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On the Role of Meridional Circulations in the Kinetic Energy Budget of the Northern Hemisphere

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With 3 Figures

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Summary

The kinetic energy budget of the troposphere between equator and 60^0 N is studied on the basis of climatic mean data for the winter and summer seasons. The intense Hadley circulation during winter is an important producer of kinetic energy. Kinetic energy generation within the domain of the Hadley cell exceeds the local frictional dissipation by about $20 \cdot 10^{20}$ erg · sec^{-1}. Transient eddy mechanisms are mainly responsible for the export from the northern portion of the Hadley cell poleward. The strong frictional dissipation within the extratropical cap and the energy consumption within the (indirect) Ferrel circulation are for about one third met by import across 30^0 N; about two-thirds of the local depletion appear to be supplied by kinetic energy generation associated with transient eddies, while the effect of standing eddies is found unimportant. Summer conditions are characterized by greatly decreased generation and dissipation rates; imports from the domaine of the Hadley cell become less important for the maintenance of circulation in the extratropical cap.

Zusammenfassung

Über die Rolle der Meridionalzirkulationen in der kinetischen Energiebilanz der Nordhalbkugel

Die kinetische Energie-Bilanz der Troposphäre zwischen Äquator und 60^0 N wird auf Grund klimatologischer Mittelwerte für die Winter- und Sommerjahreszeit untersucht. Die kräftige Hadley-Zirkulation im Winter spielt eine bedeutende Rolle in der Produktion von kinetischer Energie. Im Bereich der Hadley-Zelle übertrifft die Produktion die Vernichtung von kinetischer Energie um ungefähr $20 \cdot 10^{20}$ erg · sec^{-1}. Zeit-räumliche Störmechanismen, etwa in der Art wandernder Zyklonen, sind hauptsächlich verantwortlich für die Ausfuhr von der Nordflanke der Hadley-Zelle polwärts. Die starke Vernichtung von kinetischer Energie in außertropischen Breiten sowie der Energieverbrauch innerhalb der (indirekten) Ferrel-Zirkulation werden zu etwa einem Drittel durch Einfuhr von den Tropen ausgeglichen. Eine stark verminderte Produktion und Vernichtung von kinetischer Energie ist für die Sommerjahreszeit charakteristisch; die Energiezufuhr aus dem Bereich der Hadley-Zelle verliert dann an Bedeutung für die Aufrechterhaltung der Zirkulation in außertropischen Breiten.

Résumé

Sur le rôle des circulations méridionales dans le bilan de l'énergie cinétique de l'hémisphère septentrional

On examine ici le bilan de l'énergie cinétique de la troposphère entre l'équateur et le 60ème parallèle nord. Cette étude est faite pour l'hiver et l'été sur la base de moyennes climatologiques. La forte circulation de Hadley joue, en hiver, un rôle important dans la production d'énergie cinétique. Dans la région de la cellule de Hadley, la production d'énergie cinétique dépasse sa destruction d'environ $20 \cdot 10^{20}$ erg · sec^{-1}. Des mécanismes perturbateurs agissant aussi bien dans le temps que dans l'espace — comme par exemple les cyclones mobiles — sont les principaux agents responsables des transports du flanc nord des cellules de Hadley en direction du pôle. Les fortes destructions d'énergie cinétique dans les latitudes extra-tropicales comme la consommation d'énergie à l'intérieur de la circulation (indirecte) de Ferrel sont compensées pour un tiers environ par un apport des tropiques. L'été est caractérisé par une production et une destruction fortement réduites de l'énergie cinétique. Un apport de cette énergie de la région de la cellule de Hadley perd alors de son importance pour le maintien de la circulation aux latitudes extra-tropicales.

1. Introduction

Various studies in the course of the last fifteen years (e. g. Pisharoty [16], Palmén et al. [15], Palmén [13, 14], Kung [9], Holopainen [7]) have focused on the kinetic energy budget of the troposphere on a hemispheric scale. Although a reasonably consistent picture of the mechanical energy budget is emerging from these studies, the magnitude of the various budget terms is not yet satisfactorily known. In particular, the intensity of meridional circulations in lower latitudes and their role in the mechanical energy budget are not yet safely established.

In a larger project concerned with general circulation and atmospheric heat budget over the northern hemisphere (e. g. Hastenrath [2, 4, 5]), multi-annual mean values of zonal and meridional wind components and height of constant pressure levels were compiled for 10° latitude and 10° longitude gridpoints between equator and 60° N, at constant pressure levels in a 100 mb spacing between 1000 and 100 mb, during the winter (December—February) and summer (June—August) seasons. This material contains useful information on the role of time-averaged meridional circulations, and forms the major basis for the present study.

2. Basic Theory

The budget equation of mechanical energy can for a finite atmospheric layer be written (e. g. HASTENRATH [3])

$$\int_b^t \frac{\partial \varrho K}{\partial t} \frac{dp}{g\varrho} + \int_b^t \nabla_p \cdot \varrho K \vec{V} \frac{dp}{g\varrho} + (\varrho K w)_t - \varrho K w)_b + \tag{1}$$

$$+ \int_b^t g \varrho \vec{V} \nabla_p \cdot z \frac{dp}{g\varrho} = + \int_b^t \vec{V} \cdot \vec{F} \frac{dp}{g}.$$

Following conventional notation, $\vec{V}$ denotes the horizontal wind vector, w vertical velocity, g acceleration of gravity, ϱ air density, and z is the height of a constant pressure level. $\vec{F}$ means the frictional force, and $K = V^2/2$ the kinetic energy per unit mass; ∇_p is the two-dimensional ∇ operator on a constant pressure surface, and the subscripts t and b refer to the top and the bottom of the finite layer, respectively.

The first term on the left hand side of Eq. (1) represents the time rate of change of kinetic energy content; this term can be disregarded here, since sufficiently long periods of time are considered. The second term denotes the lateral import or export of kinetic energy, and the third and fourth terms give the import and export by vertical motion. The fifth left hand term represents the sum of the kinetic energy production inside the volume and the redistribution of kinetic energy due to boundary pressure work (cf. STARR [19]); this term will here be referred to as the net generation of kinetic energy.

Where all left hand terms of Eq. (1) can be computed independently, the right hand term, $D = \int_b^t \vec{V} \cdot \vec{F} \frac{dp}{g}$, can be obtained as a residual. The residual term D certainly leads to a dissipation of kinetic energy if only molecular viscosity and small-scale turbulent viscosity are included in this term. However, STARR [19] pointed out that this is not necessarily the case, if large-scale eddies and other large features of the atmospheric motions are included in the form of a gross turbulence as distinguished from the remaining mean motion; the quantity D may then embrace energy-producing systems and it is possible that it may change sign.

In the present study, the latitude belts 0—10, 10—20, 20—30, 30—40, and 50—60° N, and the finite layers 100—300, 300—700, and 700—1000 mb are considered, for the winter and summer seasons. Computations are performed for constant pressure levels in a 100 mb spacing, and vertical integrations are approximated by the trapezoidal rule. Gridpoints falling into high mountain areas were eliminated from the computations, in a way described in earlier reports on this project (Hastenrath [2, 4]).

Eq. (1) refers to instantaneous and simultaneous values of $\vec{V}$, K, and $\nabla_p \cdot z$. This must be taken into account when averaging over time and space. When entire latitude belts are considered, the meridional wind component, V, can be substituted for the total wind vector $\vec{V}$, in the second left hand term of Eq. (1). For convenience of notation, a bar is used in the following to denote a time mean, a bracket a space mean. Primes denote deviations from the means and the subscripts x and t specify the deviation from a space and a time mean, respectively. The space-time mean of the meridional flux of kinetic energy at a given level can then be expanded and expressed as (e. g. White [22], Starr and White [20, 21])

$$\overline{(v\,K)} = (\bar{v})\,(\bar{K}) + (\overline{v_x'}\,\overline{K_x'}) + (\overline{v_t'\,K_t'}). \tag{2}$$

For purposes of the present study, space-averaging can be thought of as extending around a complete latitude circle. The left hand term of Eq. (2) then denotes the space-time average of the meridional flux of kinetic energy across a complete latitude circle.

The first right hand term is a flux associated with a non-zero mean rate of flow $(\bar{v})$, and is called advective flux in Priestley's [17] terminology. This term can be computed from seasonal latitude-mean values of v and K.

The second right hand term represents the flux associated with standing eddies. This flux results from the correlation in space between the time means of v and K; in other words, it is due to the semi-permanent features of the atmosphere. The standing eddy flux can be computed from seasonal mean values of v and K at fixed grid points around a latitude circle; 36 gridpoints around a latitude circle were used in the present study.

Using the nomenclature proposed by Oort [12], the division of $\overline{(v\,K)}$ into components is made in a "mixed space-time domain" in Eq. (2). Expansion in a "space domain" yields correspondingly (cf. Starr and White [20])

$$\overline{(v\,K)} = (\bar{v})\,(\bar{K}) + \overline{(v)_t'\,(K)_t'} + (\overline{v_x'\,K_x'}). \tag{3}$$

The first right hand term is identical in both formulations, Eqs. (2) and (3). The second term on the right-hand side of Eq. (3) represents the so-called "oscillating cell" flux, while the last term stands for the time mean flux in zonal eddies, as appearing on synoptic charts.

Expansions in the form of Eqs. (2) and (3) are also applicable to the product $K \cdot w$, in the third and fourth left hand terms of Eq. (1). The fifth left hand term of Eq. (1) contains the dot product of the wind vector and the slope of a constant pressure surface, $\vec{V} \nabla_p \cdot z = u \frac{\partial}{\partial x} (z)_p + v \frac{\partial}{\partial y} (z)_p$. The product $v \frac{\partial}{\partial y} (z)_p$ can be treated in a form analogous to Eqs. (2) and (3). The zonal component, $u \frac{\partial}{\partial x} (z)_p$ gives only contributions corresponding to the second and third right hand terms of Eqs. (2) and (3), while the first term vanishes.

In accordance with the data used in the present study, the "mixed space-time domain", Eq. (2), offers the better framework. However, Eq. (3) is useful for a comparison with results of earlier studies (e. g. PHISHAROTY [16]).

3. Kinetic Energy Content of the Troposphere

Denoting a time mean by a bar and a deviation from the time mean by a prime, the time-average of the kinetic energy content per unit mass at a given gridpoint and pressure level can be written

$$\overline{K} = \frac{1}{2} (\overline{u}^2 + \overline{v}^2) + \frac{1}{2} (\overline{u'^2} + \overline{v'^2}). \tag{4}$$

Following conventional notation, u and v represent the zonal and meridional wind components. From the data used in the present study, only the contributions of the first right hand term can be computed. As seen from Eq. (4), this leads to an underestimate of the kinetic energy content.

The contribution of the first right hand term of Eq. (4) is summarized in table 1 for finite atmospheric layers and various latitude

Table 1
Kinetic Energy Content of the Troposphere in Various Latitudes Belts in 10^{24} erg

	0	10	20	30	40	50	60° N
Winter							
100— 300 mb	23	98	260	295	166	63	
300— 700 mb	18	49	189	259	169	70	
700—1000 mb	22	13	13	25	25	12	
100—1000 mb	63	160	462	579	360	145	
Summer							
100— 300 mb	47	44	24	49	66	33	
300— 700 mb	20	18	12	40	63	36	
700—1000 mb	14	16	9	8	10	5	
100—1000 mb	81	78	45	97	139	74	

belts. A strong concentration of kinetic energy appears in the region of the jet stream during the winter season. Values are considerably smaller in summer; maxima are indicated for the region of the temperate latitude westerlies and the upper-tropospheric easterlies in the tropical belt. Winter data agree, in the general magnitude, reasonably well with PISHAROTY's [16] computations for January and February 1949, which are reproduced in table 2 for comparison. The

Table 2. *Kinetic Energy Content between Surface and 150 mb, during January and February 1949, after* PISHAROTY *[16]*

1) total kinetic energy; 2) kinetic energy of perturbations, in 10^{24} erg

	20		30		40		50		60		70		80° N
1)		900		900		650		500		150		(50)	
2)		180		200		170		140		80		(40)	

total kinetic energy content is of interest in connection with the magnitude of transports, generation, and dissipation of kinetic energy to be discussed in the subsequent sections.

4. Poleward Transport of Kinetic Energy

Concerning the poleward transport of kinetic energy, only the contributions of the first two right hand terms of Eq. (2) could be computed directly in the present study. Transports across various

Table 3. *Poleward Transport of Kinetic Energy Associated with the Mean Meridional Circulation, in 10^{18} erg · sec^{-1}*

	0	10	20	30	40	50	60° N
Winter							
100— 300 mb	+30	+51	+137	−27	+29	+15	−12
300— 700 mb	−0	+5	+8	−63	−14	−18	−7
700—1000 mb	−35	−24	−6	+5	+3	+2	+2
100—1000 mb	−5	+32	+139	−85	+18	−1	−17
Summer							
100— 300 mb	−24	−28	−10	+7	+16	−15	−1
300— 700 mb	−0	+2	−0	+1	−3	−7	−3
700—1000 mb	+4	+4	+3	−1	−1	+1	+1
100—1000 mb	−20	−22	−7	+7	+12	−21	−3

latitude circles due to the mean meridional circulation are presented in table 3, and transports associated with standing eddies are listed in table 4.

Poleward transports by the mean meridional circulation (table 3) are largest in the upper portion and on the northern flank of the Hadley cell in winter; associated with the weakening of meridional circulations, poleward transports become very small in summer.

Table 4. *Poleward Transport of Kinetic Energy Associated with Standing Eddies, in 10^{18} erg · sec^{-1}*

	0	10	20	30	40	50	60° N
Winter							
100— 300 mb	+4	+26	+104	+332	+259	+95	+17
300— 700 mb	+0	+5	+40	+146	+148	+106	+17
700—1000 mb	+2	−2	−4	+0	+7	+6	+2
100—1000 mb	+6	+29	+140	+478	+414	+207	+36
Summer							
100— 300 mb	−35	−63	−20	+11	+19	−6	−2
300— 700 mb	−3	−13	+1	+4	−0	+5	−3
700—1000 mb	−7	−10	−3	−6	+3	+3	−0
100—1000 mb	−45	−86	−22	+9	+22	+2	−5

Standing eddies (table 4) are found to be more efficient for poleward transports than the mean meridional circulation, contributions of the second right hand term of Eq. (2) becoming comparatively large in the upper layers at latitudes 30 and 40° N in winter. Standing eddy transports are small in summer.

Tables 3 and 4 should be compared with the computations of Kao [8], Pisharoty [16], and Mintz [11]. Kao obtained for the geostrophic poleward transport of kinetic energy between 100 and 1010 mb in January 1949 a maximum of $24 \cdot 10^{20}$ erg · sec^{-1} at 30° N, with a decrease to $4 \cdot 10^{20}$ erg · sec^{-1} at 60° N. Pisharoty found for the poleward transport of kinetic energy between surface and 150 mb during January and February 1949 a maximum of $20.3 \cdot 10^{20}$ erg · sec^{-1} at latitude 30° N. Mintz computed the total poleward transport of kinetic energy between 1010 and 200 mb during winter and summer 1949. During winter he obtained a maximum of $16.8 \cdot 10^{20}$ erg · sec^{-1} at 30° N, with a decrease to $7.1 \cdot 10^{20}$ erg · sec^{-1} at 60° N. In summer a maximum of $1.8 \cdot 10^{20}$ erg · sec^{-1} was found at 40° N, and a value of $1.5 \cdot 10^{20}$ erg · sec^{-1} at 60° N. These values are considerably larger than the sum of tables 3 and 4. This points at the importance of transient eddy mechanisms for the poleward transport and the budget of kinetic energy in higher latitudes.

5. Generation of Kinetic Energy

The net production of kinetic energy due to the mean meridional circulation and standing eddies, corresponding to the first and second right hand terms of Eq. (2), has been computed directly in the present study, and is listed in tables 5 and 6 for the various

Table 5. *Generation of Kinetic Energy Associated with the Mean Meridional Circulation, in 10^{18} erg · sec^{-1}*

	0–10	10–20	20–30	30–40	40–50	50–60° N
Winter						
100— 300 mb	−300	+1095	+607	+46	+214	−71
300— 700 mb	−122	+204	−108	−339	−260	−206
700—1000 mb	+276	+335	+106	+138	+61	+95
100—1000 mb	−146	+1634	+605	−155	+15	−182
Summer						
100— 300 mb	+228	+166	+46	+199	−20	−98
300— 700 mb	−30	−17	+19	−1	−105	−115
700—1000 mb	+29	−29	+7	−17	+12	+58
100—1000 mb	+227	+120	+72	+181	−113	−155

Table 6
Generation of Kinetic Energy Associated with Standing Eddies, in 10^{18} erg · sec^{-1}

	0–10	10–20	20–30	30–40	40–50	50–60° N
Winter						
100— 300 mb	+105	+67	−16	+25	−39	−395
300— 700 mb	+50	+211	+45	+332	+321	−730
700—1000 mb	+2	−19	+84	+267	+225	−86
100—1000 mb	+157	+259	+113	+624	+507	−1211
Summer						
100— 300 mb	+222	−98	−5	−7	−8	+131
300— 700 mb	+188	+15	−87	−72	−20	−12
700—1000 mb	+51	+101	+95	+143	+61	+24
100—1000 mb	+461	+18	+3	+64	+33	+143

latitude belts. The net generation of kinetic energy by the mean meridional circulation between equator and 30° N has been calculated by PALMÉN et al. [15] for the winter, and by HOLOPAINEN [7] for the winter and summer seasons. Their values for winter are somewhat larger than the ones arrived at in the present study; this difference seems to stem mainly from inadequate observations available for the latitude belt equator to 10° N. In agreement with the findings of Palmén et al. [15], generation within the Hadley cell shows a strong maximum in the upper troposphere, and a weaker one in the lower layers. Generation within the Hadley circulation is small in summer.

Kinetic energy production by the mean meridional circulation in the belt equator to 30^0 N in winter has the same general magnitude as the total poleward transport of kinetic energy across 30^0 N given by Pisharoty [16]. As pointed out by Palmén et al. [15], this indicates the importance of the Hadley cell for the kinetic energy budget of the northern hemisphere as a whole.

Kinetic energy production associated with standing eddies seems not to have been calculated in earlier studies. Contributions of zonal and meridional components were calculated separately, as indicated in section 2; their sum is listed in table 6.

Pisharoty [16] studied the production of eddy kinetic energy in winter on the basis of daily synoptic maps. Due to the different partitioning used here, his values cannot be directly compared. The total generation of kinetic energy is obtained as a residual in Pisharoty's study, and should therefore be considered with due reservation.

6. Frictional Dissipation

Frictional dissipation within the boundary layer, D_0, can be estimated from the following straightforward relationship

$$D_0 = \varrho_0 \cdot C_D \cdot V_0^3. \tag{5}$$

The air density near the surface, ϱ_0, is about $1.25 \cdot 10^{-3}$ gm $\cdot$ cm^{-3}; instead of the surface wind speed V_0 only mean resultant winds were available in the present study; following data presented by Priestley [18] and Palmén [14], values of 2 and $4 \cdot 10^{-3}$ were adopted for the drag coefficient over sea and land surfaces, respectively. Since only mean resultant winds were available, the dissipa-

Table 7. *Frictional Dissipation in the Surface Layer, Associated with the Mean Resultant Wind, in* 10^{18} *erg* $\cdot$ *sec*$^{-1}$

	0		10		20		30		40		50		60° N
Winter		93		103		57		28		40		31	
Summer		87		108		88		26		8		3	

tion values in table 7 represent a strong underestimate. Kung [9] has computed the total frictional dissipation in the surface layer over the northern hemisphere. Values compiled from his data are included in table 8 for comparison; Palmén's [13] estimates are

Table 8. *Kinetic Energy Budget of the Troposphere, 100—1000 mb*

I. generation of kinetic energy, $\int g \varrho \vec{V}_\nabla \cdot Z \frac{dp}{g\varrho}$, by the mean meridional circulation and standing eddies; II. divergence of the kinetic energy transport, $\int \left(\frac{\partial \varrho K v}{\partial y} \right)_p \frac{dp}{g\varrho}$, by the mean meridional circulation and standing eddies; III. frictional dissipation in the surface layer, after Kung [9] and Palmén [13]; in 10^{18} erg · sec^{-1}

	0	10	20	30	40	50	60	70° N
Winter								
I	+11	+1893	+718	+469	+522	−1393		
II	+60	+218	+114	+39	−226	−187		
III	—	—	342	725	887	1127	390	
Summer								
I	+688	+138	+75	+245	−80	−12		
II	−43	+79	+45	+18	−53	+11		
III	—	—	201	211	283	346	135	

listed for 0—20° N in winter. Estimates presented by Pisharoty [16] for winter 1949 are considerably smaller than Kung's values, between 30 and 60° N.

Assessment of the frictional dissipation within the free atmosphere appears difficult at the present time. Brunt [1] estimated the frictional dissipation within the free atmosphere to be about 0.66 times that in the surface layer. Jensen, Holopainen [6], and Kung [10] obtained ratios between 0.2 and 2.5. This idea of the general magnitude of frictional dissipation within the atmosphere is useful in the following summary of the kinetic energy budget.

7. Tentative Budget of Kinetic Energy in the Troposphere

Estimates of meridional transport, generation, and frictional dissipation of kinetic energy, as presented in the preceding section, will now be combined in a tentative budget for the tropospheric column in the various latitude belts.

Figs. 1 and 2 summarize the computations for finite atmospheric layers. Only the combined contribution of advective and standing eddy fluxes is considered in the lateral transports. Concerning the vertical transports, only the contribution of the first right hand term of Eq. (2) could be computed directly; transports across the 300 and 700 mb levels may thus also be greatly underestimated. Values of the net generation include the combined effect of mean meridional circulations and standing eddies; and KUNG's [9] and PALMÉN's [13] data are entered for the kinetic energy dissipation in the boundary layer. Contributions of the third right hand term of Eq. (2), as well as

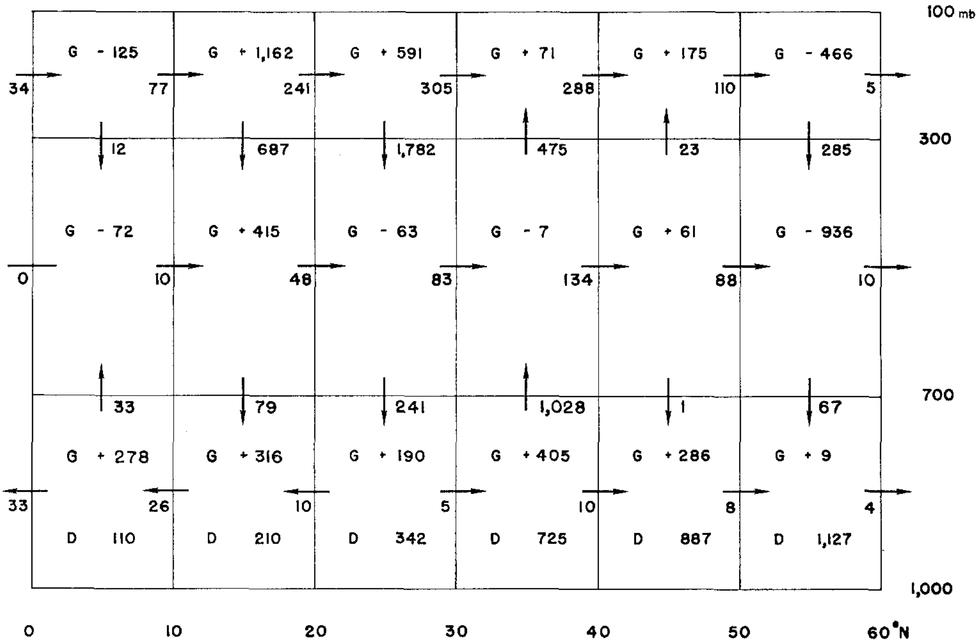

Fig. 1. Kinetic energy budget of the troposphere in winter. Vertical arrows denote advective, and horizontal arrows the sum of advective and standing eddy transports. G = net generation of kinetic energy associated with mean meridional circulations and standing eddies; D = boundary layer dissipation, after KUNG [9], and PALMÉN [13]; in 10^{18} erg · sec^{-1}

the frictional dissipation of kinetic energy in the free atmosphere, could not be determined in the present study. These effects would account for most of the surplus and deficit in the kinetic energy budget of finite layers in Figs. 1 and 2.

Estimates of various budget terms are summarized in table 8 and Fig. 3 for the tropospheric column as a whole. During winter, the Hadley cell is best developed, and its poleward limit is situated near 30° N. As tables 5 and 6 show, the Hadley circulation is an important producer of kinetic energy. According to table 8, the net generation of kinetic energy between equator and 30° N due to the combined effect of mean meridional circulations and standing eddies is about $26 \cdot 10^{20}$ erg · sec^{-1}. Assuming that the frictional dissipation in the free atmosphere has about the same magnitude as that in the boundary layer, the total frictional dissipation within the domain of the Hadley cell is found to be about $9 \cdot 10^{20}$ erg · sec^{-1}, as estimated by PALMÉN [14]. With zero transport across the equator, and ignoring the contribution of transient eddies this would leave for the poleward transport across latitude 30° N an amount comparable to the values obtained by KAO [8], PISHAROTY [16], and MINTZ [11]. Tables 3 and 4 indicates that the bulk of this transport has to be effected by transient eddy mechanisms. Values of the net generation between equator and 30° N in table 8 have the same general magni-

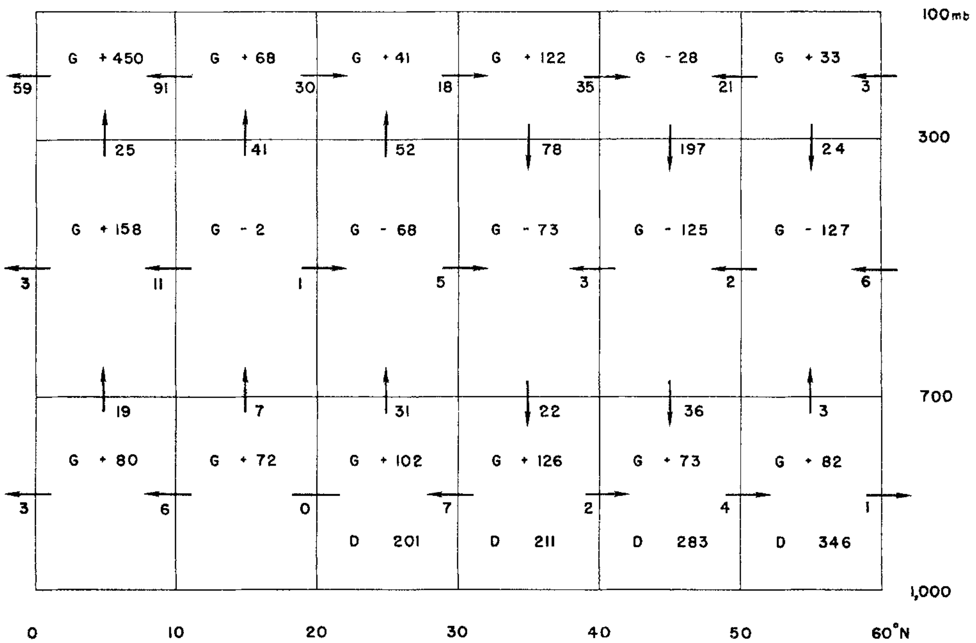

Fig. 2. Kinetic energy budget of the troposphere in summer. Symbols used as in Fig. 1

tude as the net generation by the Hadley circulation as presented by PALMÉN et al. [15] and PALMÉN [13]; the contribution of standing eddies was found to be comparatively small in the present study.

Beyond the poleward boundary of the Hadley cell, frictional dissipation in the boundary layer becomes much larger than in the tropical belt. This can be estimated to be of the order of $32 \cdot 10^{20}$ erg · sec^{-1} for the cap poleward of 30° N, according to table 8. The total frictional dissipation in the entire tropospheric column may correspondingly be about double that value, which would agree with crude estimates by BRUNT [1] and PALMÉN [13]. Considering the kinetic energy content listed in table 2, this would correspond to

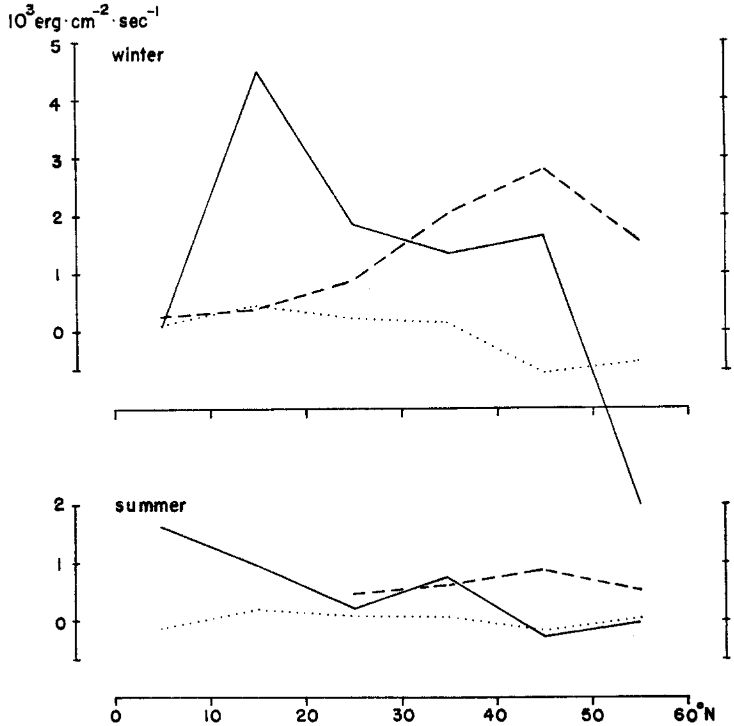

Fig. 3. Latitudinal characteristics of the kinetic energy budget of the entire tropospheric column, 1000 to 100 mb. Net generation of kinetic energy associated with mean circulations and standing eddies, solid line; divergence of the poleward transport of kinetic energy by mean meridional circulations and standing eddies, dotted line; and frictional dissipation in the boundary layer, after KUNG [9] and PALMÉN [13], broken line; in 10^3 erg · cm^{-2} · sec^{-1}

a dissipation of all kinetic energy in the extra-tropical cap within about 4 days. Furthermore, the Ferrel circulation of temperate latitudes consumes rather than produces kinetic energy (cf. table 5). The resulting total loss of kinetic energy would have to be made up by import across latitude 30° N, and net generation due to standing eddy and transient eddy mechanism. PISHAROTY's [16] estimate of the kinetic energy flux across 30° N would account for about one third of this depletion. About two-thirds would have to be supplied by generation of kinetic energy associated with transient eddies, since the effect of standing eddies was found to be comparatively small.

During summer, the Hadley cell is much weaker and its poleward limit is at a somewhat higher latitude than in winter. Accordingly, kinetic energy production is substantially decreased, in particular that due to the mean meridional circulations (cf. tables 5, 6, and 8). Frictional dissipation within the domain of the Hadley cell is also considerably smaller than in winter. However, it appears that at most a small amount of kinetic energy could be spared for export into extra-tropical regions. Tables 3 and 4 indicate that transport by mean meridional circulations and standing eddies across 30 and 40^0 N in summer are indeed small, as is the total poleward transport of kinetic energy computed by Mintz [11] and listed in section 4.

Beyond the poleward boundary of the Hadley cell, mean meridional circulations during summer are also kinetic energy consuming; this is counteracted by the effect of standing eddies. Table 8 shows that the total frictional dissipation within the troposphere is considerably smaller than in winter.

Although only climatic mean data were available, some basic features of the kinetic energy budget over the northern hemisphere are emerging from the present study. The intense Hadley circulation during winter plays a vital role in the production of kinetic energy; this is supplemented by the effect of standing eddies; transient eddy contributions appear to be comparatively small. Kinetic energy generation within the domain of the Hadley cell greatly exceeds the local frictional dissipation. Transient eddy mechanisms are mainly responsible for the export from the northern portion of the Hadley cell poleward. The strong frictional dissipation within the extra-tropical cap is mainly met by imports across 30^0 N and kinetic energy generation associated with transient eddies. Summer conditions are characterized by greatly decreased generation and dissipation rates; imports from the domain of the Hadley cell become less important for the maintenance of circulation in the extra-tropical cap.

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