). In July, the sensible heating in the low troposphere is much enhanced over land, especially over Africa Continent, eastern Asia, Iran Plateau, southern North America, and eastern South America. However, the oceans appear to be cooling

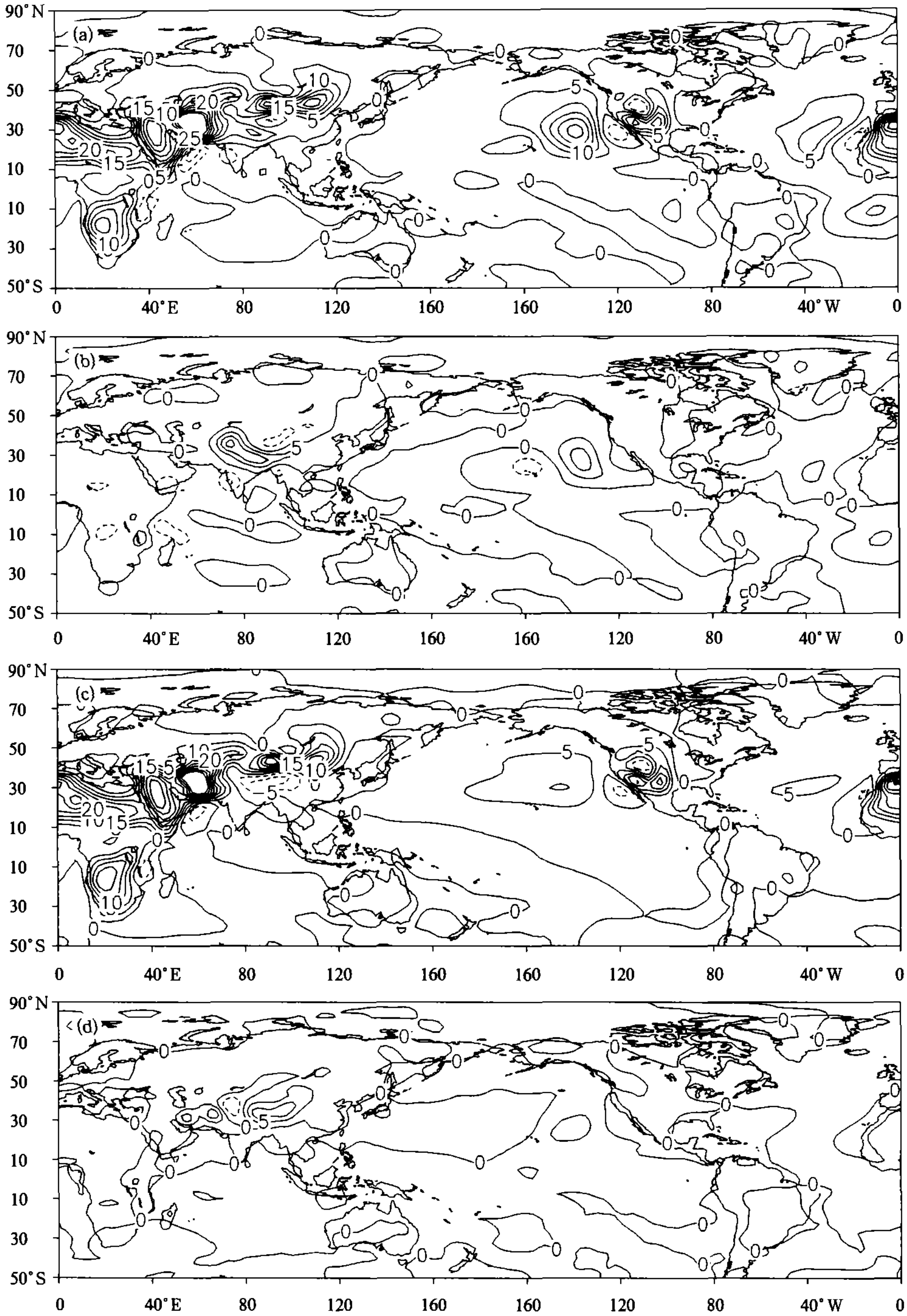

Fig.5. Geographical distributions at 850 hPa in July of $\overline{q^* T^*}$ (in 10^{-2}K W kg^{-1}). (a) The contribution from the total diabatic heating, (b) the contribution from the latent heating ($\overline{LH^* T^*}$), (c) the contribution from the sensible heating ($\overline{SH^* T^*}$), and (d) the contribution from net radiation ($\overline{RD^* T^*}$).

regions induced by the sensible heating (shaded areas) (Fig.6d). In the meanwhile, the continent is warm region and the ocean is cold region for the northern summer (Fig.6c). Therefore, this unique pattern of sensible heating and temperature is responsible for the ubiquitously positive contribution to G_{SE} both over

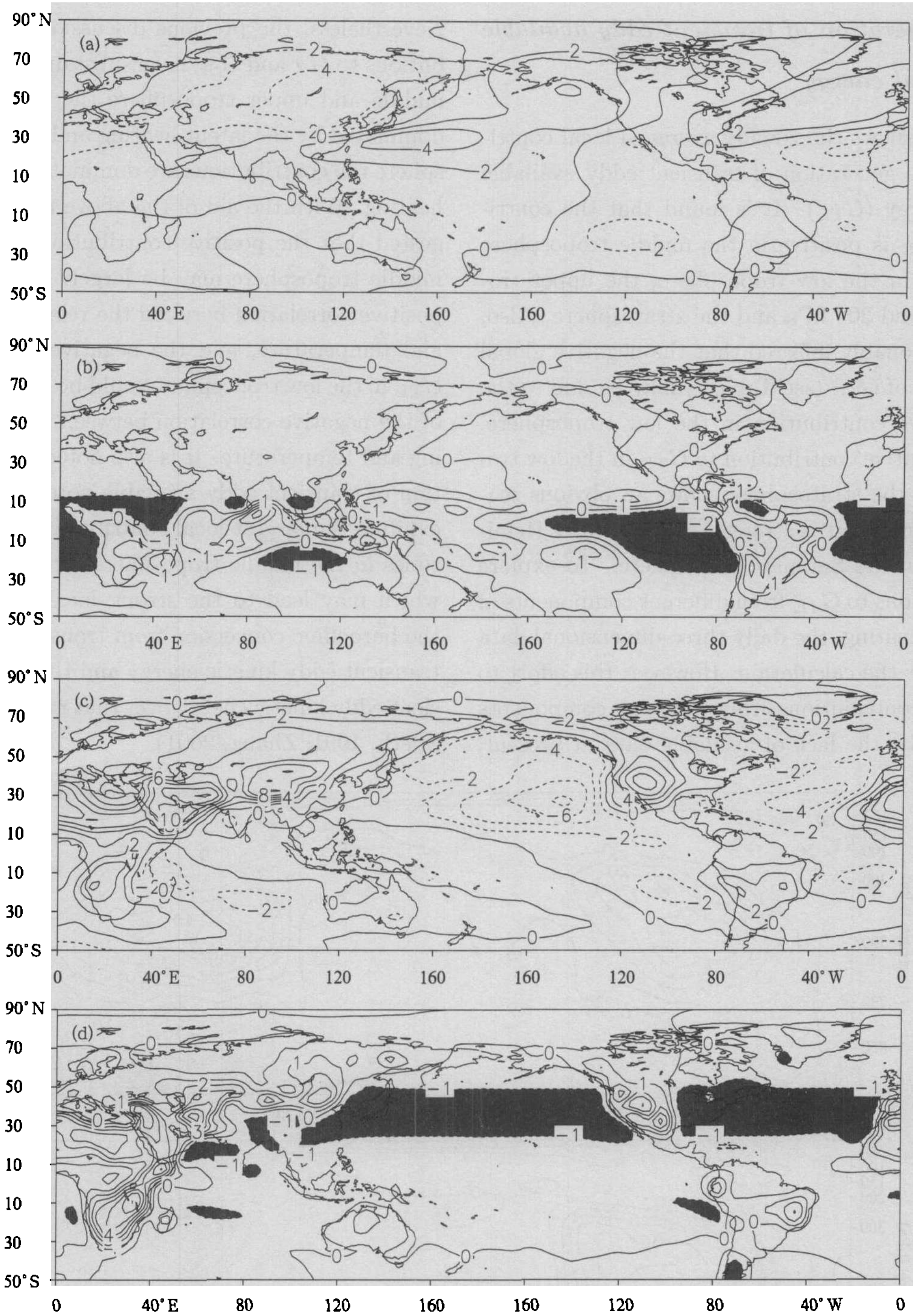

Fig.6. Geographical distributions of stationary eddy temperature $\overline{T}^*$(i.e., $\overline{T} - [\overline{T}]$) and stationary eddy diabatic heating $\overline{q}^*$(i.e., $\overline{q} - [\overline{q}]$). Unit: K; 10^{-2} W kg^{-1}. (a) Temperature at 300 hPa, January, (b) latent heating at 300 hPa, January, (c) temperature at 850 hPa, July, and (d) sensible heating at 850 hPa, July.

land and over the oceans (Fig.5c). It also suggests that the correlation of warm (cold) region and heating (cooling) region is a crucial determinant of the sign of contribution to G_{SE}.

3.4 *The generation of transient eddy available potential energy*

Figure 7 shows the zonally averaged local contributions to the generation of transient eddy available potential energy (G_{TE}). It is found that the contribution to G_{TE} is positive in the middle troposphere and negative in the low troposphere, the upper troposphere around 200 hPa and the stratosphere. Also, it can be reasonably inferred that the negative global integral value of G_{TE} (see Table 1) may be due to the larger negative contribution in the low troposphere. The local negative contribution to G_{TE} in the low troposphere and the stratosphere shows an obvious seasonal variation that it is stronger in the Winter Hemisphere than in the Summer Hemisphere. To explore the contributions to G_{TE} from different components of the diabatic heating, the daily three-dimensional data are needed for the calculation. However, this effort to identify the contributions from different components is hampered by the lack of available data at present. Nevertheless, the previous discussions on the contributions to G_Z and G_{SE} have substantiated that in the middle and upper troposphere the contributions are dominated by the latent heating and in the low troposphere the contributions are dominated by the sensible heating. With the aid of the above findings, it is suggested that the positive contributions to G_{TE} in the middle troposphere may be largely attributed to the positive correlation between the release of latent heat and temperature, and the negative contributions to G_{TE} in the low troposphere could be mainly the results of the negative correlation between the sensible heating and temperature. It is also noted that the generation of transient eddy available potential energy G_{TE} exhibits the largest local contributions at middle latitudes in the middle troposphere for two hemispheres, which may lead to the strong local contributions to the baroclinic conversion from transient eddy APE to transient eddy kinetic energy and the assoicated transient eddy kinetic energy over that region (Ulbrich and Speth, 1991; Zhang, 2001).

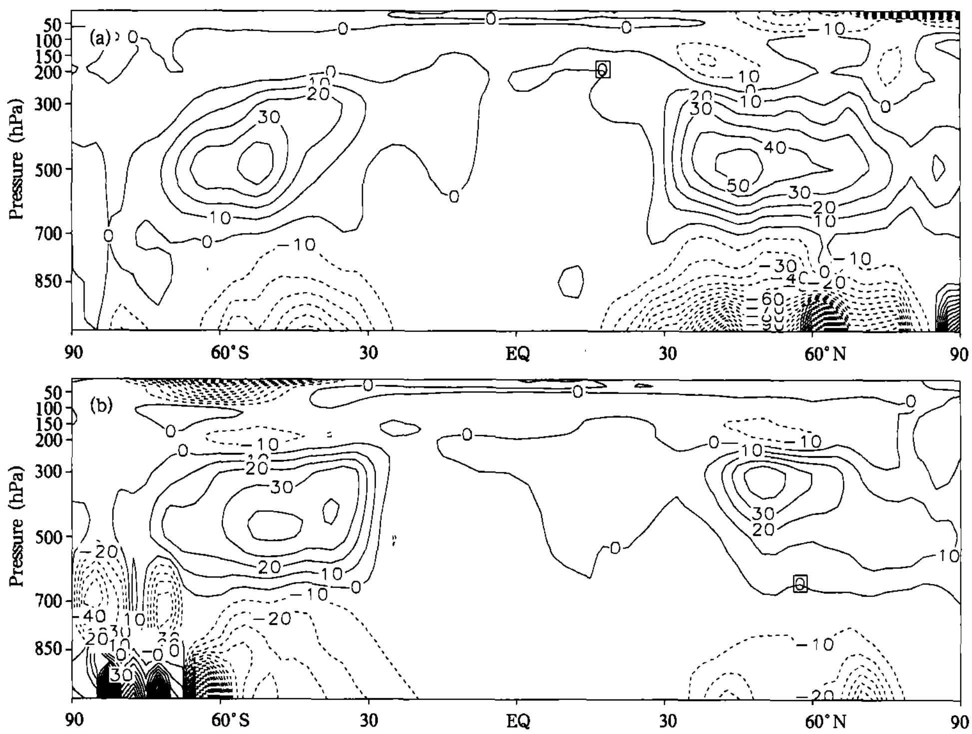

Fig.7. Zonally averaged contribution to the generation of transient eddy available potential energy (G_{TE}). Unit: 10^{-6}W m^{-2} Pa^{-1}. (a) January, and (b) July.

From the geographical distributions of $G_{\rm TE}$ (Fig.8), it can be seen that the contribution to $G_{\rm TE}$ is negative at 200 hPa in the upper troposphere. For the Southern Hemisphere, the negative contribution is basically over the oceans around 50°S both in January and July. For the Northern Hemisphere, it is over the continents and oceans around 40°N in January (Fig.8a), and moves northward to 50°N with reduced magnitudes in July (Fig.8b). The contribution in low latitudes is negligible, which is in agreement with the zonal mean results shown in Fig.7.

The contribution to $G_{\rm TE}$ is primarily positive at 500 hPa in the middle troposphere (Figs.8c and 8d). In January, the significant positive contributions are found to be located in the stormtrack regions of the northern Pacific and Atlantic Oceans (Fig.8c). In July, the positive contributions are considerably weakened in the stormtrack regions, and they are also somewhat reduced in the east of North America and North Europe, but enhanced in middle and high latitudes of the Southern Hemisphere (Fig.8d).

In the low troposphere (1000 hPa), the contribution to $G_{\rm TE}$ is almost negative in middle and high latitudes of two hemispheres (Figs.8e and 8f). For the Northern Hemisphere, the negative contribution is very significant over both land and oceans with maximum occurring at the stormtrack regions as well in January (Fig.8e), and it is much weaker in July (Fig.8f). For the Southern Hemisphere, this case is reversed, that is, the negative contribution is very weak in January (Fig.8e) but very strong in July (Fig.8f). It is also found that the $G_{\rm TE}$ contrast between the Winter Hemisphere and the Summer Hemisphere is more notable in the low troposphere than in the middle and upper tropospheres.

3.5 *A consistency study of the diabatic heating*

The inaccuracy of the generation of APE is determined by the errors in the diabatic heating term. The monthly mean diabatic heating data from NCEP/NCAR reanalysis are used in the calculation of $G_{\rm Z}$ and $G_{\rm SE}$ (see Eq.(5), the direct method hereinafter), while the field of diabatic heating for the calculation of $G_{\rm TE}$ is obtained as a residual in the thermodynamic energy equation (see Eq.(4), the indirect method hereinafter). Thus, it is required to perform a consistency study of the diabatic heating derived by using these two methods, with the purpose of better understanding and validating the findings presented in this study.

Figure 9 shows the zonally averaged distributions of the diabatic heating obtained by using the above two methods. It can be seen that there is a good agreement between these two kinds of the diabatic heating in most of troposphere. The main discrepancy lies in low latitudes from the low troposphere. Due to the strong radiative cooling, the diabatic heating obtained by the direct method is negative (Figs.9a and 9c), but the diabatic heating obtained by the indirect method is positive over that region (Figs.9b and 9d), being consistent with previous findings (Michael and Baader, 1978). Because the dominant contribution to $G_{\rm TE}$ occurs at middle and high latitudes (Fig.7) and the magnitude of diabatic heating is considerably small over the tropics in the low troposphere, it is believed that the discrepancy between the above two kinds of diabatic heating data in low latitudes will not affect the conclusions on the contribution to $G_{\rm TE}$ in this study. It is also found that the large contributions to $G_{\rm TE}$ in the stratosphere of the Winter Hemisphere (Figs.7a and 7b) and in the low troposphere of the Antarctic in July (Fig.7b) are associated with the strong diabatic heating derived by using the indirect method over there (Figs.9b and 9d). The strong diabatic heating in the Antarctic may be due to the effects induced by the steep topography, and that in the stratosphere is attributed to the large vertical gradient of potential temperature that partially determines the residual heating.

4. Summary and discussions

The previous studies on the generation of available potential energy are restricted to its global mean value. In this study, the generation of APE in the atmosphere according to Lorenz' (1955a, b) equations, which is separated into three parts (zonal and time-mean, stationary eddy, and transient eddy), is investigated in the space-time domain with the emphasis on the contributions of different components of the

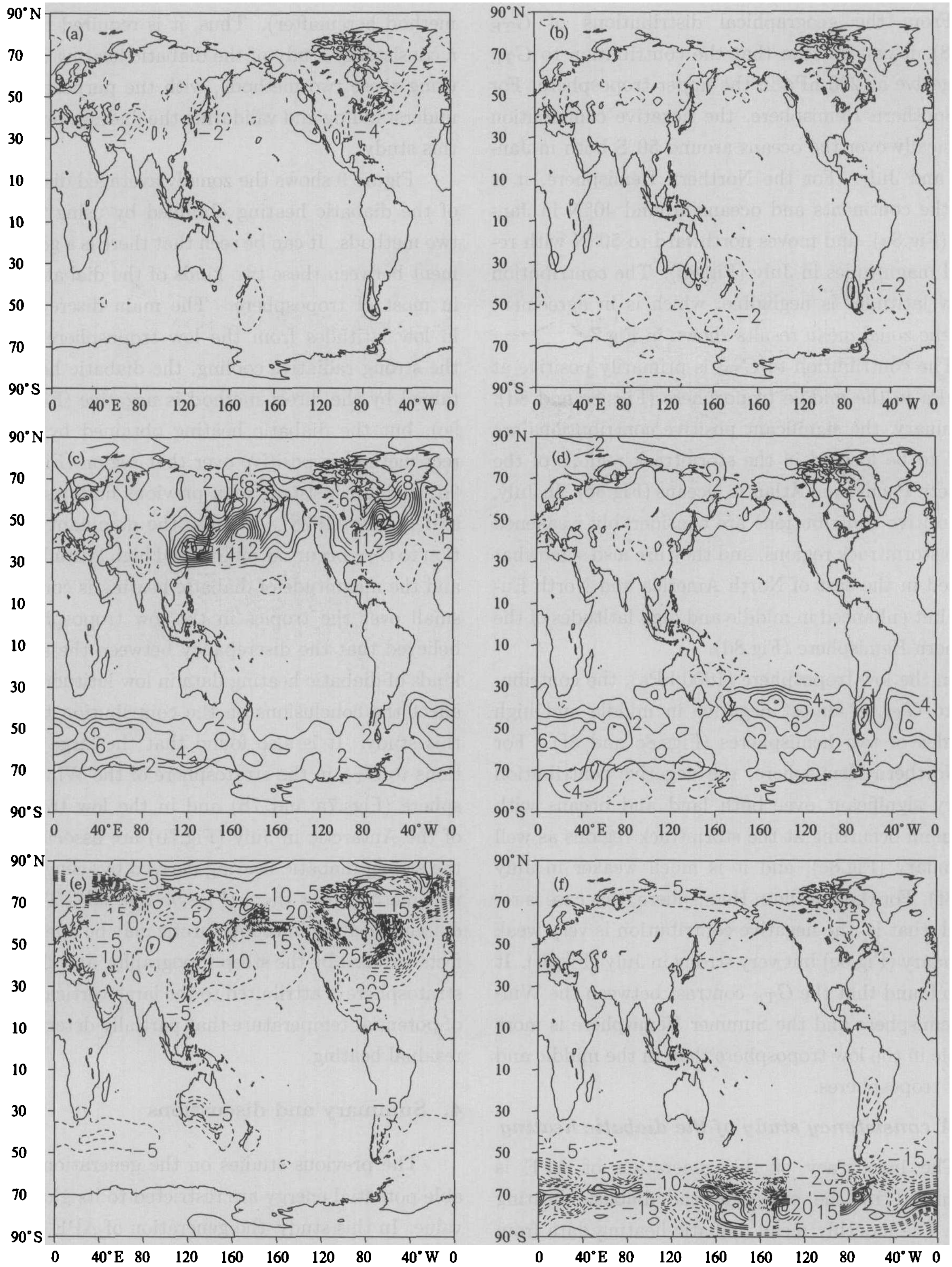

Fig.8. Geographical distributions of the generation of transient eddy available potential energy (G_{TE}). Unit: 10^{-5}W m^{-2} Pa^{-1}. (a) January, 200 hPa, (b) July, 200 hPa, (c) January, 500 hPa, (d) July, 500 hPa, (e) January, 1000 hPa, and (f) July, 1000 hPa.

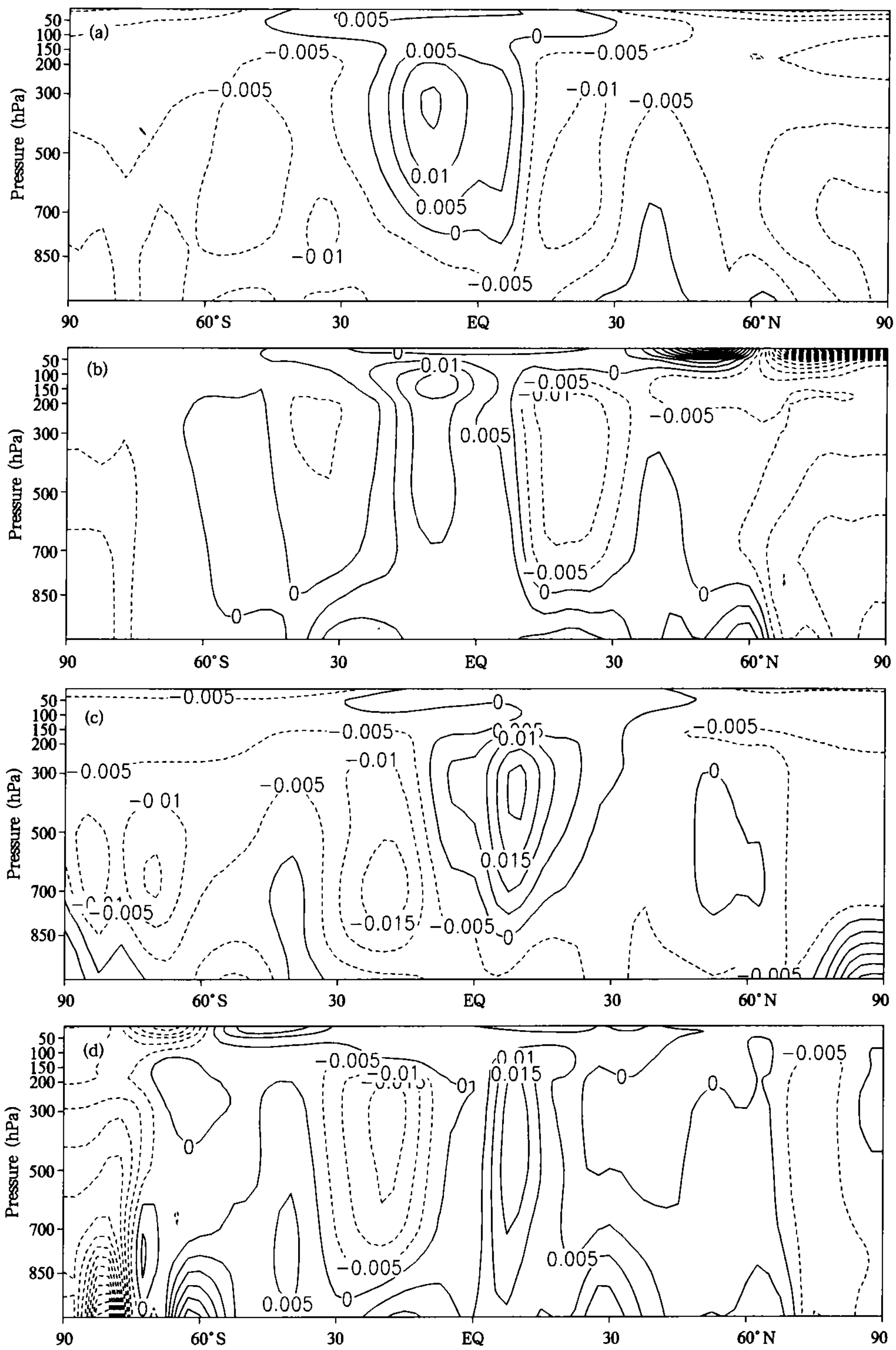

Fig.9. Zonally averaged distributions of the diabatic heating $[\bar{q}]$. Unit: W kg^{-1}. (a) January, derived from NCEP/NCAR reanalysis (see Eq.(5)), (b) January, obtained as a residual in the thermodynamic energy equation (see Eq.(4)). (c) July, derived from NCEP/NCAR reanalysis (see Eq.(5)), and (d) July, obtained as a residual in the thermodynamic energy equation (see Eq.(4)).

diabatic heating (latent heating, sensible heating, and net radiation). A preliminary study on the physics of the generation of APE is also explored in this paper.

By using the fields of the diabatic heating and temperature to directly estimate the generation of APE, the results show that the global integral values of G_Z and G_{SE} are positive whereas those of G_{TE} are negative. As far as the seasonal variation is concerned, the value of G_Z is about 12% larger in January than in July, but the value of G_{SE} is 35% less in January than in July.

The local contribution to G_Z shows that the positive contribution from the latent heating, which is centered around 500 hPa in the Summer Hemisphere, dominates in the tropical troposphere and there is also a small negative contribution from the latent heating in the subtropical troposphere. In high latitudes the effect of the latent heating on G_Z is that the contribution from the low troposphere (negative) is opposite to that from the middle and upper tropospheres (positive). The contribution of the sensible heating is largely positive and dominates in middle and high latitudes, where the contribution of the net radiation is basically negative. It is also found that in high latitudes the contribution to G_Z is much stronger for the Winter Hemisphere than for the Summer Hemisphere, being in line with the asymmetrical pattern that the reservoir of zonal and time-mean APE exhibits in two hemispheres (Ulbrich, 1989), which suggests that the generation of APE plays a fundamental role in maintaining the APE in the global atmospheric energy cycle.

The positive contributions to G_{SE} in the upper tropospheres are dominated by the latent heating which are mainly located over the tropical Pacific and the tropical Atlantic in January and due to the release of latent heat in the monsoon region in July, while the effects of the sensible heating and the net radiation appear to be small. In the middle troposphere, overall, the contributions to G_{SE} are also the results of the latent heating. The major feature of G_{SE} in the low troposphere for January is that the contributions from the latent heating are largely located in the east of Asia Continent and the northern Atlantic, and that the contributions from the sensible heating are found to be mainly around 30°S with three positive maxima occurring at south of Africa, Australia, and South America, respectively. The contribution to G_{SE} in the low troposphere for July is dominated by the sensible heating over the Asia-Africa Continent and less affected by the latent heating. In general, the contribution from the net radiation is negative and the magnitude is very small.

The same contributions to G_{SE} and G_Z from the different regions likely result from different physics. For example, the positive contribution to G_Z in high latitudes of the middle and upper tropospheres is due to the cooling at cold regions while that in low latitudes is due to the heating at warm regions. The positive contributions to G_{SE} from the latent heating in the western tropical Pacific and from the sensible heating over land are dominated by the heating at warm regions, whereas those from the latent heating in the eastern tropical Pacific and from the sensible heating over the oceans are dominated by the cooling at cold regions. These findings provide an important observational reference for clarifying the errors of the generation of eddy APE on regional scales in the climate simulations because it might be correct for the wrong reasons in the general circulation model (GCM).

The contributions to the generation of transient eddy APE (G_{TE}) are confined to the regions at middle and high latitudes where they are negative in the low troposphere, upper troposphere and the stratosphere but positive in the middle troposphere. The strongly positive contribution is mainly in the winter stormtrack region. The largest contributions to G_{TE} are found to be at middle latitudes of the middle troposphere, which corresponds to the largest local contributions to the baroclinic conversion from transient eddy APE to transient eddy kinetic energy and the resulting transient eddy kinetic energy over there (Ulbrich and Speth, 1991; Zhang, 2001).

The monthly mean diabatic heating data obtained as a residual in the thermodynamic energy equation and from NCEP/NCAR reanalysis are compared to investigate the possible effect of the discrepancy between these two kinds of data on the contribution to G_{TE} in this study. The results show that these two kinds of the diabatic heating are consistent with each other in most of troposphere except for the low troposphere over the tropics. Considering that the dominant contribution to G_{TE} is located at middle and high latitudes and the magnitude of diabatic heating is considerably weak over the tropics in the low troposphere, it is suggested that the discrepancy between two kinds of data will only have a negligible effect on the contribution to G_{TE} in this paper.

As an extremely vital component of the global atmospheric energy cycle, the generation of APE plays a crucial role in revealing the main climatological features of the atmospheric circulation, which will be highlighted in a separate study.

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