# On the role of mean meridional circulations in the energy balance of the atmosphere

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ABSTRACT

The poleward energy flux in the atmosphere over the Northern Hemisphere is first discussed. The flux associated with the mean meridional circulations is computed and compared with the calculations of the eddy flux. The results indicate a great difference between the tropics and the extratropics with respect to the mechanism of the flux: south of about 30° N the mean meridional circulations are the principal flux agency, whereas eddies dominate at higher latitudes. The total flux is compared with the mean meridional distribution of the heat sources and sinks of the atmosphere. Satisfactory agreement is found, particularly regarding the annual mean conditions.

The role of mean meridional circulations in the hemispheric balance of kinetic energy is found to be small in summer but relatively large in winter, when they seem to be important, especially for the maintenance of the kinetic energy of the mean motion.

## 1. Introduction

Quantitative estimates of the mean meridional circulations in the atmosphere have been made both on the basis of actual wind observations and by resorting to some indirect methods. Nevertheless, the magnitude of these circulations and their role in the energetics and dynamics of the atmosphere are not yet satisfactorily established.

The main purpose of the present article is to discuss the role of the mean meridional circulations in the poleward flux of energy (sensible heat + potential energy) and in the balance of kinetic energy in the Northern Hemisphere. With this in view, patterns of the mean meridional motions for winter, summer and the whole year have been constructed by using the models of MINTZ & LANG (1955) for areas north of 30°N and those of PALMÉN & VUORELA (1963) and VUORELA & TUOMINEN (1964) for the lower latitudes. It is not argued *a priori* that the particular patterns so obtained fully represent the actual conditions. They merely serve as reference patterns, whose correctness can be inferred from how well they match some balance requirements of the atmosphere.

## 2. Poleward flux of energy

### (a) *General considerations*

The poleward flux of sensible heat and potential energy, per unit mass, is given by

$$F = (c_p T + \Phi)v, \tag{1}$$

where $T$ denotes temperature, $\Phi = gz$ potential energy per unit mass ($g$ is the acceleration of gravity, $z$ the elevation), $v$ the meridional wind component and $c_p$ is the specific heat of air at constant pressure. If the brackets are used to represent a zonal average along an isobaric surface and the bar a time average, the energy equation of the atmosphere per unit area of the earth's surface can, in an approximate form, be written as

$$[\overline{R}_a] + [\overline{LP}] + [\overline{Q}_s] = \frac{1}{a \cos \varphi} \frac{\partial}{\partial \varphi} \times \left( \cos \varphi \int_{100\ \mathrm{mb}}^{1000\ \mathrm{mb}} [\overline{F}] \frac{dp}{g} \right). \tag{2}$$

Here $a$ is the radius of the earth, $\varphi$ denotes latitude and $p$ pressure. The left-hand side of

Eq. (2) represents the time mean diabatic heating of the air column in the mean meridiaonal cross-section: $R_a$ is the heating due to radiation, LP the heating due to condensation of water vapor ($L$ is the heat of vaporization, $P$ the precipitation intensity) and $Q_s$ the heating due to transfer of sensible heat from the earth to the atmosphere. In the derivation of Eq. (2) the time period considered has been assumed to be such that the storage of energy in the atmosphere can be disregarded.[1] The flux of kinetic energy, which is small compared with that of sensible heat and potential energy, is neglected. Furthermore, it is assumed, as usual, that the condensation heating of the air column is determined by the precipitation measured at the ground. Surface pressure is treated as a constant (1000 mb) and the contribution of the stratosphere to the heat budget of the atmosphere is neglected. In the following discussion Eq. (2), which states that in the long-term steady conditions the net diabatic heating must be compensated by the divergence of energy flux, serves as the basic relationship.

With regard to the different mechanisms of the mean poleward energy flux, the normally used formal procedure of defining them is as follows: Let an asterisk denote the deviation from the zonal average and a prime the deviation from the time average. Then the zonal mean and time mean meridional energy flux can be written in the following two ways (cf. Starr & White, 1952):

$$[\overline{F}] = (c_p[\overline{T}] + [\overline{\Phi}])[\overline{v}] + \overline{[c_p T + \Phi]'[v]'} + c_p\overline{[T^* v^*]} + \overline{[\Phi^* v^*]} \tag{3}$$

or $$[\overline{F}] = c_p[\overline{T}] + [\overline{\Phi}])[\overline{v}] + c_p[\overline{T}^* \overline{v}^*] + [\overline{\Phi}^* \overline{v}^*] + c_p\overline{[T'v']} + \overline{[\Phi'v']}. \tag{4}$$

The first term on the right-hand side of both equations represents the energy flux associated with the mean meridional mass circulations. The second term on the right-hand side of Eq. (3) represents the so-called "oscillating cell" flux, while the last two terms stand for the time mean energy flux in zonal eddies, as appearing on synoptic charts. In Eq. (4) the second and third terms represent the contribution to the flux made by "standing" zonal eddies, the fourth and fifth terms that due to the "transient" eddies. Using the nomenclature proposed by Oort (1964), the division of $[\overline{F}]$ into components is made in a "space domain" in Eq. (3) and in a "mixed space-time domain" in Eq. (4).

Concerning empirical estimates of the flux in the "space domain", the importance of the zonal eddies in the poleward flux of sensible heat in the extratropical latitudes has been demonstrated by several authors (e.g. White, 1951; Mintz, 1955*a*). Mintz (1955*b*), using the model of mean meridional circulation by Mintz & Lang (1955), has estimated the circulation flux of energy north of 20° N for two winter months and two summer months of 1949. At the present time there seems to be no estimate of either the "oscillating cell" flux or the eddy flux of potential energy. Regarding the latter, some comments can be made. Namely, fluctuations of the sensible heat at a given isobaric level are typically larger than those of the potential energy. In addition, the correlation between $\Phi$ and $v$ is, according to all the synoptic evidence, smaller than that between $T$ and $v$. Accordingly, it can be expected that the eddy flux of potential energy (which does not appear at all when the height is used as the vertical coordinate (cf. Starr, 1951)) is much smaller than the eddy flux of sensible heat. In any case the former must for the present be disregarded in both Eqs. (3) and (4).

Regarding the "mixed space-time domain", Starr & White (1954) and Peixoto (1960) have reported calculations of the transient eddy flux of sensible heat for the winter half, summer half and whole year of 1950 and also the standing eddy flux for the six winter months of the same year.

Because of the time coverage of the existing empirical results just mentioned, it is better in the following to use Eq. (3) in the discussion of the energy flux in winter and summer. However, when the annual mean conditions are considered, Eq. (4) offers a better framework. In addition to the energy flux associated with the mean meridional circulations, estimates in the following are also presented concerning the flux of sensible heat associated with the annual mean standing eddies.

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[1] Generally the heat storage in the atmosphere is small compared with the terms in Eq. (2). This is especially true at the times when the atmospheric temperature reaches an extreme (winter and summer).

### (b) *Data and methods of calculation*

With regard to the patterns of mean meridional circulation in winter, the low-latitude circulation proposed by Palmén & Vuorela and the pattern north of 30° N computed by Mintz & Lang fit together well. In summer there is some disagreement at 30° N between the patterns computed by Vuorela & Tuominen and by Mintz & Lang; for this latitude, the average of the two was used. For the annual mean pattern of the mean meridional circulation the average of the winter and summer circulations has been taken.

Temperature and isobaric height data were taken for the 100, 200, 300, 500 and 700 mb levels from Goldie *et al.* (1957) and from Heastie & Stephenson (1960), respectively. For the lower troposphere the data of Jacobs (1958) and Hennig (1958) and also the U.S. Weather Bureau tabulations (taken from London (1957)) were used.

In computations of the energy flux associated with the mean meridional circulations the pressure levels of 100, 200, 300, 500, 700, 850, 900, 950 and 1000 mb were used in the region south of 30° N. For the latitudes north of 30° N the treatment of the troposphere (200–1000 mb) in 100-mb layers by Mintz & Lang was adopted. The integrations with respect to pressure were performed numerically. An essential point in these integrations was the requirement of mass balance ($\int[[\overline{v}]dp = 0$).

With regard to the evaluation of the energy flux associated with the annual mean standing eddies, Crutcher's (1959, 1961) wind statistics for different seasons were used to compute the annual mean distribution of $v$ at the 100, 200, 300, 500, 700 and 850 mb levels. Similarly, the normal temperatures for January, April, June and October from Goldie *et al.* (1957) were averaged to yield an estimate of the annual mean temperatures at the same pressure levels, except at 850 mb, where the value taken for the temperature was the average temperature between the 1000 mb and 700 mb levels, as computed from the thickness of this layer. The flux at the 1000 mb level was obtained by linear extrapolation from the 700 mb and 850 mb levels.

### (c) *Results*

Fig. 1 shows a tentative model of the normal poleward energy flux in winter and in summer, referring to the periods December–February and June–August, respectively. The flux associated with the mean meridional circulation

$$\frac{2\pi a \cos\varphi}{g}\int (c_p[\overline{T}]+[\overline{\Phi}])[\overline{v}]\,dp$$

is computeed as described in (*b*); the eddy flux

$$\frac{2\pi a \cos\varphi}{g}\int c_p[\overline{T^*v^*}]\,dp$$

is taken from Mintz (1955*a*) and the sum of these taken to represent the total flux of sensible heat and potential energy.

The most outstanding feature of the figure is the difference between the lower and higher latitudes with respect to the mechanism of energy flux. During both seasons, south of about 30° N the *mean meridional circulations* play the dominant role in the poleward energy transport, whereas at higher latitudes the eddies are clearly the main agency of flux. It should be noticed that, owing to the monotonous increase of the quantity ($c_p[\overline{T}]+[\overline{\Phi}]$) with height, the direction of the mean mass circulation also determines the direction of the associated energy flux. Thus, for example, the direct Hadley circulation at low latitudes in winter results in northward transport of energy and the indirect Ferrel circulation of the middle latitudes in a southward transport. Similarly, the direction of the interhemispheric mass circulations, as given by Palmén & Vuorela and Vuorela & Tuominen, implies a considerable energy flux from the Southern Hemisphere to the Northern Hemisphere in winter and an even larger southward flux across the Equator in summer. The characteristics of the total flux in winter are the two maxima, one at about 12° N, where the Hadley circulation is most intense, the other in the middle latitudes associated with the eddy flux. In summer the magnitude of the total flux is much smaller than in winter, except at very low latitudes.

With regard to the representativeness of Fig. 1 of the true mean conditions in winter and summer, it should first be noted that the eddy flux computed by Mintz refers only to two winter months (January–February) and two summer months (July–August) of the year 1949, while the flux due to the mean meridional motions has been computed from the

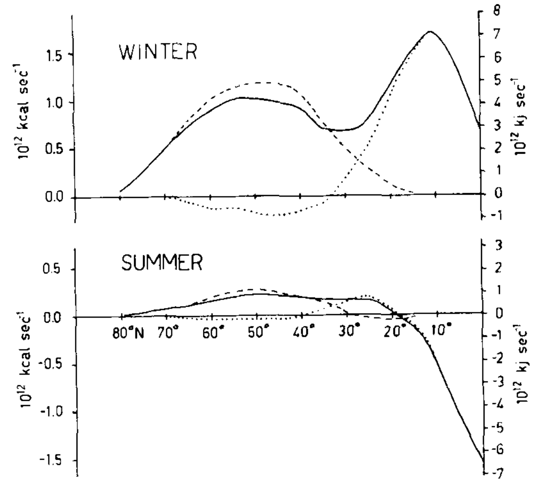

FIG. 1

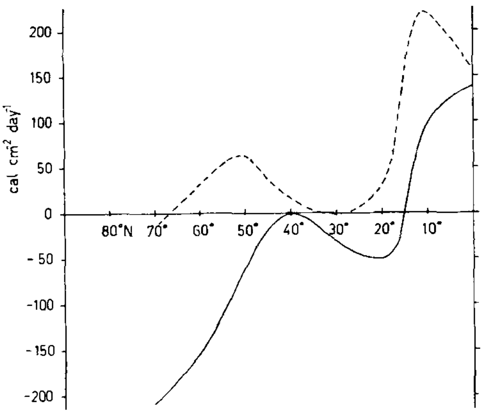

FIG. 2

FIG. 1. *Tentative model of the mean poleward flux of energy (sensible heat + potential energy) in the atmosphere over the Northern Hemisphere in winter (December–February) and in summer (June–August).* ——, total flux; · · · ·, flux associated with the mean meridional circulations; – – – –, flux associated with the zonal eddies (after MINTZ, 1955*a*).

FIG. 2. Meridional distribution of the mean diabatic heating of the atmosphere over the Northern Hemisphere in December (*full line*) and in June (*dashed line*), according to BERLIAND (1956).

wind and temperature statistics of several years. However, the magnitude and the latitudinal distribution of the eddy flux in the extratropical latitudes has been confirmed by several investigators (e.g. WHITE, 1951; WIIN-NIELSEN, BROWN & DRAKE, 1963, 1964), whereas very few quantitative estimates seem to exist on the obviously very important role of the mean meridional circulations in the tropics (see VUORELA, 1957). PALMÉN, RIEHL & VUORELA (1958), in their article on the Hadley cell in winter, have determined the flux of total energy (including latent heat) across latitude 15° N. They also give the vertical distribution of the mean meridional velocity and different energy forms at this particular latitude. From these one can compute the flux of sensible heat and potential energy at $7.8 \times 10^{12}$ kj sec$^{-1}$, which should be compared with the value $6.2 \times 10^{12}$ kj sec$^{-1}$ of the present study. The difference between these values can mainly be attributed to the different intensities of the mass circulations. On the other hand, these mass circulations are not determined quite independently (see "Introduction" in PALMÉN & VUORELA, 1963) and accordingly the flux in Fig. 1 may have a wider margin of error than is indicated by the above numbers. In Fig. 1 the relatively small flux due to the mean meridional circulations in extratropical latitudes is close, both in winter and in summer, to the values for the "potential heat flux" obtained by MINTZ (1955*b*).

The most rigorous test of the computed flux values would be provided by Eq. (2), if the diabatic heating of the atmosphere could be determined accurately enough by independent means. Unfortunately, this is not the case. The most complete estimate of the net diabatic heating for different seasons of the year seems to be that by BERLIAND (1956), who has considered the heat balance of the atmosphere in March, June, September and December; his results for the net heating in December and June are reproduced in Fig. 2. DAVIS (1963), CLAPP (1961) and ASAKURA & KATSYAMA (1964) have also studied the heating in winter and summer. However, DAVIS considers only the heat budget between 20° N and 70° N and the other authors that of the lower troposhere. Because it is primarily the total atmospheric flux at low latitudes which is to be considered here, the above studies are irrelevant for the present purpose. It should be noted that the estimates of the diabatic heating by the so-called dynamic method (e.g. BROWN, 1964) do

TABLE 1. *Mean diabatic heating of the atmosphere in different latitudinal zones as computed from the divergence of the total energy flux in Fig. 1.*

Unit: cal $\text{cm}^{-2}\ \text{day}^{-1}$.

| $\Delta\varphi$(° N) | 60–90 | 50–60 | 40–50 | 30–40 | 20–30 | 10–20 | 0–10 |
|---|---|---|---|---|---|---|---|
| Winter | −224 | −42 | 24 | 58 | −104 | −106 | 203 |
| Summer | −40 | −22 | 12 | 6 | 32 | 108 | 202 |

not provide an independent test of the computed flux values.

Fig. 2 is now to be compared with Table 1, which gives the diabatic heating of the atmosphere as implied by the divergence of the computed flux (the right-hand side of Eq. (2)).

It must be emphasized that the estimates of radiation, precipitation and the exchange of sensible heat between the earth and the atmosphere are at present very uncertain for individual months. Therefore **BERLIAND**'s heating curves in Fig. 2 should be considered to have qualitative value only. With regard to the winter conditions it is seen from Fig. 2 that the heating function is positive close to the Equator and changes sign between 10° N and 20° N, thus implying the existence of a flux maximum in this latitudinal zone, in agreement with Fig. 1. The numerical values of the tropical heating (flux convergence) and subtropical cooling (flux divergence) are smaller, however, in Fig. 2 than in Table 1. This discrepancy could mean that the tropical maximum of energy flux in Fig. 1 is somewhat overestimated but nothing definite can be said about this. Regarding the summer conditions, the values in Fig. 2 and Table 1 for the low latitudes compare well, thus giving some support to the reality of the flux depicted in Fig. 1.

Fig. 3 shows the annual mean poleward flux of energy and its different components in the "mixed space-time domain". The flux due to mean meridional circulations

$$\frac{2\pi a \cos\varphi}{g}\int (c_p[\overline{T}]+[\overline{\Phi}])[\overline{v}]\,dp$$

has been computed by using for $[\overline{v}]$ average of the mean meridional wind component for winter and summer. The flux associated with the transient eddies

$$\frac{2\pi a \cos\varphi}{g}\int c_p[\overline{T'v'}]\,dp$$

is taken from **PEIXOTO**'s results for the year 1950 and that associated with the standing zonal eddies

$$\frac{2\pi a \cos\varphi}{g}\int c_p[\overline{T}^*\,\overline{v}^*]\,dp$$

calculated as described in (*b*).

The latitudinal difference in the mechanism of energy flux is also clear in the annual mean picture: at low latitudes the energy flux is almost entirely associated with the mean meridional circulations and at higher latitudes with the transient eddies. The standing eddy transport of energy is relatively small everywhere. It is largest in the middle latitudes but has here a tendency to cancel out with the southward directed flux due to mean meridional circulations.

In order to get some idea of the representativeness of the "observed" flux in Fig. 3, use was made of the new Russian heat atlas (edited by **BUDYKO**, 1963), which includes, among other things, a chart of the annual mean diabatic heating of the atmosphere. From this chart zonal averages were computed between the Equator and latitude 60° N; between 60° N and 90° N the heating function was determined by taking the radiational cooling of the troposphere from **LONDON** (1957) and the release of latent heat and the turbulent heat transfer to the atmosphere from the Russian heat atlas. The extrapolations needed are insignificant for the following discussion. The meridional distribution of the diabatic heating so obtained is shown in Fig. 4. The corresponding energy flux, determined by the integration of Eq. (2) with respect to latitude and the requirement of vanishing flux at the pole, is shown in Fig. 5,

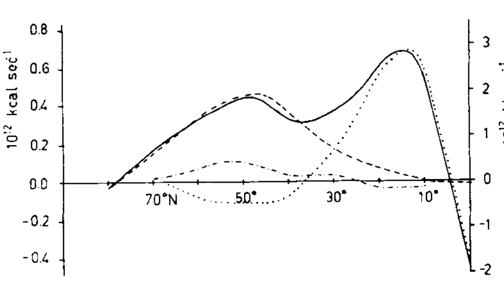

FIG. 3

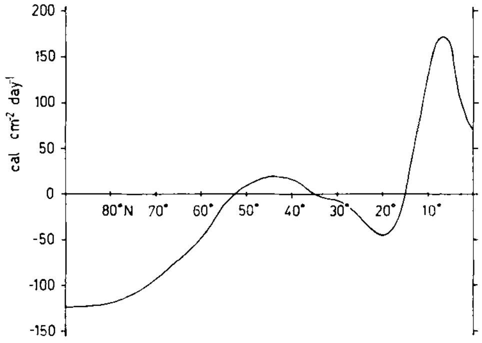

FIG. 4

FIG. 3. Tentative model of the annual mean poleward flux of energy (sensible heat + potential energy) in the atmosphere over the Northern Hemisphere. ——, total flux; ····, flux associated with the mean meridional circulations; ----, flux associated with the transient eddies (after PEIXOTO, 1960); -·-·, flux associated with the standing zonal eddies.

FIG. 4. Meridional distribution of the annual mean diabatic heating of the atmosphere over the Northern Hemisphere, computed from BUDYKO (1963) and LONDON (1957).

together with the "observed" flux. In the light of the approximate nature of Eq. (2) and the inaccuracy in the evaluation of all its terms, the agreement between the two independently determined curves must be considered satisfactory. It can be stated that the annual mean energy flux has two maxima, one at about 15° N with a value between 2 and 3 × $10^{12}$ kj $sec^{-1}$ and the other, somewhat smaller, between 45° N and 55° N. SMAGORINSKY (1963), by adjusting the data given by LONDON (1957) and BUDYKO (1956), has deduced similar results, with the tropical flux maximum of 2.4 × $10^{12}$ kj $sec^{-1}$ and the extratropical maximum of 2.1 × $10^{12}$ kj $sec^{-1}$. Both curves in Fig. 5 give zero energy flux at about 5° N, which is probably close to the average position of the intertropical convergence zone. Both also give an energy flux across the Equator to the Southern Hemisphere, implying an average heating (cooling) of the atmosphere in the Northern (Southern) Hemisphere due to diabatic processes at a rate of 0.03–0.07°C $day^{-1}$. The greatest discrepancy between the "observed" and the "required" energy flux occurs between 10°N and 30° N. This difference would be eliminated if, for example, the mass circulation in the Hadley cell in winter were 20–30 per cent smaller than that deduced by PALMÉN & VUORELA. PALMÉN, in a personal communication to the author, has expressed his feeling that this really may be the case. However, for lack of information, for instance, about the mean mass circulations in spring and fall, no definite conclusion can be drawn. In any case the fair agreement between the "observed" and "required" fluxes indicates that the patterns used to represent the mean meridional motions correspond fairly closely with reality.

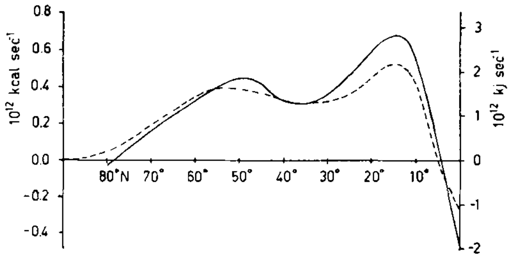

FIG. 5. Annual mean "observed" poleward flux of energy over the Northern Hemisphere (*full line*, the same as in Fig. 3) and the flux required by the mean heat sources and sinks (*dashed line*).

It should be noticed that in the present study the flux of the latent heat of water vapor has been taken into account only implicitly in the heating function of the air. If the poleward flux of the total energy (sensible heat + potential energy + latent heat) of the atmosphere is considered, the results will be different from those given above. However, because the latent heat does not directly enter the budget of kinetic energy, as the other energy forms do, it is sometimes better to consider it separately. With regard to the compatibility between the mean meridional circulations used in the present study and the water budget at low latitudes, the reader is referred to PALMÉN & VUORELA (1963) and VUORELA & TUOMINEN (1964).

As a summary of the present section it can be said to be fairly well established that in the poleward energy flux over the Northern Hemisphere the mean meridional circulations are as important a mechanism as the large-scale zonal eddies. However, the two mechanisms operate in different regions. The mean meridional circulations dominate south of about 30° N, where the conditions to some extent resemble those of the "Hadley regime" as defined in the laboratory experiments of the general circulation of the atmosphere. In the extratropical latitudes the zonal eddies are the more important mechanism, ("Rossby regime").

## 3. Maintenance of kinetic energy

During the last fifteen years much effort has been devoted to the investigation of energy transformations in the atmosphere; the latest review of the research in this field is given by OORT (1964). The role of the mean meridional circulations in the maintenance of the kinetic energy on a global or hemispheric scale is not yet satisfactorily known, especially owing to the fact that in many investigations the tropical regions have been excluded. It therefore appeared of interest to calculate what, in this respect, is implied by the patterns of mean meridional motion, which were used above with some success in the discussion of the poleward flux of energy.

The production of kinetic energy by the action of the mean meridional pressure forces on the mean meridional circulation is given by

$$C = -\int_M [\bar{v}]\,\frac{1}{a}\,\frac{\partial[\bar{\Phi}]}{\partial\varphi}\,dm = \int_M f\,[\bar{u}_g]\,[\bar{v}]\,dm \qquad (5)$$

where $f$ is the Coriolis parameter and $u_g$ the geostrophic zonal wind component, and the integration is to be taken over the mass $M$ of the system considered. $C$ was calculated for winter (December–February) and summer (June–August) and, by using the average of the winter and summer circulations, also for the whole year. The same data and numerical technique were used as in the case of the energy flux. The results are given in Table 2.

TABLE 2. *Production of kinetic energy by the mean meridional circulations over the Northern Hemisphere.*

Unii: $10^{10}$ kj sec$^{-1}$.

| | 30° N–90° N | 0°–30° N | Northern Hemisphere |
|---|---|---|---|
| Winter (December–February) | −11 | 30 | 19 |
| Summer (June–August) | −2 | 3 | 1 |
| Year | −5 | 9 | 4 |

From this table, a marked seasonal variation in the rate of energy production is first to be noticed, the values for the winter being of much larger magnitude than those for the summer and for the whole year. Regarding the latitudinal variation the results indicate generation of kinetic energy south of 30° N and destruction of it north of 30° N in winter and summer, as well as in the annual mean. For the net effect over the Northern Hemisphere generation of kinetic energy is obtained in all three cases but only in winter is its magnitude large. It should be noticed that the $[\bar{v}]$-data used actually extend only to 80° N and do not perhaps properly depict the possible direct meridional mass circulation at high latitude. However, owing to relative smallness of its mass, the role of the polar cap must be small in the energetics of the whole hemisphere.

Regarding the annual mean balance of kinetic energy, the estimates of the total production of kinetic energy over the Northern Hemisphere vary from 50 to 130 × $10^{10}$ kj sec$^{-1}$ (from 2 to 5 watts m$^{-2}$). When the value from Table 2 is compared with this it can be concluded that the role of the annual mean meridional circulations in the mean budget of total kinetic energy is insignificant. This has often been emphasized by STARR, who (STARR, 1959) used the expression $\int_M f[\bar{u}][\bar{v}]dm$ to evaluate the energy production by the mean meridional circulations. His results for the years 1950 and 1951 are —2 and—3 × $10^{10}$ kj sec$^{-1}$, respectively, compared with the value of 4 × $10^{10}$ kj sec$^{-1}$ obtained in the present study. The difference between the results is of no importance as far as the budget of total kinetic energy is concerned. It becomes significant, however, when

TABLE 3. *Production of kinetic energy by the mean meridional circulations in winter.*

Unit: $10^{10}$ kj sec$^{-1}$.

| | $-\int[\bar\alpha][\bar\omega]\,dm$ | $-\int[\bar v]\frac{1}{a}\frac{\partial[\bar\Phi]}{\partial\varphi}\,dm$ |
|---|---|---|
| Hadley cell | 30 | 30 |
| Ferrel cell | −11 | −12 |
| Sum | 19 | 18 |

the only kinetic energy considered is that associated with the zonal mean and time mean motion. So far, even the sign of this production term remains uncertain, although the numerical experiments on the general circulation of the atmosphere (PHILLIPS, 1956; SMAGORINSKY, 1963) qualitatively support the results obtained by STARR.

The rate of production of kinetic energy over the Northern Hemisphere in winter is probably not larger than 100 × $10^{10}$ kj sec$^{-1}$ (cf. PALMÉN, 1960). The production by the mean meridional circulations is, according to Table 2, 19 × $10^{10}$ kj sec$^{-1}$ and thus a non-negligible fraction of the total production. In order to get an idea of the effect of the calculation methods on the results, the rate of energy production in winter was also evaluated in another way. Using the equations of hydrostatics and mass continuity, one can write:

$$[\bar v]\,\frac{1}{a}\,\frac{\partial[\Phi]}{\partial\varphi} = \frac{1}{a\cos\varphi}\,\frac{\partial}{\partial\varphi}([\bar\Phi]\,[\bar v]\cos\varphi) + \frac{\partial}{\partial p}([\bar\Phi]\,[\bar\omega]) + [\bar\alpha]\,[\bar\omega],$$

where $\omega$ is the vertical $p$-velocity and $\alpha$ the specific volume. When this expression is integrated in a meridional plane over the mass of a system which is closed with respect to the mean motion, such as the Hadley cell, Ferrel cell or the two combined, the first two terms on the right-hand side disappear and one is left with

$$C = -\int_M [\bar\alpha]\,[\bar\omega]\,dm = -R\int\frac{[\bar T_v]\,[\bar\omega]}{p}\,dm, \qquad (6)$$

where $R$ is the gas constant and $T_v$ the virtual temperature. The calculations were made separately for the Hadley cell (5° S–32.5° N; 100–1000 mb) and the Ferrel cell (32.5° N–80° N; 200–1000 mb). For both regions the requirement of mass balance (vanishing at each pressure level of the area-averaged $\omega$) was used in the calculations. In Table 3 the results are compared with the values of energy production computed from Eq. (5). It is seen that expressions (5) and (6) give practically the same result, thus indicating the reliability of the numerical calculation methods.

The results of Table 3 are now to be compared with the earlier investigations of the kinetic energy production by the mean meridional circulations in winter. PISHAROTY (1955) has estimated the upper and lower limits of the energy production in the Hadley cell at 29 × $10^{10}$ kj sec$^{-1}$ and 24 × $10^{10}$ kj sec$^{-1}$, respectively, and those for the Ferrel cell at −5 × $10^{10}$ kj sec$^{-1}$ and −10 × $10^{10}$ kj sec$^{-1}$. The corresponding limits of the net production over the Northern Hemisphere would then be 24 × $10^{10}$ kj sec$^{-1}$ and 14 × $10^{10}$ kj sec$^{-1}$. These values all agree relatively well with those in Table 3. PALMÉN, RIEHL & VUORELA (1958) computed the production of kinetic energy in the Hadley cell at 31 × $10^{10}$ kj sec$^{-1}$, which is practically the same as in the present study. WIIN-NIELSEN (1959) and SALTZMAN & FLEISHER (1960, 1961) have made investigations on a nearly hemispheric scale of the production of kinetic energy in the framework of quasi-geostrophic, adiabatic theory of the atmosphere's large-scale behaviour. These investigations are in principle inadequate to give a true idea of the energy conversion by the mean meridional circulations over the whole Northern Hemisphere, because usually only the area north of about 20° N is considered with the result that the whole ascending branch of the Hadley circulation is lost. However, SALTZMAN & FLEISHER (1960, 1961) extrapolated their calculations to the Equator and found a positive net production of kinetic energy by the mean meridional circulations both for a single month (February 1959) and for a period of six winter months.

As discussed by PALMÉN (1959), in winter the Hadley circulation is essential for the maintenance of kinetic energy in the tropics and particularly for the maintenance of the subtropical jet stream on the northern border of the Hadley cell. The consumption of kinetic energy in the Ferrel cell is probably also important for the distribution of the mean zonal motion in extratropical latitudes. However, the point to be stressed here is the net effect of the two circulation cells in winter. In most of the modern studies on the hemispherical statistics of atmospheric motion, the mean meridional circulations have been considered to be of minor importance compared with the eddies in maintaining the kinetic energy of the zonal mean and time mean motion. In the light of the results in Table 3 this may not be the case in winter, when the different types of motion systems are best developed over the Northern Hemisphere. If we allow that in Table 3 the contribution by the Hadley cell is possibly overestimated by 20–30 per cent, we can conclude that the net production of kinetic energy over the Northern Hemisphere in winter is probably 10–20 × $10^{10}$ kj $sec^{-1}$ (0.4–0.8 watts $m^{-2}$). This value is quite comparable with the estimated rates of transformation of eddy kinetic energy to the kinetic energy of mean motion (e.g. STARR, 1953).

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