The Observed Annual Cycle in the Meridional Transport of Atmospheric Energy

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ABSTRACT

The annual cycles in the atmospheric storage and in the meridional transport of energy are discussed. The calculations are based on a five-year sample from more than 500 radiosonde stations mainly located in the Northern Hemisphere. All statistics represent values integrated vertically between the earth's surface and 75 mb and horizontally along a latitude circle.

Several new and interesting features of the eddy and mean transports of potential energy, sensible heat, latent heat and kinetic energy become apparent by the breakdown according to calendar month.

In December through February more than half of the sensible heat is transported poleward by the standing eddies. The transient eddy heat flux does not peak in winter but in April and November.

The strong annual cycle in the tropical Hadley circulation does not contribute to the poleward transfer of energy for the year as a whole.

1. Introduction

The meridional transport of energy forms one of the important links in the energy cycle of the atmosphere. While radiational cooling and sensible plus latent heat exchange with the earth's surface tend to give an excess heating at low and a deficit at high latitudes, the poleward transport of energy maintains the climatic balance. Of these effects the atmospheric transport can be determined perhaps most accurately, at least in the Northern Hemisphere, because of the elaborate system of radiosonde stations in existence.

The annual mean conditions of the general circulation are never realized during the course of a year due to the continuous change in solar declination. Thus, it is well known that there are large differences at all latitudes between the basic winter and summer circulation regimes. To investigate these differences we have undertaken a study of the vertically integrated meridional transport of energy for each calendar month of the year. The results are described in the present paper.

The total energy will be divided into its four components; these are the potential energy, the internal energy, the latent heat and the kinetic energy. Before the discussion of the main topic of the paper (i.e., the energy fluxes) we shall first consider the actual month-to-month changes in the storage of energy in the atmosphere (Section 3). Then will follow the discussion of the meridional fluxes of energy by the mean meridional circulation and by the large-scale horizontal eddy motions (Section 4). The transports by the mean meridional circulations are difficult to evaluate but a knowledge of them is essential for an understanding of the total transfer. These circulations were discussed in detail in an earlier paper (Oort and Rasmusson, 1970; this paper will be referred to as ORa in what follows). Finally, estimates of the radiational cooling by London (1957) and of the upward fluxes of latent and sensible heat at the earth's surface by Budyko (1964) will be compared with the computed energy convergence due to horizontal motions and also with the observed rate of change in energy content (Section 5).

The results given in this paper have been derived from five years of general circulation statistics. These statistics were calculated using an extensive network of radiosonde stations over the Northern and Southern Hemisphere tropics from what is known as the MIT General Circulation Library. The transports for the twelve calendar months were analyzed in exactly the same manner. This makes a strict comparison possible between the results for the different months of the year. The overall consistency in analysis techniques as well as the uniform character of the basic data set are important and relatively new features in general circulation studies.

2. Data and method of analysis

The basic data set came from the MIT General Circulation Library. This library contains daily radiosonde observations for about 500 regularly reporting stations over the Northern Hemisphere for the period May 1958 through April 1963. The data were collected and processed by the Travelers Research Center, Inc., (TRC) at Hartford, Conn., for Prof. V. P. Starr at the Massachusetts Institute of Technology (MIT). This imaginative project was supported by several grants from the National Science Foundation. Some 40 im-

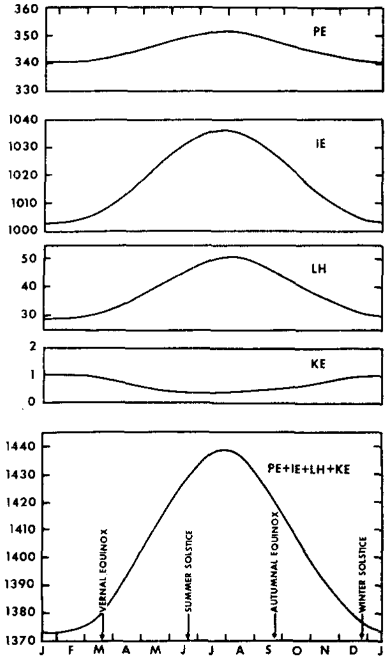

FIG. 1. The annual variation in the energy content of the atmosphere. The integration is carried out over the Northern Hemisphere between the surface and 75 mb. The annual mean values of potential energy, internal energy, latent heat and kinetic energy are 345.4, 1018.4, 38.9 and 0.72×10^{20} cal, respectively.

portant additional stations in the tropics were kindly supplied by Prof. R. E. Newell and Dr. J. W. Kidson, also of MIT. At 1000 mb we used the analyses of Crutcher *et al.* (1966) for the mean wind field.

From the raw radiosonde reports for each station five-month mean statistics were computed (i.e., all January data from the five-year period were used to estimate the average for a typical January month, etc.). Next the necessary parameters were machine-analyzed on a polar stereographic grid at 11 levels between 1000 and 50 mb. Zonal averages were calculated, and as a last step these averages were vertically summed for the layer from the surface up to 75 mb. The vertical integration was only carried up to 75 mb because the reporting frequency of many stations deteriorated markedly above 100 mb. A smoothed topography was taken into account. For a more extensive discussion of the data sources and analysis procedures the reader is referred to ORa. Extensive tabulations (from the surface up to 50 mb) and vertical cross sections of the basic zonal-mean parameters from which the present results are derived by vertical integration will be published separately (Oort and Rasmusson, 1971; we shall refer to this paper as ORb). The humidity statistics in this paper were very kindly supplied by the author's colleague, Dr. Eugene M. Rasmusson.

3. Month-to-month changes in energy content

The following notation will be used throughout the paper:

$PE=gz$	potential energy
$IE=c_vT$	internal energy
$SH=c_pT$	sensible heat
$LH=Lq$	latent heat
$KE=(u^2+v^2)/2$	kinetic energy

$\bar{A}=(t_2-t_1)^{-1}\int_{t_1}^{t_2} A\,dt$	time average
$A'=A-\bar{A}$	deviation from time average
$[A]=(2\pi)^{-1}\int_0^{2\pi} A\,d\lambda$	zonal average
$A^*=A-[A]$	deviation from zonal average
$\langle A\rangle=(z_t-z_0)^{-1}\int_{z_0}^{z_t} A\,dz$	vertical average
$A''=A-\langle A\rangle$	deviation from vertical average

λ	longitude	a	radius of earth
ϕ	latitude	g	acceleration due to gravity
z	height of isobaric surface	c_v	specific heat at constant volume
p	pressure	c_p	specific heat at constant pressure
ρ	density	L	heat of condensation
T	temperature	u,v	west-to-east and south-to-north wind components
q	specific humidity		

Averaged over the year the total energy content of the Northern Hemisphere below 75 mb is 1.403×10^{23} cal. The potential energy, internal energy, latent heat and kinetic energy contribute, respectively, 24.6, 72.6, 2.8 and 0.05% to the total energy. The annual variation in the energy is shown in Fig. 1. Only the kinetic energy has a maximum in winter while all other components have a peak about 1.5 months following the summer solstice. Adding up the different energy components the amplitude of the annual variation amounts to 2.3%. Another interesting effect is the difference in curvature of the $PE+IE+LH+KE$ curve in summer and in winter. During winter, uniform conditions appear to prevail for a longer period than during summer.

The energy as a function of latitude and month is presented in Table 1. As mentioned before, all values are integrated from the surface up to 75 mb and over a zonal strip 1° latitude wide.[1] The rates of change of

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[1] It is rather surprising that the quotient of the vertical integrals of the potential and internal energy varies between 0.33 and 0.35, instead of being exactly equal to $R/c_v=0.40$ as one might expect. To explain this discrepancy one has to go back to the original derivation of the relation between PE and IE. The potential energy of a vertical column between the surface and the "top"

potential energy, internal energy, latent heat, kinetic energy and total energy are shown in Fig. 2. Since the values are calculated for latitude strips and not per unit mass, the effect of the decrease in length of a latitude circle from equator to pole is clearly noticeable. The diagram shows that the energy content in middle latitudes changes most rapidly in May and October. It is also of interest to note that the annual cycle at these latitudes does not have a regular sinusoidal shape. The time difference between largest positive and largest negative change is about 4.5 months in summer and 7.5 months in winter. Near the equator there is a clear semiannual variation in the rates of change of internal energy and of latent heat.

The energy content above 75 mb cannot be evaluated from our data. However, using the 1962 U. S. Standard Atmosphere we derive for the layer between 75 and 1 mb a density-weighted mean temperature and geopotential height of approximately 223K and 24 km. For the Northern Hemisphere this would be equivalent to an additional 110×10^{20} and 73×10^{20} cal in the form of potential and internal energy, respectively (compare Fig. 1).

4. Annual cycle mean and eddy fluxes

A knowledge of the meridional convergence of energy is, of course, necessary in order to be able to account for the observed structure of the atmosphere. In Section 5 we shall consider the other factors which together with the heating due to horizontal advection determine the structure.

The horizontal flux of energy passing through a latitudinal wall can be written as (see e.g., Starr, 1951)

$$F=F_{PE}+(F_{IE}+W)+F_{LH}+F_{KE},$$

where $W=\int\int\overline{pv}dxdz$ expresses the work done by the air south of the wall on the air north of it through the action of pressure forces. The flux of internal energy and the work term can be taken together as the flux of sensible heat. In general, the flux of kinetic energy is much smaller than any of the other fluxes. Nevertheless, for completeness, estimates of this flux are in-

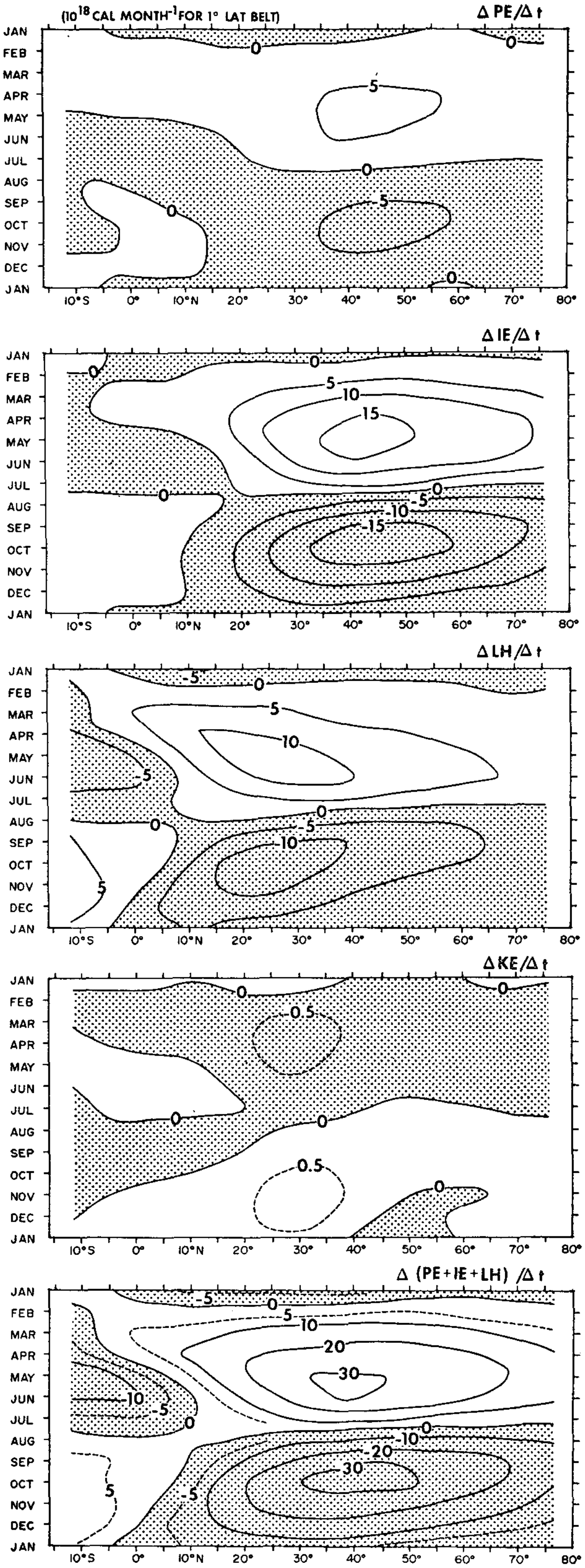

Fig. 2. The variation with latitude of the month-to-month changes in energy content (10^{18} cal month^{-1}) of the atmosphere, integrated between the surface and 75 mb and over a latitude strip 1° wide.

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of the atmosphere is given by

$$\int_{z_0}^{\infty}\rho g\,z dz.$$

Because of poor data coverage above 100 mb, the top level of integration was in this study chosen at 75 mb. Making use of the hydrostatic relation and the ideal gas law one can then derive

$$\int_{z_0}^{z_t}\rho\,PEdz=Rc_v^{-1}\int_{z_0}^{z_t}\rho\,IEdz-p_tz_t+p_0z_0.$$

The last two terms which cause the discrepancy are of opposite sign and are equal to the products of the pressure and the height at the top and bottom levels, respectively. In our case the main contribution is from the first term, $-p_tz_t$. One can verify that this term contributes -1.4×10^{20} cal at the equator. The second term, p_0z_0, is due to the topography of the earth's surface. Its contribution is smaller than that of the first term. However, the deviation from the R/c_v relation due to the topography is important since it will always be present independent of the height of the top level. In latitude belts with extensive mountain ranges, such as in the vicinity of 30N, it contributes $\sim0.5\times10^{20}$ cal.

TABLE 1. The energy content (10^{20} cal) of the atmosphere as a function of latitude and month of the year integrated between the surface and 75 mb for strips 1° latitude wide.

POTENTIAL ENERGY (10^{20}CAL FOR 1° LAT BELT)

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	6.11	6.18	6.20	6.17	6.10	5.99	5.80	5.54	5.18	4.82	4.45	4.08	3.67	3.25	2.81	2.35	1.89	1.42
FEB	6.11	6.18	6.20	6.17	6.11	5.99	5.80	5.54	5.18	4.82	4.45	4.08	3.68	3.25	2.81	2.35	1.89	1.42
MAR	6.11	6.18	6.20	6.17	6.11	5.99	5.81	5.55	5.20	4.83	4.47	4.10	3.70	3.27	2.83	2.36	1.90	1.43
APR	6.12	6.18	6.20	6.18	6.11	5.99	5.81	5.57	5.23	4.88	4.52	4.15	3.75	3.32	2.87	2.40	1.93	1.45
MAY	6.13	6.19	6.21	6.19	6.12	6.00	5.83	5.60	5.27	4.93	4.58	4.21	3.80	3.37	2.92	2.45	1.97	1.49
JUN	6.11	6.19	6.21	6.19	6.12	6.01	5.85	5.63	5.32	4.99	4.64	4.27	3.86	3.42	2.96	2.49	2.01	1.51
JUL	6.11	6.18	6.20	6.18	6.11	6.00	5.84	5.64	5.34	5.03	4.69	4.31	3.89	3.45	2.99	2.52	2.03	1.53
AUG	6.11	6.18	6.20	6.17	6.11	6.00	5.84	5.63	5.34	5.03	4.69	4.32	3.89	3.44	2.98	2.50	2.01	1.52
SEP	6.11	6.18	6.20	6.17	6.10	5.99	5.84	5.63	5.32	5.00	4.65	4.28	3.85	3.40	2.94	2.46	1.97	1.49
OCT	6.11	6.18	6.20	6.17	6.10	5.99	5.83	5.61	5.29	4.95	4.60	4.22	3.79	3.34	2.88	2.41	1.94	1.46
NOV	6.10	6.18	6.20	6.17	6.10	5.99	5.82	5.58	5.25	4.89	4.53	4.15	3.73	3.29	2.84	2.38	1.91	1.44
DEC	6.11	6.18	6.20	6.17	6.11	5.99	5.81	5.56	5.21	4.85	4.48	4.10	3.68	3.25	2.81	2.35	1.89	1.43
YEAR	6.11	6.18	6.20	6.17	6.11	5.99	5.82	5.59	5.26	4.92	4.56	4.19	3.77	3.34	2.88	2.42	1.94	1.46

INTERNAL ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	18.21	18.41	18.50	18.45	18.27	17.85	17.20	16.26	14.80	13.68	12.72	11.91	10.86	9.69	8.40	7.01	5.64	4.26
FEB	18.21	18.41	18.50	18.44	18.26	17.85	17.19	16.26	14.81	13.68	12.73	11.93	10.88	9.72	8.42	7.02	5.65	4.27
MAR	18.21	18.41	18.50	18.45	18.28	17.87	17.23	16.30	14.85	13.73	12.79	11.99	10.94	9.76	8.45	7.05	5.67	4.29
APR	18.20	18.42	18.51	18.46	18.30	17.90	17.28	16.38	14.96	13.86	12.93	12.14	11.09	9.90	8.58	7.17	5.77	4.36
MAY	18.20	18.43	18.53	18.47	18.32	17.95	17.37	16.50	15.09	14.01	13.09	12.30	11.24	10.05	8.73	7.31	5.90	4.46
JUN	18.16	18.39	18.49	18.44	18.29	17.95	17.42	16.60	15.23	14.17	13.26	12.47	11.40	10.20	8.87	7.44	6.01	4.56
JUL	18.14	18.36	18.47	18.41	18.26	17.93	17.42	16.64	15.31	14.29	13.39	12.59	11.51	10.30	8.96	7.52	6.07	4.60
AUG	18.14	18.37	18.47	18.42	18.27	17.94	17.42	16.64	15.32	14.29	13.39	12.59	11.50	10.28	8.93	7.48	6.04	4.57
SEP	18.14	18.38	18.48	18.43	18.28	17.94	17.41	16.60	15.25	14.19	13.27	12.45	11.37	10.15	8.80	7.36	5.93	4.48
OCT	18.17	18.39	18.49	18.43	18.28	17.92	17.35	16.50	15.11	14.02	13.08	12.27	11.19	9.98	8.64	7.22	5.81	4.39
NOV	18.17	18.39	18.49	18.44	18.27	17.88	17.27	16.39	14.96	13.85	12.90	12.08	11.01	9.82	8.50	7.10	5.72	4.33
DEC	18.19	18.40	18.50	18.44	18.27	17.86	17.22	16.30	14.86	13.74	12.78	11.97	10.91	9.73	8.42	7.03	5.66	4.28
YEAR	18.17	18.39	18.49	18.43	18.27	17.90	17.31	16.44	15.04	13.96	13.02	12.22	11.15	9.96	8.64	7.22	5.82	4.40

LATENT HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	1.18	1.19	1.18	1.09	.94	.77	.61	.48	.35	.27	.21	.17	.13	.10	.07	.05	.03	.02
FEB	1.18	1.20	1.18	1.08	.92	.75	.61	.48	.35	.27	.21	.16	.12	.09	.07	.05	.03	.02
MAR	1.17	1.23	1.23	1.13	.96	.79	.65	.51	.38	.29	.22	.18	.13	.10	.07	.05	.03	.02
APR	1.16	1.26	1.28	1.20	1.05	.89	.75	.60	.45	.35	.27	.22	.18	.14	.10	.07	.04	.03
MAY	1.07	1.21	1.28	1.25	1.15	1.01	.86	.70	.54	.43	.35	.30	.24	.19	.14	.10	.07	.04
JUN	.96	1.09	1.18	1.20	1.16	1.09	1.00	.86	.68	.55	.45	.39	.33	.27	.21	.16	.11	.07
JUL	.92	1.05	1.16	1.20	1.19	1.14	1.05	.93	.77	.66	.55	.48	.41	.34	.28	.21	.15	.10
AUG	.89	1.03	1.14	1.19	1.20	1.16	1.08	.96	.79	.67	.56	.48	.40	.33	.26	.19	.14	.09
SEP	.93	1.05	1.15	1.20	1.19	1.14	1.05	.91	.73	.58	.46	.39	.31	.25	.19	.14	.10	.06
OCT	.98	1.10	1.19	1.22	1.16	1.06	.93	.77	.59	.46	.36	.29	.22	.17	.13	.09	.06	.04
NOV	1.03	1.12	1.21	1.21	1.11	.95	.79	.63	.47	.36	.28	.22	.17	.13	.09	.06	.04	.03
DEC	1.12	1.19	1.22	1.16	1.02	.85	.68	.53	.39	.30	.23	.19	.14	.11	.08	.05	.03	.02
YEAR	1.05	1.14	1.20	1.18	1.09	.97	.84	.70	.54	.43	.35	.29	.23	.18	.14	.10	.07	.05

KINETIC ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.003	.004	.004	.005	.006	.008	.016	.027	.033	.030	.022	.017	.013	.011	.008	.006	.005	.004
FEB	.003	.004	.004	.005	.005	.008	.016	.028	.034	.030	.021	.015	.012	.010	.008	.006	.005	.003
MAR	.003	.003	.004	.004	.005	.007	.014	.024	.029	.026	.020	.014	.011	.009	.007	.005	.004	.003
APR	.003	.003	.003	.003	.004	.006	.011	.017	.020	.019	.016	.014	.012	.009	.007	.005	.003	.002
MAY	.004	.003	.003	.003	.004	.004	.007	.010	.013	.014	.013	.012	.010	.008	.006	.004	.003	.002
JUN	.004	.004	.004	.004	.004	.004	.004	.005	.008	.011	.011	.010	.009	.007	.005	.004	.003	.002
JUL	.004	.004	.004	.005	.005	.005	.005	.004	.004	.007	.010	.010	.008	.006	.004	.003	.003	.002
AUG	.004	.004	.004	.005	.005	.005	.004	.004	.004	.007	.010	.011	.010	.008	.005	.004	.003	.002
SEP	.003	.004	.004	.004	.004	.004	.004	.004	.006	.009	.012	.013	.012	.009	.007	.005	.003	.002
OCT	.003	.003	.003	.003	.003	.004	.005	.007	.011	.013	.015	.015	.014	.011	.008	.005	.004	.003
NOV	.003	.003	.003	.004	.004	.005	.008	.013	.018	.020	.019	.017	.014	.011	.008	.005	.004	.003
DEC	.003	.003	.003	.004	.005	.007	.013	.022	.028	.027	.022	.017	.014	.010	.007	.005	.004	.003
YEAR	.003	.003	.004	.004	.004	.006	.009	.014	.017	.018	.016	.014	.011	.009	.007	.005	.004	.003

TOTAL ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	25.49	25.78	25.89	25.71	25.32	24.62	23.63	22.31	20.38	18.80	17.41	16.17	14.67	13.04	11.28	9.42	7.56	5.71
FEB	25.51	25.78	25.87	25.69	25.29	24.59	23.62	22.30	20.38	18.80	17.41	16.18	14.69	13.07	11.31	9.43	7.57	5.70
MAR	25.49	25.82	25.94	25.75	25.35	24.66	23.70	22.38	20.45	18.88	17.50	16.28	14.78	13.14	11.36	9.47	7.60	5.74
APR	25.48	25.86	26.00	25.84	25.46	24.79	23.86	22.57	20.66	19.11	17.74	16.53	15.02	13.37	11.56	9.64	7.74	5.85
MAY	25.41	25.83	26.02	25.92	25.59	24.96	24.07	22.82	20.91	19.38	18.03	16.82	15.29	13.62	11.80	9.86	7.94	6.00
JUN	25.23	25.67	25.88	25.83	25.58	25.05	24.26	23.09	21.24	19.72	18.36	17.14	15.59	13.90	12.05	10.09	8.13	6.15
JUL	25.17	25.60	25.83	25.79	25.57	25.07	24.31	23.20	21.43	19.98	18.64	17.40	15.82	14.10	12.24	10.25	8.25	6.24
AUG	25.15	25.58	25.81	25.78	25.58	25.10	24.35	23.24	21.46	20.00	18.65	17.40	15.80	14.06	12.17	10.17	8.19	6.19
SEP	25.19	25.61	25.83	25.80	25.58	25.08	24.30	23.14	21.30	19.78	18.39	17.13	15.54	13.80	11.93	9.96	8.00	6.03
OCT	25.27	25.67	25.89	25.83	25.55	24.97	24.12	22.89	21.00	19.45	18.05	16.79	15.22	13.51	11.66	9.72	7.81	5.89
NOV	25.31	25.69	25.90	25.82	25.49	24.83	23.89	22.61	20.70	19.13	17.73	16.47	14.92	13.25	11.44	9.54	7.67	5.80
DEC	25.41	25.77	25.93	25.78	25.40	24.71	23.73	22.41	20.49	18.92	17.52	16.27	14.75	13.10	11.32	9.44	7.59	5.73
YEAR	25.33	25.71	25.89	25.78	25.47	24.86	23.98	22.74	20.86	19.32	17.94	16.71	15.17	13.49	11.67	9.75	7.84	5.92

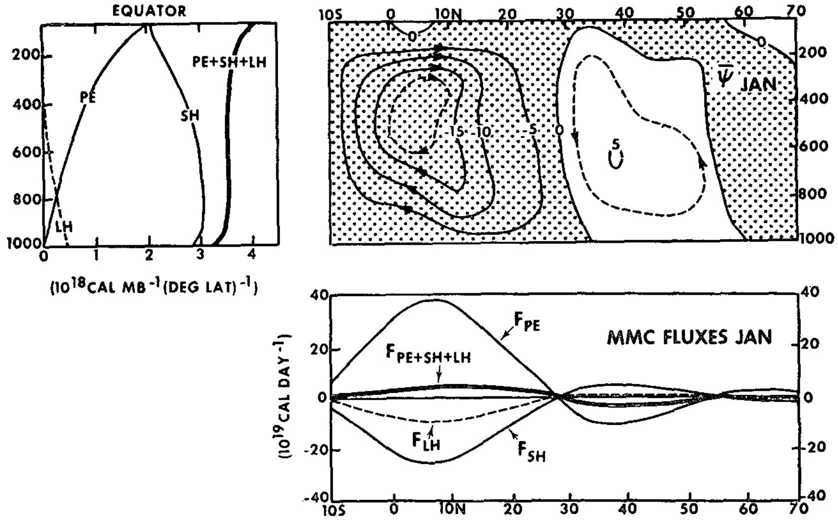

FIG. 3. Vertical distribution of potential energy, sensible and latent heat at the equator integrated over a latitude strip 1° wide and 1 mb thick (upper left); streamlines of the mean meridional circulation (10^{13} gm sec^{-1}) for January (upper right); and corresponding vertically integrated energy fluxes (10^{19} cal day^{-1}).

cluded in the tables. The northward flux of total energy can be rewritten as the average flux through a unit area of the wall multiplied by the total area of the wall (c_1), i.e.,

$$F=c_1\{g\langle[\overline{\rho vz}]\rangle+c_p\langle[\overline{\rho vT}]\rangle+L\langle[\overline{\rho vq}]\rangle+\langle[\overline{\rho vKE}]\rangle\},$$

where

$$c_1=2\pi a\cos\phi(z_t-z_0).$$

Since we are interested in the details of the transfer mechanism, we shall divide the zonal mean and time mean fluxes into three different terms. For example, the flux of potential energy can be written as

$$[\overline{\rho vz}]=[\overline{\rho v}][\bar{z}]+\rho[\overline{v'z'}]+\rho[\bar{v}^*\bar{z}^*].$$

On the right-hand side appear the contributions by the mean meridional circulation, the transient eddies, and the standing or stationary eddies.

a. Mean fluxes

The flux due to the mean meridional circulation is given by

$$F_M=c_1\{g\langle[\overline{\rho v}][\bar{z}]\rangle+c_p\langle[\overline{\rho v}][\bar{T}]\rangle+L\langle[\overline{\rho v}][\bar{q}]\rangle+\langle[\overline{\rho v}][\overline{KE}]\rangle\}.$$

The value of the vertically integrated mass flow, $\langle[\overline{\rho v}]\rangle$, is very small, and only deviations from the vertical average play a role in the transfer (see discussion in ORa). First of all one has to measure the vertical distribution of the energy components before the effects of a mean meridional overturning can be evaluated. The results are illustrated in Fig. 3. The energy increase from the surface to 900 mb is in a way artificial; it is due to the rapid increase in volume of the atmospheric layer because less of the volume is taken up by mountains. Except for the layer below 900 mb the agreement with the results of Palmén *et al.* (1958) is very good. It is found that specific potential energy increases with altitude, while, on the other hand, sensible and latent heat both decrease with altitude. This means that the Northern Hemisphere Hadley cell will transport potential energy northward and sensible plus latent heat southward. Since the sum of the three components increases with altitude, the net effect will be an energy transport northward. In an analogous fashion the Ferrel cell in middle latitudes will cause a southward flow of potential energy, a northward flow of sensible plus latent heat, and a net energy flow southward.

The individual energy fluxes are surprisingly large (Table 2, Fig. 4). However, compensation between the fluxes of potential energy and of sensible plus latent heat reduces the net transfer by the powerful Hadley cell to a value smaller than the mid-latitude eddy transfer. We shall see later that one cannot conclude from this that the Hadley cell is of less importance than the eddy circulations in the overall picture of the energy cycle.

The net energy divergence and energy convergence are large in the rising and sinking branches of the Hadley cell and give rise to adiabatic cooling and heating rates of several degrees Celcius per day (see Fig. 11). The more detailed energy cycle in the Hadley cell appears to be as follows. Latent and to a lesser degree sensible heat are accumulated by the low-level air during its travel along the earth's surface from the subtropics to the region of rising motion in the equatorial trough zone. Latent heat is then converted into internal en-

TABLE 2. The meridional flux of energy (10^{19} cal day^{-1}) by the mean meridional circulations as a function of latitude and month of the year integrated between the surface and 75 mb. Note the differences in the fluxes calculated as the straight average of the 12 monthly fluxes (MEAN), and those calculated using the annual mean analyses (YEAR). In the case of the transient and standing eddies these differences are significant (see text) and not due to inaccuracy in the computation.

MMC FLUX POTENTIAL ENERGY (10^{19} CAL DAY^{-1})

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	6.7	18.4	30.8	37.5	37.2	26.5	16.0	7.9	-4.1	-10.2	-8.9	-6.5	-4.6	-.1	2.4	2.8	2.1	.9
FEB	7.1	23.2	40.3	44.0	38.6	26.7	15.3	5.6	-5.5	-11.1	-10.2	-7.7	-6.6	-3.5	-.7	.8	.7	2.0
MAR	-2.1	16.2	35.9	42.2	36.6	24.3	12.2	5.6	.9	-1.9	-1.7	-1.3	-1.1	.1	.6	1.7	2.6	2.3
APR	-18.7	-3.7	12.3	25.2	27.3	19.0	9.2	2.0	-2.4	-4.8	-3.4	-1.2	-1.1	1.0	1.4	.9	.9	.4
MAY	-30.6	-20.8	-9.7	4.5	12.4	12.3	6.6	.7	-3.3	-5.3	-6.1	-3.3	-1.7	-.3	1.2	2.3	2.4	.9
JUN	-39.5	-32.5	-21.8	-11.8	-5.1	-3.9	-8.3	-8.5	-5.0	-2.0	-2.5	-2.2	-2.8	-1.6	-.1	.5	1.6	2.3
JUL	-42.8	-40.3	-30.3	-16.1	-4.8	1.2	1.1	-.5	-2.6	-1.5	-1.6	-3.1	-4.4	-2.6	-.4	.9	1.3	.9
AUG	-40.0	-40.1	-31.1	-18.2	-7.8	-1.8	-1.3	-1.4	-2.8	-2.4	-2.2	-3.1	-4.3	-2.3	.2	1.1	1.9	1.9
SEP	-39.2	-35.0	-26.3	-16.9	-8.7	-.9	4.5	7.0	5.2	2.4	-2.5	-4.8	-4.9	-2.6	-1.4	-.4	.3	.5
OCT	-29.3	-23.4	-13.9	-3.0	5.0	10.1	12.6	11.6	6.4	2.4	-.5	-2.0	-3.8	-1.8	.9	1.7	1.8	2.1
NOV	-14.2	-6.8	7.5	19.2	25.2	24.2	17.8	11.2	3.5	-1.0	-2.9	-4.1	-5.1	-3.9	-1.9	.1	.9	.6
DEC	-1.3	11.2	24.6	33.6	37.3	31.1	19.8	9.3	.8	-3.6	-4.3	-3.4	-2.6	-.5	1.5	3.3	3.4	1.3
MEAN	-20.3	-11.1	1.5	11.7	16.1	14.1	8.8	4.2	-.7	-3.2	-3.9	-3.6	-3.6	-1.5	.3	1.3	1.7	1.3
YEAR	-20.3	-11.1	1.5	11.6	16.1	14.1	8.8	4.2	-.7	-3.3	-3.9	-3.6	-3.6	-1.5	.3	1.3	1.7	1.3

MMC FLUX SENSIBLE HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-4.7	-12.3	-20.5	-24.9	-24.3	-16.9	-9.7	-4.4	2.4	5.4	4.7	3.5	2.3	.1	-1.1	-1.2	-.9	-.5
FEB	-4.9	-15.5	-26.8	-29.3	-25.4	-17.1	-9.4	-3.3	3.1	5.9	5.2	3.7	2.9	1.4	.2	-.2	-.3	-.8
MAR	1.2	-10.9	-23.9	-28.1	-24.2	-15.7	-7.6	-3.3	-.5	1.1	1.2	.9	.5	-.2	-.2	-.5	-.9	-.8
APR	12.2	2.4	-8.2	-16.5	-17.9	-12.3	-5.6	-1.0	1.5	2.8	2.4	1.2	.9	-.3	-.5	-.4	-.5	-.3
MAY	19.8	13.3	6.3	-2.8	-8.0	-7.9	-4.0	-.3	2.0	3.1	3.7	2.3	1.4	.4	-.5	-.9	-.9	-.3
JUN	25.1	20.6	14.0	7.8	3.4	2.6	5.5	5.5	3.1	1.2	1.6	1.5	1.7	1.0	.1	-.3	-.9	-1.0
JUL	26.8	25.7	19.4	10.4	3.2	-.7	-.6	.5	1.7	1.0	.9	1.7	2.4	1.4	.3	-.3	-.5	-.2
AUG	25.0	25.5	19.9	11.8	5.2	1.2	1.0	1.1	1.9	1.6	1.4	1.8	2.4	1.3	-.1	-.6	-.8	-.7
SEP	25.3	22.5	17.0	11.1	5.8	.7	-2.6	-4.0	-3.0	-1.3	1.7	2.9	2.7	1.4	.7	.2	-.1	-.2
OCT	19.1	15.0	8.9	2.0	-3.1	-6.3	-7.9	-7.1	-3.8	-1.4	.3	1.1	2.0	.9	-.5	-.9	-.8	-.7
NOV	9.3	4.3	-5.2	-12.7	-16.4	-15.5	-11.0	-6.6	-2.0	.6	1.6	2.2	2.7	1.9	.8	-.1	-.4	-.3
DEC	.8	-7.7	-16.6	-22.4	-24.5	-19.9	-12.0	-5.3	-.5	1.8	2.1	1.7	1.2	.0	-.7	-1.3	-1.3	-.6
MEAN	12.9	6.9	-1.3	-7.8	-10.5	-9.0	-5.3	-2.3	.5	1.8	2.2	2.0	1.9	.8	-.1	-.5	-.7	-.5
YEAR	13.0	7.0	-1.2	-7.7	-10.5	-9.0	-5.4	-2.4	.5	1.9	2.3	2.0	1.9	.7	-.1	-.6	-.7	-.6

MMC FLUX LATENT HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-1.3	-4.4	-7.2	-8.7	-8.8	-6.2	-3.4	-1.5	.2	.9	.9	.6	.4	.1	-.1	-.1	-.1	-.0
FEB	-1.6	-5.7	-9.4	-10.1	-9.1	-6.3	-3.3	-1.2	.5	1.0	.9	.6	.4	.2	.0	-.0	-.0	-.0
MAR	.6	-3.7	-8.2	-9.3	-8.1	-5.5	-2.8	-1.1	.0	.4	.4	.3	.1	.0	-.0	-.0	-.0	-.0
APR	5.3	1.8	-2.4	-5.9	-6.7	-5.1	-3.0	-1.2	.1	.7	.6	.4	.3	.0	-.0	-.0	-.0	-.0
MAY	8.0	6.8	3.9	-.7	-3.4	-3.7	-2.5	-1.1	.1	.6	.8	.6	.4	.1	-.1	-.1	-.1	-.0
JUN	9.6	9.5	7.2	3.9	1.5	.6	.8	.8	.7	.5	.7	.6	.6	.3	.1	-.1	-.1	-.1
JUL	10.2	11.0	9.4	5.5	2.2	.1	-.6	-.6	.2	.3	.5	.7	.8	.5	.1	.0	-.1	-.0
AUG	9.2	10.7	9.4	6.0	2.8	.5	-.4	-.6	.1	.3	.4	.6	.8	.5	.1	-.1	-.1	-.1
SEP	8.9	9.3	8.0	5.2	2.5	-.2	-2.1	-2.6	-1.6	-.6	.5	.9	.8	.4	.2	.1	-.0	-.0
OCT	6.5	6.7	5.1	1.9	-1.4	-3.4	-3.7	-3.0	-1.5	-.5	.2	.5	.6	.3	-.0	-.1	-.1	-.1
NOV	3.3	2.6	-.2	-3.8	-6.7	-6.9	-4.9	-2.8	-.8	.2	.5	.6	.5	.3	.1	.0	-.0	-.0
DEC	.5	-1.9	-4.9	-7.6	-9.2	-7.6	-4.7	-2.3	-.4	.4	.5	.4	.3	.1	-.0	-.1	-.1	-.0
MEAN	4.9	3.5	.9	-1.9	-3.7	-3.6	-2.5	-1.4	-.2	.4	.6	.6	.5	.2	.0	-.0	-.1	-.0
YEAR	5.2	3.8	1.0	-2.1	-4.0	-3.9	-2.8	-1.5	-.2	.5	.7	.6	.5	.2	.0	-.1	-.1	-.1

MMC FLUX KINETIC ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.00	.01	.02	.03	.03	.04	.04	.05	-.01	-.08	-.08	-.04	-.02	-.00	.00	.00	.00	.00
FEB	.00	.01	.03	.03	.02	.03	.06	.05	-.05	-.11	-.08	-.04	-.01	.00	.01	.00	-.00	.00
MAR	.00	.01	.02	.02	.02	.03	.03	.03	-.00	-.04	-.05	-.02	-.00	.01	.00	.00	.00	.00
APR	-.00	-.00	.00	.01	.01	.02	.02	-.00	-.02	-.05	-.05	-.03	-.02	-.00	.00	.00	.00	.00
MAY	-.01	-.01	-.00	-.00	.00	.01	.00	.00	-.00	-.02	-.03	-.03	-.02	-.01	.00	.00	.00	.00
JUN	-.01	-.01	-.01	-.01	-.00	-.00	-.01	-.01	-.01	-.01	-.03	-.02	-.01	-.01	-.00	.00	.00	.00
JUL	-.02	-.02	-.02	-.02	-.00	.00	.00	-.00	-.00	-.01	-.02	-.02	-.01	-.00	-.00	-.00	-.00	-.00
AUG	-.01	-.02	-.03	-.02	-.01	-.00	-.00	-.00	-.00	-.01	-.02	-.02	-.02	-.00	.00	.00	.00	-.00
SEP	-.01	-.02	-.02	-.01	-.01	-.00	.00	.00	.01	.00	-.02	-.04	-.03	-.01	-.00	.00	.00	.00
OCT	-.01	-.01	-.01	-.00	.00	.00	.01	.02	.02	.01	-.01	-.02	-.02	-.01	.00	.01	.00	.00
NOV	-.00	-.00	.00	.01	.01	.01	.02	.03	.02	-.00	-.03	-.03	-.02	-.01	.00	.00	.00	.00
DEC	-.00	.00	.01	.02	.02	.04	.05	.06	.03	-.03	-.05	-.03	-.01	.00	.01	.00	.00	.00
MEAN	-.01	-.00	-.00	.00	.01	.01	.02	.02	-.00	-.03	-.04	-.03	-.02	-.00	.00	.00	.00	.00
YEAR	-.01	-.00	.00	.01	.01	.01	.01	.01	-.00	-.02	-.03	-.03	-.01	-.00	.00	.00	.00	.00

MMC FLUX TOTAL ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.7	1.7	3.2	4.0	4.1	3.5	3.0	2.0	-1.5	-3.9	-3.4	-2.5	-1.9	.0	1.3	1.6	1.1	.4
FEB	.6	2.1	4.1	4.7	4.2	3.3	2.6	1.2	-2.0	-4.3	-4.2	-3.4	-3.3	-2.0	-.4	.5	.4	1.2
MAR	-.3	1.6	3.8	4.8	4.4	3.1	1.9	1.2	.4	-.4	-.2	-.1	-.5	-.1	.3	1.1	1.6	1.4
APR	-1.2	.4	1.8	2.8	2.7	1.6	.6	-.1	-.8	-1.3	-.5	.4	.1	.7	.9	.5	.3	.1
MAY	-2.8	-.7	.4	1.0	1.1	.8	.1	-.6	-1.2	-1.6	-1.6	-.5	-.0	.2	.6	1.2	1.4	.5
JUN	-4.8	-2.4	-.6	-.1	-.1	-.7	-2.0	-2.2	-1.3	-.3	-.2	-.2	-.5	-.3	.1	.1	.6	1.2
JUL	-5.8	-3.7	-1.6	-.2	.6	.6	-.1	-.6	-.7	-.2	-.2	-.8	-1.3	-.8	.0	.6	.8	.6
AUG	-5.7	-4.0	-1.8	-.4	.1	-.1	-.7	-1.0	-.8	-.5	-.4	-.7	-1.1	-.6	.1	.5	.9	1.2
SEP	-5.1	-3.1	-1.3	-.6	-.4	-.3	-.2	.4	.6	.5	-.4	-1.1	-1.4	-.8	-.4	-.1	.2	.3
OCT	-3.7	-1.7	.1	.8	.5	.4	1.0	1.6	1.1	.5	.0	-.4	-1.3	-.7	.4	.7	1.0	1.3
NOV	-1.6	.1	2.1	2.7	2.1	1.8	1.9	1.8	.7	-.3	-.8	-1.3	-2.0	-1.7	-1.0	-.0	.4	.3
DEC	-.1	1.7	3.1	3.6	3.7	3.7	3.1	1.8	-.1	-1.5	-1.7	-1.3	-1.0	-.4	.7	1.9	2.0	.6
MEAN	-2.5	-.7	1.1	1.9	1.9	1.5	.9	.4	-.5	-1.1	-1.1	-1.0	-1.2	-.5	.2	.7	.9	.7
YEAR	-2.1	-.3	1.3	1.9	1.6	1.2	.7	.3	-.4	-.9	-1.0	-.9	-1.2	-.6	.2	.7	.9	.7

ergy. Next the internal energy is converted into potential energy and the air becomes rather cold. The vertical transfer in this zone probably takes place in the form of "hot" towering cumulonimbus clouds as was proposed by Riehl and Malkus (1958). After its arrival at high levels the relatively cold air is transported by the upper branch of the Hadley cell back to the subtropics, where it becomes warm again in the sinking branch of the cell. In other words, here its potential energy is converted back into internal energy. This cycle appears to be an efficient process for cooling the atmosphere near the equator and heating it in the subtropics of the winter hemisphere by adiabatic processes. Thus, the mean circulation in the meridional plane tends to steepen the temperature gradient in middle latitudes necessary for the development of baroclinic waves.

One can pose the question as to whether the seasonal cycle in the mean meridional circulation contributes to the poleward transfer of energy. It would seem plausible that during the course of a year the strength of the meridional circulation at a certain latitude be correlated with, for example, the vertical temperature structure at the same latitude. If this is the case, one should find significantly different values for the yearly mean meridional flux of heat computed as the average of the 12 monthly fluxes (see MEAN in Table 2) and for the mean meridional flux computed using the yearly mean circulation and the yearly mean temperature structure (see YEAR in Table 2). However, the numbers in the table show that this is not the case. Thus, one can conclude that the strong seasonal cycle in the mean meridional circulation does *not* contribute to the annual mean poleward flow of energy.[2] We shall see later that in the case of the annual flux of sensible and latent heat due to the *standing* eddies there does exist an important seasonal eddy contribution.

b. Eddy fluxes

The northward flux of energy due to the transient and stationary eddy circulations is given by

$$F_E = F_{TE} + F_{SE},$$

where

$$\left.\begin{aligned} F_{TE} &= c_1\{g\langle\rho[\overline{v'z'}]\rangle + c_p\langle\rho[\overline{v'T'}]\rangle \\ &\qquad + L\langle\rho[\overline{v'q'}]\rangle + \langle\rho[\overline{v'KE'}]\rangle\} \\ F_{SE} &= c_1\{g\langle\rho[\bar{v}^*\bar{Z}^*]\rangle + c_p\langle\rho[\bar{v}^*\bar{T}^*]\rangle \\ &\qquad + L\langle\rho[\bar{v}^*\bar{q}^*]\rangle + \langle\rho[\bar{v}^*\overline{KE}^*]\rangle\} \end{aligned}\right\}.$$

Proceeding northward from the equator, the longitudinal asymmetries in the circulation become more and more important and at middle and high latitudes they tend to dominate over the mean circulation as the preferred mechanism of energy transfer (Tables 3 and 4, Figs. 5 and 6). However, the transfer of potential energy by the eddies is negligible at all latitudes. Thus, we shall limit the discussion to the fluxes of sensible and latent heat.

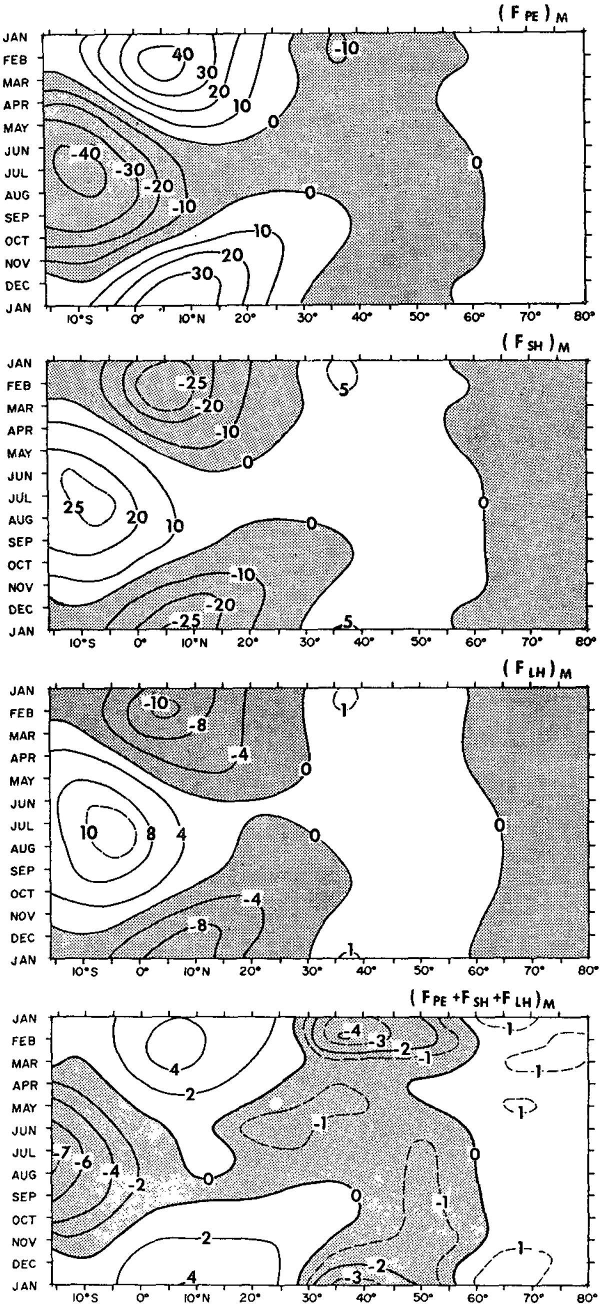

FIG. 4. The annual variation of the meridional fluxes of potential energy, sensible heat and latent heat by the mean meridional circulation: all units 10^{19} cal day^{-1}.

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[2] It is of interest to note that there does exist at least one parameter for which the seasonal eddy is important, i.e., the flux of relative angular momentum (not presented here). In the case of angular momentum we have found that there is a positive correlation between the intensity of the Northern Hemisphere Hadley cell and the strength of the high-level westerly flow, as one would expect in view of the conservation of absolute angular momentum. This effect is most pronounced at about 10–15N. An analogous relation was found for the Southern Hemisphere.

TABLE 3. The meridional flux of energy (10^{19} cal day^{-1}) by the transient eddy circulations as a function of latitude and month of the year integrated between the surface and 75 mb.

TE FLUX POTENTIAL ENERGY $(10^{19}$ CAL DAY$^{-1})$

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.02	.01	-.02	-.05	-.07	-.06	-.02	-.06	-.14	-.24	-.25	-.19	-.06	.04	.06	.02	.01	.05
FEB	.09	.06	.04	.00	-.02	-.02	-.07	-.21	-.34	-.41	-.38	-.29	-.16	-.02	.04	-.06	-.08	-.01
MAR	.05	-.02	-.06	-.07	-.07	-.10	-.15	-.14	-.11	-.13	-.19	-.17	-.13	-.10	-.08	-.09	-.04	.01
APR	-.01	-.02	-.00	.01	.01	-.01	-.04	-.10	-.19	-.21	-.22	-.21	-.20	-.15	-.10	-.06	-.01	.01
MAY	.03	.01	.01	.02	.01	-.01	-.03	-.06	-.09	-.13	-.21	-.23	-.20	-.10	-.01	.01	.00	-.01
JUN	.09	.04	.02	.01	-.00	-.00	-.02	-.06	-.08	-.09	-.06	-.04	-.04	-.07	-.05	-.04	-.06	-.07
JUL	.05	.01	.01	-.00	-.01	-.02	-.00	.01	-.00	-.03	-.08	-.13	-.14	-.08	-.01	-.00	-.02	-.02
AUG	.03	.04	.03	.01	-.01	-.02	-.01	-.02	-.05	-.06	-.03	-.03	-.10	-.11	-.08	-.03	.02	.03
SEP	.02	.04	.03	.00	-.01	-.02	-.02	-.04	-.09	-.12	-.13	-.11	.06	-.03	-.05	-.06	-.02	.04
OCT	-.03	-.03	-.04	-.04	-.05	-.07	-.08	-.08	-.07	-.04	-.06	-.11	.12	-.06	-.00	.00	-.01	-.00
NOV	-.00	-.01	-.01	-.03	-.06	-.08	-.07	-.05	-.06	-.08	-.06	-.03	-.13	-.19	-.15	-.09	-.04	-.02
DEC	-.04	-.01	-.00	-.01	-.02	-.05	-.10	-.09	.01	.03	-.05	-.05	-.07	-.12	-.07	-.01	-.01	-.03
MEAN	.03	.01	.00	-.01	-.03	-.04	-.05	-.08	-.10	-.13	-.14	-.13	-.12	-.08	-.04	-.03	-.02	-.00
YEAR	.04	.03	.02	.01	-.03	-.07	-.11	-.13	-.10	-.05	-.08	-.12	-.15	-.15	-.09	-.08	-.07	-.05

TE FLUX SENSIBLE HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-.1	-.1	-.3	-.6	-.8	-.6	.1	1.4	2.9	3.7	3.8	3.6	3.6	3.6	3.3	2.5	1.9	1.2
FEB	.0	-.2	-.2	-.2	-.2	.0	.8	2.1	3.5	4.4	4.4	4.2	3.7	3.2	2.8	2.2	1.8	1.2
MAR	.0	-.1	-.4	-.6	-.7	-.7	-.2	1.3	3.5	4.9	4.9	4.2	3.7	3.2	2.6	2.1	1.7	1.2
APR	-.1	-.2	-.2	-.2	-.2	-.2	.2	1.3	2.8	4.2	5.2	5.2	4.5	3.6	2.8	2.3	1.7	1.1
MAY	.2	.0	-.0	-.0	-.1	-.2	-.2	.3	1.5	2.8	3.7	4.0	4.0	3.4	2.6	1.9	1.4	.8
JUN	.4	.1	-.0	-.2	-.3	-.3	-.3	-.1	.4	1.1	1.8	2.7	3.1	2.7	2.1	1.7	1.2	.8
JUL	.3	.1	.1	.0	-.1	-.2	-.2	-.1	.1	.7	1.5	2.1	2.5	2.4	1.9	1.4	1.0	.6
AUG	.0	.2	.2	.1	-.0	-.2	-.3	-.2	.1	.8	1.8	2.6	2.8	2.3	1.8	1.4	1.1	.9
SEP	-.2	-.0	-.1	-.1	-.1	-.2	-.3	-.0	.4	1.2	2.3	3.3	3.9	3.6	2.8	1.9	1.3	1.0
OCT	.0	.1	-.0	-.2	-.3	-.3	-.2	.4	1.3	2.3	3.4	4.2	4.4	3.9	3.0	2.1	1.4	.9
NOV	-.3	-.3	-.2	-.2	-.2	-.2	.1	1.1	2.3	3.4	4.3	4.9	4.3	3.4	2.7	2.2	1.8	1.3
DEC	.1	.1	-.0	-.2	-.3	-.4	-.1	1.1	2.7	3.9	4.2	4.4	4.1	3.4	2.8	2.5	1.8	1.0
MEAN	.0	-.0	-.1	-.2	-.3	-.3	-.0	.7	1.8	2.8	3.4	3.8	3.7	3.2	2.6	2.0	1.5	1.0
YEAR	-.1	-.1	-.2	-.2	-.3	-.3	-.1	.8	2.1	3.3	4.1	4.5	4.5	3.8	2.9	2.2	1.5	.9

TE FLUX LATENT HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-.8	-.0	.6	1.1	1.3	1.5	2.0	2.8	3.1	2.9	2.4	1.9	1.4	1.1	.8	.6	.4	.2
FEB	-.6	-.0	.5	.9	1.0	1.2	1.9	2.9	3.3	3.1	2.5	1.9	1.4	1.1	.8	.6	.4	.3
MAR	-.8	-.0	.5	.8	.9	1.0	1.6	2.6	3.1	2.9	2.4	1.8	1.3	1.0	.7	.5	.4	.3
APR	-.9	-.5	-.1	.3	.6	.9	1.4	2.2	2.7	2.8	2.5	2.2	1.7	1.3	.9	.6	.4	.2
MAY	-1.0	-.5	-.1	.4	.9	1.1	1.4	2.0	2.5	2.7	2.6	2.3	1.9	1.5	1.0	.7	.5	.3
JUN	-.9	-.5	-.2	.2	.5	.7	.7	1.0	1.3	1.5	1.6	1.8	1.7	1.4	1.1	.8	.5	.3
JUL	-.9	-.5	-.2	.1	.4	.5	.4	.5	.8	1.4	1.9	2.0	2.0	1.7	1.2	.9	.6	.4
AUG	-.8	-.5	-.3	-.0	.4	.6	.5	.5	.8	1.3	1.8	1.9	1.8	1.5	1.2	.9	.6	.4
SEP	-.8	-.4	-.1	.0	.4	.6	.8	1.1	1.6	2.1	2.5	2.5	2.3	1.8	1.4	.9	.6	.4
OCT	-.7	-.3	-.2	-.0	.5	1.1	1.6	2.2	2.6	2.9	2.8	2.6	2.2	1.6	1.2	.7	.4	.2
NOV	-.7	-.3	-.0	.3	.7	1.1	1.7	2.4	2.8	2.8	2.6	2.4	1.8	1.3	.9	.6	.3	.2
DEC	-.7	-.1	.5	1.0	1.3	1.5	1.9	2.7	3.2	3.0	2.5	2.1	1.6	1.2	.9	.6	.4	.2
MEAN	-.8	-.3	.0	.4	.7	1.0	1.3	1.9	2.3	2.4	2.3	2.1	1.8	1.4	1.0	.7	.5	.3
YEAR	-1.3	-.6	-.0	.6	1.2	1.5	1.8	2.3	2.6	2.7	2.6	2.3	1.9	1.5	1.1	.7	.5	.3

TE FLUX KINETIC ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.01	.01	.01	.01	.01	.02	.05	.12	.24	.25	.15	.09	.07	.07	.04	.01	-.00	-.00
FEB	.01	.01	.02	.01	.01	.02	.09	.22	.34	.27	.11	.06	.09	.12	.08	.03	.00	-.01
MAR	.01	.01	.02	.01	.01	.03	.08	.13	.19	.15	.04	.00	.03	.04	.03	.01	.01	.00
APR	-.00	.00	.00	.00	.01	.04	.11	.19	.24	.18	.05	-.01	-.00	.01	-.00	-.01	-.00	-.00
MAY	-.01	-.00	-.00	.00	.00	.02	.04	.08	.12	.12	.06	.01	-.01	-.01	-.01	-.00	-.00	-.01
JUN	.00	-.00	-.01	-.01	-.00	-.00	.00	.02	.06	.09	.08	.06	.03	.01	-.01	-.01	.00	-.00
JUL	-.01	-.02	-.02	-.01	-.01	-.01	-.01	-.00	.01	.02	.04	.04	.02	.01	-.00	-.01	-.01	-.01
AUG	-.01	-.01	-.02	-.02	-.01	-.00	-.01	.00	.01	.05	.07	.07	.04	.01	.00	-.00	-.01	-.01
SEP	-.00	-.01	-.01	-.01	-.00	-.00	.00	.01	.04	.06	.07	.06	.02	.01	.01	.01	.00	-.00
OCT	-.00	-.01	-.01	-.01	-.01	-.00	.00	.03	.08	.10	.10	.08	.04	.00	-.00	-.00	-.01	-.01
NOV	-.00	.00	.00	.00	.00	.01	.03	.08	.14	.16	.13	.08	.04	.04	.05	.04	.02	.01
DEC	-.00	.00	.01	.01	.00	.01	.06	.13	.19	.19	.10	.03	.01	.03	.03	.01	.00	-.00
MEAN	-.00	-.00	-.00	-.00	.00	.01	.04	.08	.14	.14	.08	.05	.03	.03	.02	.01	-.00	-.00
YEAR	-.00	-.00	-.00	-.00	-.00	.01	.04	.10	.15	.15	.10	.05	.03	.02	.01	.00	-.00	-.00

TE FLUX TOTAL ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-.9	-.1	.3	.4	.4	.8	2.1	4.2	6.0	6.6	6.1	5.4	5.0	4.8	4.2	3.1	2.3	1.5
FEB	-.5	-.1	.3	.7	.8	1.2	2.7	5.1	6.8	7.3	6.6	5.9	5.0	4.4	3.7	2.8	2.1	1.4
MAR	-.7	-.1	.1	.2	.1	.2	1.3	3.9	6.6	7.8	7.1	5.9	4.9	4.1	3.3	2.5	2.1	1.5
APR	-1.0	-.7	-.3	.1	.4	.7	1.7	3.6	5.5	6.9	7.5	7.2	6.0	4.7	3.6	2.8	2.0	1.3
MAY	-.8	-.5	-.2	.4	.8	.9	1.2	2.3	3.9	5.5	6.1	6.1	5.7	4.8	3.7	2.7	1.9	1.2
JUN	-.5	-.4	-.2	-.0	.2	.3	.4	.9	1.7	2.6	3.5	4.5	4.8	4.1	3.1	2.4	1.7	1.0
JUL	-.6	-.4	-.2	.1	.3	.3	.2	.4	.9	2.1	3.3	4.1	4.4	4.0	3.1	2.3	1.6	1.0
AUG	-.8	-.2	-.1	.1	.4	.4	.2	.3	.9	2.1	3.6	4.6	4.5	3.8	2.9	2.2	1.7	1.3
SEP	-.9	-.3	-.2	-.0	.2	.4	.6	1.0	1.9	3.3	4.7	5.8	6.1	5.4	4.1	2.8	1.9	1.4
OCT	-.7	-.3	-.3	-.2	.1	.7	1.4	2.5	3.9	5.2	6.2	6.8	6.5	5.5	4.2	2.8	1.8	1.1
NOV	-.9	-.6	-.2	.1	.4	.8	1.8	3.5	5.2	6.3	7.1	7.3	6.1	4.5	3.5	2.7	2.0	1.4
DEC	-.6	-.0	.4	.8	1.0	1.0	1.7	3.8	6.1	7.1	6.8	6.5	5.7	4.5	3.7	3.1	2.2	1.2
MEAN	-.7	-.3	-.0	.2	.4	.6	1.3	2.6	4.1	5.2	5.7	5.8	5.4	4.5	3.6	2.7	1.9	1.3
YEAR	-1.4	-.7	-.2	.4	.8	1.1	1.7	3.1	4.8	6.2	6.7	6.8	6.3	5.1	4.0	2.8	1.9	1.1

Table 4. The meridional flux of energy (10^{19} cal day^{-1}) by the standing or stationary eddy circulations as a function of latitude and month of the year integrated between the surface and 75 mb.

SE FLUX POTENTIAL ENERGY (10^{19} CAL DAY^{-1})

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.01	.00	-.01	-.03	-.03	-.03	-.01	-.01	-.08	-.09	.01	.05	-.07	-.12	.07	.07	-.04	-.01
FEB	.01	.01	-.00	-.02	-.03	-.05	-.07	-.08	-.11	-.08	.04	.09	.08	.09	.15	.05	-.03	.02
MAR	.01	.01	.00	-.00	-.00	-.00	.02	.01	-.06	-.07	.04	.09	.09	.11	.07	-.00	-.03	-.00
APR	.00	.00	.00	.00	.01	.02	.05	.06	.03	.03	.09	.10	.07	.06	.07	.04	.00	.01
MAY	.01	.01	.01	.00	-.02	-.03	-.04	-.06	-.06	-.03	.01	.05	.07	.08	.06	.03	.02	.02
JUN	.00	.01	.02	.01	-.03	-.06	-.06	-.04	-.06	-.06	-.04	-.03	-.01	.02	.03	.02	.02	.02
JUL	.01	.01	.01	.01	-.03	-.06	-.06	-.02	-.02	-.05	-.03	.02	.04	.03	.02	.00	-.02	-.04
AUG	.01	.02	.02	.02	.00	-.02	-.03	-.01	-.02	-.03	-.01	.01	.01	.00	-.00	-.00	-.00	.00
SEP	.01	.02	.02	.02	.01	-.01	-.03	-.03	-.04	-.00	.03	.04	.04	.02	-.03	-.07	-.05	-.00
OCT	.00	.01	.01	.01	.00	-.00	-.02	-.05	-.05	-.02	-.03	-.00	.07	.08	.02	-.08	-.10	-.05
NOV	.00	.01	.00	-.01	-.02	-.03	-.02	-.03	-.08	-.11	-.18	-.10	.13	.26	.23	.04	-.06	-.01
DEC	.01	.01	-.01	-.03	-.04	-.05	-.05	-.06	-.12	-.14	-.09	-.05	.02	.14	.14	.02	-.01	.03
MEAN	.01	.01	.01	-.00	-.02	-.03	-.03	-.03	-.05	-.06	-.01	.02	.05	.06	.07	.01	-.03	-.00
YEAR	.01	.01	.01	.01	.00	.00	.01	.01	-.01	-.01	.02	.04	.06	.07	.06	.01	-.01	.01

SE FLUX SENSIBLE HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-.1	-.1	-.0	.0	.0	.0	.2	.7	1.3	2.3	3.7	5.4	6.0	4.8	3.0	1.3	.1	-.2
FEB	-.0	-.0	-.0	-.1	-.1	-.2	-.1	.2	.7	1.3	2.1	3.6	4.9	4.9	3.6	1.5	.1	-.1
MAR	.0	-.0	-.0	-.0	-.1	-.2	-.1	.0	.2	.4	1.2	2.3	2.9	2.9	2.2	1.0	-.0	-.3
APR	-.0	-.0	-.0	-.0	-.0	-.0	.0	.2	.3	.3	.4	.9	1.4	1.6	1.3	.6	.0	-.1
MAY	-.0	.0	.1	.1	.0	-.1	-.1	.0	.4	.2	-.0	.0	.2	.4	.4	.3	.2	.1
JUN	-.0	.0	.1	.1	.2	.1	-.0	-.2	-.0	-.1	-.3	-.5	-.6	-.5	-.1	.0	.2	.2
JUL	-.1	-.0	.0	.1	.1	.0	-.2	-.2	.0	.1	-.2	-.3	-.4	-.3	-.2	-.1	-.1	-.1
AUG	-.1	-.0	.0	-.0	.0	-.1	-.3	-.4	-.2	-.1	-.2	-.2	-.3	-.3	-.2	-.0	-.0	.0
SEP	-.1	-.1	-.0	.0	.0	-.0	-.1	-.0	.3	.4	.4	.4	.4	.4	.4	.3	.2	.2
OCT	-.1	-.0	.0	.0	.0	.0	.0	.1	.4	.5	.7	1.2	1.7	1.9	1.6	.8	.2	.0
NOV	-.1	-.0	-.0	.0	.1	.1	.2	.3	.4	.6	.9	2.0	3.5	4.1	3.6	2.0	.8	.3
DEC	-.1	-.1	-.1	-.1	-.1	.0	.1	.3	.5	1.0	1.9	3.6	4.6	4.3	2.7	.8	-.1	-.2
MEAN	-.0	-.0	.0	.0	.0	-.0	-.0	.1	.4	.6	.9	1.5	2.0	2.0	1.5	.7	.1	-.0
YEAR	-.0	-.0	-.0	.0	.0	.0	.1	.1	.2	.2	.4	.8	1.2	1.4	1.1	.5	.1	-.0

SE FLUX LATENT HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-.1	-.1	-.0	.1	.2	.3	.5	.6	.6	.7	.8	.8	.7	.5	.2	.1	-.0	-.0
FEB	-.1	-.1	-.1	.0	.2	.4	.6	.5	.5	.5	.5	.6	.7	.6	.4	.1	.0	-.0
MAR	-.1	-.1	-.0	-.0	.2	.7	.9	.7	.4	.2	.3	.5	.5	.4	.3	.1	-.0	-.1
APR	-.1	-.1	-.0	.0	.2	.7	.9	.8	.5	.3	.2	.2	.3	.3	.2	.0	-.0	-.0
MAY	-.1	-.0	-.0	.0	.4	.9	1.2	1.0	.5	.2	-.0	-.1	-.0	.0	.0	.0	-.0	-.0
JUN	.0	.1	.1	.1	.5	1.2	1.9	2.0	1.2	.4	-.0	-.3	-.3	-.2	-.0	.0	.1	.1
JUL	.0	.1	.1	.1	.3	.7	1.5	2.2	1.9	1.1	.4	-.0	-.2	-.1	-.0	.0	.0	-.0
AUG	-.0	.0	-.0	-.0	.0	.3	.9	1.6	1.5	.9	.4	-.0	-.1	-.1	-.0	.0	.0	.0
SEP	.0	.1	.0	.0	.1	.3	.7	1.0	.8	.4	.2	.1	.1	.1	.1	.1	.1	.0
OCT	.0	-.0	-.1	-.0	.2	.4	.6	.7	.5	.3	.1	.2	.3	.4	.3	.2	.0	-.0
NOV	-.0	-.0	-.1	-.0	.0	.0	.1	.3	.4	.3	.2	.3	.5	.5	.5	.3	.1	.0
DEC	-.1	-.1	-.0	.0	.0	.2	.3	.3	.3	.4	.4	.6	.6	.5	.3	.1	-.0	-.0
MEAN	-.1	-.0	-.0	.0	.2	.5	.9	1.0	.7	.5	.3	.2	.2	.2	.2	.1	.0	-.0
YEAR	-.1	-.0	-.0	-.1	.0	.3	.5	.6	.4	.1	-.0	-.0	.1	.1	.1	.1	.0	-.0

SE FLUX KINETIC ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.00	.00	-.00	-.00	-.00	-.01	.02	.09	.12	.13	.08	.05	.04	.03	.01	-.01	-.01	.00
FEB	.00	.00	.00	-.00	-.00	-.00	.03	.08	.10	.10	.07	.07	.08	.09	.05	.00	-.01	.00
MAR	.00	.00	-.00	-.00	-.00	-.00	.01	.05	.08	.07	.04	.03	.02	.02	.01	-.01	-.01	-.00
APR	.00	.00	.00	-.00	-.00	-.01	-.01	.00	.01	.02	.01	.02	.02	.01	-.00	-.00	-.00	.00
MAY	.00	.00	.00	-.00	-.00	.00	.01	.02	.02	.01	-.01	-.01	-.01	-.01	-.01	-.01	-.00	-.00
JUN	.00	.00	-.00	-.01	-.01	-.00	-.00	.00	.02	.01	.00	.01	.02	.01	.00	-.00	.00	.00
JUL	.00	.00	-.00	-.01	-.01	-.01	-.01	-.00	.00	.01	.00	-.00	-.00	-.00	.00	.00	-.00	-.00
AUG	.00	-.00	-.00	-.01	-.01	-.01	-.01	-.00	.01	.01	.00	.00	.01	.00	.00	-.00	-.00	-.00
SEP	.00	-.00	-.00	-.00	-.00	.00	.00	.01	.02	.03	.02	.02	.01	.02	.01	.01	.00	.00
OCT	.00	.00	.00	.00	.00	.00	.01	.01	.03	.06	.08	.09	.08	.06	.03	.01	-.00	-.00
NOV	.00	.00	.00	.00	.00	.00	.01	.05	.10	.11	.09	.09	.08	.07	.04	.02	.00	.00
DEC	-.00	-.00	-.00	-.00	-.00	-.00	.01	.04	.08	.11	.07	.05	.04	.04	.01	-.00	-.01	-.00
MEAN	.00	.00	-.00	-.00	-.00	-.00	.01	.03	.05	.06	.04	.03	.03	.03	.01	-.00	-.00	-.00
YEAR	.00	.00	-.00	.00	.00	.00	.01	.01	.02	.02	.02	.03	.04	.03	.01	.00	-.00	-.00

SE FLUX TOTAL ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-.2	-.2	-.0	.1	.2	.3	.8	1.4	1.9	3.0	4.5	6.3	6.7	5.1	3.3	1.4	.1	-.2
FEB	-.2	-.2	-.1	-.1	.0	.2	.4	.7	1.2	1.8	2.7	4.4	5.7	5.7	4.2	1.7	.1	-.1
MAR	-.1	-.1	-.0	-.0	.1	.5	.8	.7	.5	.6	1.6	2.9	3.5	3.4	2.6	1.1	-.1	-.4
APR	-.1	-.1	-.0	.0	.2	.6	1.0	1.0	.9	.7	.7	1.2	1.8	2.0	1.5	.6	.0	-.1
MAY	-.1	.0	.0	.1	.4	.8	1.1	1.0	.8	.4	-.0	.0	.2	.5	.5	.4	.2	.1
JUN	.0	.1	.2	.2	.6	1.2	1.8	1.8	1.1	.3	-.3	-.7	-.9	-.6	-.2	.1	.2	.3
JUL	-.1	.1	.1	.2	.3	.6	1.3	2.0	1.9	1.1	.2	-.4	-.5	-.5	-.2	-.0	-.1	-.2
AUG	-.1	-.0	.0	-.0	.1	.2	.6	1.2	1.3	.9	.2	-.2	-.4	-.4	-.2	-.0	.0	.0
SEP	-.0	.0	.0	.0	.1	.2	.5	1.0	1.1	.9	.6	.6	.5	.5	.5	.3	.2	.2
OCT	-.1	-.0	-.0	.0	.2	.5	.6	.8	.8	.8	.8	1.5	2.2	2.5	2.0	.9	.1	-.0
NOV	-.1	-.1	-.1	-.0	.1	.1	.2	.6	.8	.9	1.1	2.4	4.2	5.0	4.3	2.4	.8	.3
DEC	-.2	-.1	-.1	-.1	-.1	.1	.4	.6	.8	1.3	2.3	4.1	5.2	5.0	3.2	1.0	-.2	-.2
MEAN	-.1	-.0	.0	.0	.2	.4	.8	1.1	1.1	1.1	1.2	1.8	2.3	2.3	1.8	.8	.1	-.0
YEAR	-.1	-.1	-.0	-.0	.1	.3	.6	.7	.6	.4	.4	.9	1.4	1.6	1.3	.6	.1	-.0

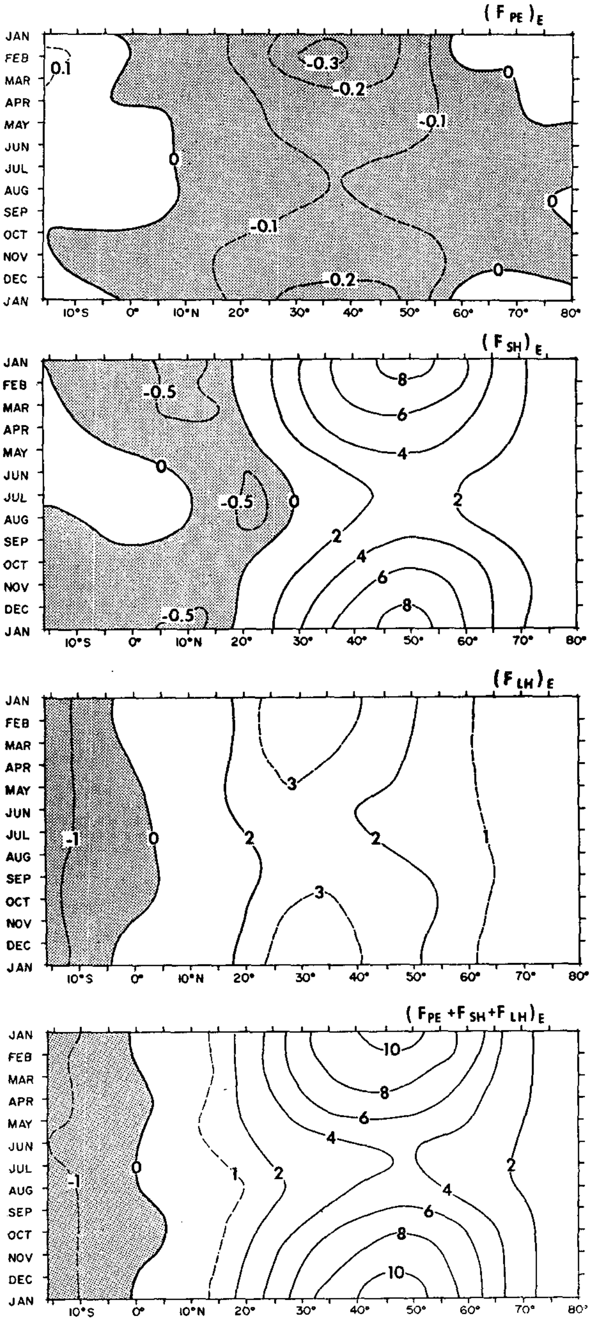

FIG. 5. The annual variation of the meridional fluxes of potential energy, sensible heat and latent heat by the transient plus standing eddy circulations: all units 10^{19} cal day^{-1}.

Peixóto (1960), Wiin Nielsen *et al.* (1964) and other investigators have found that the maximum flux of sensible heat occurs in winter and that it is accomplished mainly by large-scale transient waves. The present study confirms the existence of a winter maximum due to transient plus standing waves. However, the bulk of the mid-winter transport is not accomplished by the transient waves, but by the standing or stationary waves. These standing waves are very important in December through February. In spring and fall the transient waves take over the task of transporting heat poleward. If one studies the vertical distribution of the transient eddy flux, one finds two layers of strong northward transport of sensible heat, one below 500 mb and the other between 300 and 100 mb. A harmonic analysis of these features shows that the lower maximum is strongest during fall and winter but that the upper maximum very surprisingly has only a small annual variation with the tendency of a maximum in summer. The vertically integrated flux has maximum values in April and November (see also ORb).

At low latitudes in summer we find a weak, northward flow of sensible heat, while the flow is predominantly southward during the rest of the year. This southward flux was discussed before by Starr and Wallace (1964) using Peixóto's statistics for the year 1950. In summer the standing eddies transport sensible heat equatorward at almost all latitudes; the transient eddies dominate outside the tropics and cause a small net heat flux poleward.

The eddy flow of latent heat is of considerable importance between 20 and 40N. Rasmusson (1970) has pointed out the large standing eddy flux of latent heat in summer, which is associated with the Asian monsoon and the oceanic high pressure cells. This is the only eddy flux with a maximum in summer. For a comparison of some of our results with those of earlier investigators see Figs. 7 and 9.

The potential and kinetic energy fluxes[3] are relatively small and generally have opposite signs. The eddy flux of potential energy is mainly equatorward and has a maximum in winter between 30 and 40N. This flux from middle latitudes is one of the possible sources of kinetic energy for the eddies in the tropics as shown by Mak (1969) and Holopainen (1969). However, it appears more likely that the main source of eddy kinetic energy is the local conversion of eddy available potential energy generated by the heat of condensation (Manabe and Smagorinsky, 1967; Manabe *et al.*, 1970).

The fluxes by both mean and eddy circulations together are given in Table 5 and Fig. 8. Indirect estimates of these fluxes by Rakipova (1966) for the yearly mean conditions are in rather good agreement with the present results (see Fig. 9). The main differences are at low latitudes where our calculations show a more equatorward displacement of the maximum transports. Our values compare well with those of Holopainen (1965) and Kidson *et al.* (1969).

If one averages the twelve monthly values of $[\bar{v}^*\bar{T}^*]$ (see MEAN in Table 4) one finds a larger value than if one would compute the flux from the annual mean

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[3] In the calculation of the transient eddy flux of kinetic energy terms containing third-order time correlations were neglected, i.e.,

$$(F_{KE})_{TE}=c_1\langle\rho[\overline{v'KE'}]\rangle=c_1\{\langle\rho[\overline{v'u'}\,\bar{u}]\rangle+\langle\rho[\overline{v'v'}\,\bar{v}]\rangle\}.$$

This approximation is perhaps not valid in view of the results of a study by Saltzman *et al.* (1961).

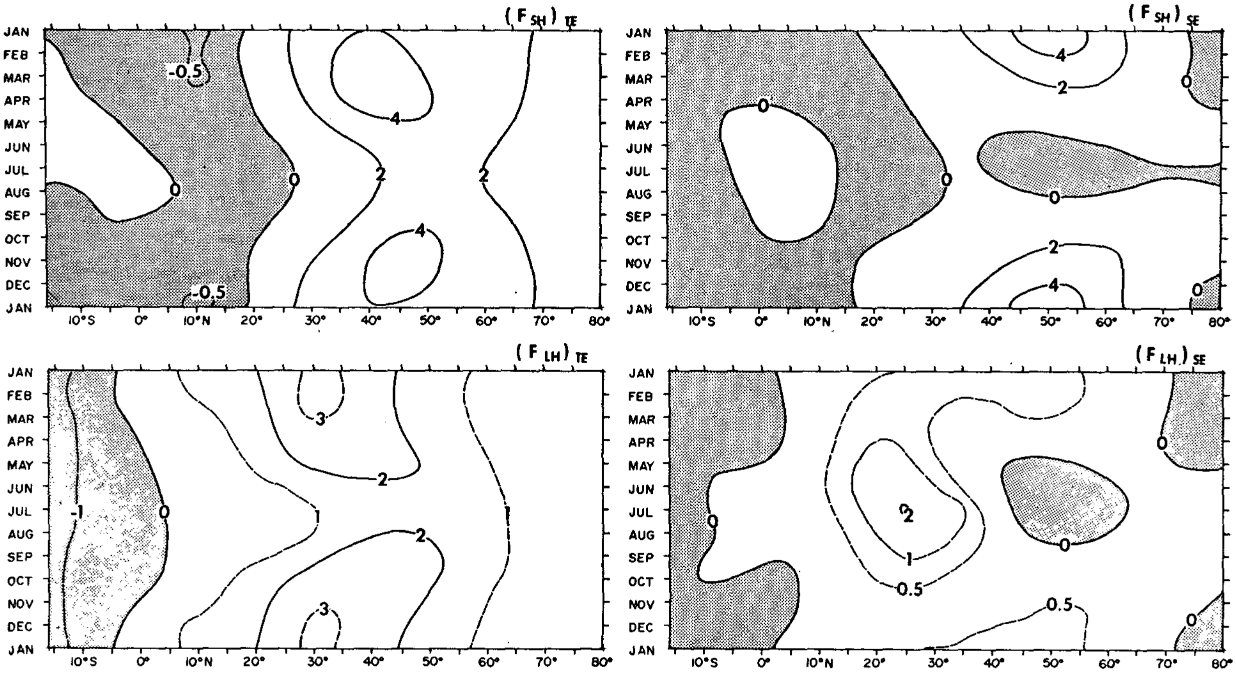

FIG. 6. The annual variation of the transient and standing eddy fluxes (10^{19} cal day^{-1}) of sensible and latent heat.

flow field and the annual mean temperature or humidity fields (see YEAR in Table 4). One can interpret this as a positive contribution from the annual cycle in the monthly-mean flow field to the northward transport of heat. On an annual basis this contribution is counted as a transient eddy. One can indeed verify that the sum of the transient and stationary eddy fluxes are the same by adding up the corresponding values for MEAN and YEAR in Tables 3 and 4.

Since we have used data from five years to compute the statistics for each calendar month, it would seem possible that inter-annual variability could also contribute significantly to the eddy fluxes. However, we have found that this is not the case.

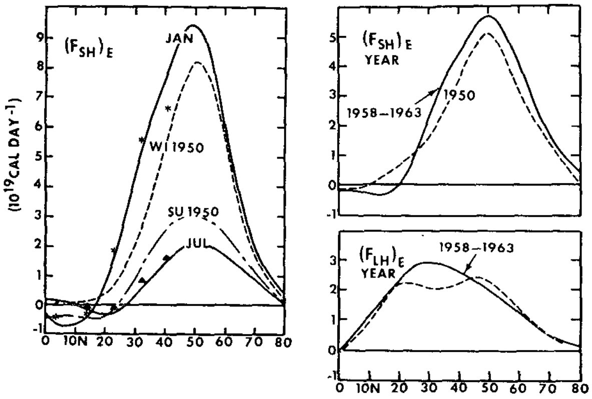

FIG. 7. The meridional flux of sensible heat by transient plus standing eddies for January and July compared with Peixóto's (1960) results for the winter and summer half year of 1950 (left), the estimates by Kidson *et al.* (1969) for December–February and June–August being shown by stars and triangles; and the annual mean eddy fluxes of sensible and latent heat compared with Peixóto's (1960, 1965) results for the year 1950 (right).

5. The overall energy balance

One of the obvious checks on the computed energy fluxes is to compare them with estimates of the other factors important in the heat balance of the atmosphere. One can then determine if the necessary balance is accomplished. The energy flux above 75 mb (the top level of integration in this study) is probably of the order of a few percent of the total energy flux and can be safely neglected here. Disregarding errors, our estimates of the horizontal convergence of total energy should thus be balanced at each latitude by the sum of three effects: 1) the energy flux from the earth's surface, 2) the net radiation cooling, and 3) the storage of energy in the atmosphere. From global maps of the flux of sensible and latent heat from the earth's surface

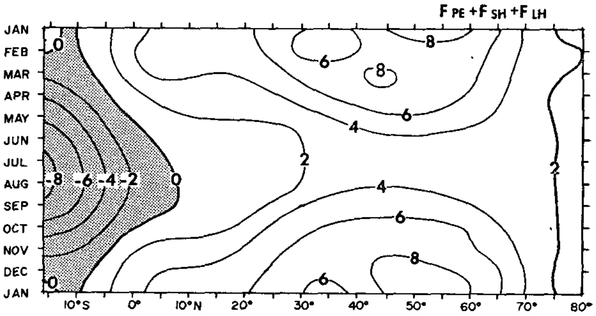

FIG. 8. The annual variation of the meridional flux of total energy (10^{19} cal day^{-1}).

TABLE 5. The meridional flux of energy (10^{19} cal day^{-1}) by mean plus eddy circulations as a function of latitude and month of the year integrated between the surface and 75 mb.

FLUX POTENTIAL ENERGY (10^{19}CAL DAY^{-1})

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	6.8	18.4	30.8	37.4	37.1	26.4	16.0	7.8	-4.3	-10.5	-9.2	-6.7	-4.7	-.2	2.6	2.9	2.1	1.0
FEB	7.2	23.3	40.3	44.0	38.6	26.6	15.2	5.3	-6.0	-11.6	-10.6	-7.8	-6.7	-3.4	-.5	.8	.6	2.0
MAR	-2.0	16.2	35.8	42.1	36.6	24.2	12.1	5.5	.7	-2.1	-1.9	-1.4	-1.2	.1	.6	1.6	2.5	2.3
APR	-18.7	-3.8	12.3	25.2	27.3	19.0	9.2	2.0	-2.6	-5.0	-3.6	-1.3	-1.2	.9	1.4	.9	.9	.4
MAY	-30.5	-20.8	-9.7	4.5	12.4	12.3	6.5	.6	-3.4	-5.4	-6.3	-3.5	-1.8	-.3	1.2	2.4	2.4	.9
JUN	-39.4	-32.4	-21.8	-11.8	-5.1	-4.0	-8.4	-8.6	-5.1	-2.1	-2.6	-2.3	-2.8	-1.6	-.1	.5	1.6	2.3
JUL	-42.7	-40.3	-30.2	-16.1	-4.9	1.1	1.0	-.5	-2.6	-1.6	-1.7	-3.2	-4.5	-2.7	-.4	.9	1.3	.8
AUG	-39.9	-40.1	-31.1	-18.2	-7.8	-1.8	-1.4	-1.5	-2.9	-2.5	-2.2	-3.1	-4.4	-2.5	.1	1.1	1.9	2.0
SEP	-39.2	-34.9	-26.3	-16.9	-8.7	-.9	4.4	6.9	5.1	2.3	-2.6	-4.9	-4.9	-2.6	-1.5	-.5	.3	.5
OCT	-29.3	-23.4	-13.9	-3.1	4.9	10.0	12.5	11.5	6.3	2.4	-.6	-2.1	-3.9	-1.8	.9	1.6	1.7	2.0
NOV	-14.2	-6.8	7.5	19.1	25.1	24.1	17.7	11.1	3.3	-1.2	-3.2	-4.3	-5.1	-3.9	-1.8	.0	.8	.6
DEC	-1.3	11.2	24.6	33.5	37.2	31.0	19.7	9.2	.7	-3.7	-4.4	-3.5	-2.6	-.4	1.6	3.3	3.3	1.3
MEAN	-20.3	-11.1	1.5	11.7	16.1	14.0	8.7	4.1	-.9	-3.4	-4.1	-3.7	-3.7	-1.5	.4	1.3	1.6	1.3
YEAR	-20.2	-11.1	1.5	11.6	16.0	14.0	8.7	4.1	-.9	-3.3	-4.0	-3.7	-3.7	-1.6	.3	1.3	1.6	1.3

FLUX SENSIBLE HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-4.9	-12.5	-20.8	-25.5	-25.1	-17.4	-9.4	-2.3	6.6	11.4	12.2	12.5	11.8	8.4	5.2	2.7	1.0	.5
FEB	-4.9	-15.7	-27.0	-29.6	-25.6	-17.2	-8.8	-.9	7.3	11.5	11.7	11.5	11.5	9.5	6.6	3.6	1.6	.3
MAR	1.3	-11.0	-24.3	-28.7	-25.1	-16.6	-7.9	-2.0	3.1	6.4	7.3	7.5	7.1	5.8	4.6	2.6	.8	.1
APR	12.1	2.2	-8.4	-16.7	-18.2	-12.5	-5.3	.5	4.6	7.4	8.0	7.3	6.8	4.9	3.6	2.4	1.2	.7
MAY	19.9	13.4	6.3	-2.8	-8.1	-8.2	-4.3	.0	3.8	6.2	7.4	6.3	5.5	4.2	2.6	1.3	.6	.6
JUN	25.4	20.8	14.1	7.8	3.3	2.4	5.1	5.2	3.4	2.1	3.2	3.7	4.2	3.3	2.1	1.4	.5	-.0
JUL	27.1	25.8	19.5	10.5	3.3	-.9	-1.0	.1	1.9	1.8	2.2	3.5	4.5	3.4	1.9	1.0	.5	.3
AUG	25.0	25.7	20.1	11.9	5.2	.9	.4	.5	1.9	2.4	3.1	4.2	4.9	3.3	1.5	.8	.3	.2
SEP	25.0	22.5	17.0	11.0	5.8	.5	-3.0	-4.1	-2.2	.4	4.4	6.6	7.0	5.4	3.9	2.4	1.4	1.0
OCT	19.1	15.1	8.9	1.8	-3.4	-6.6	-8.0	-6.6	-2.2	1.4	4.3	6.5	8.2	6.7	4.1	2.1	.9	.2
NOV	9.0	3.9	-5.4	-12.9	-16.6	-15.6	-10.7	-5.2	.7	4.6	6.9	9.2	10.5	9.4	7.1	4.2	2.1	1.2
DEC	.9	-7.7	-16.7	-22.6	-24.9	-20.3	-12.0	-4.0	2.7	6.6	8.2	9.7	10.0	7.7	4.8	2.0	.3	.2
MEAN	12.9	6.9	-1.4	-8.0	-10.8	-9.3	-5.4	-1.5	2.6	5.2	6.6	7.4	7.7	6.0	4.0	2.2	.9	.4
YEAR	12.9	6.9	-1.4	-7.9	-10.7	-9.3	-5.4	-1.5	2.8	5.5	6.7	7.4	7.6	5.8	3.9	2.1	.9	.3

FLUX LATENT HEAT

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-2.3	-4.5	-6.6	-7.5	-7.3	-4.4	-.9	1.8	3.9	4.5	4.0	3.4	2.5	1.6	1.0	.6	.3	.2
FEB	-2.3	-5.8	-9.0	-9.2	-8.0	-4.8	-.9	2.2	4.3	4.6	3.8	3.1	2.4	1.8	1.2	.7	.4	.2
MAR	-.3	-3.9	-7.8	-8.5	-7.0	-3.9	-.3	2.2	3.4	3.6	3.1	2.6	1.9	1.4	1.0	.6	.3	.2
APR	4.3	1.2	-2.5	-5.5	-5.9	-3.6	-.7	1.8	3.3	3.7	3.3	2.8	2.3	1.6	1.0	.6	.3	.2
MAY	7.0	6.2	3.7	-.3	-2.1	-1.7	.2	2.0	3.0	3.4	3.4	2.8	2.2	1.6	1.0	.6	.4	.3
JUN	8.7	9.0	7.1	4.2	2.5	2.4	3.5	3.8	3.2	2.5	2.3	2.1	2.0	1.5	1.1	.8	.4	.2
JUL	9.2	10.5	9.2	5.8	2.9	1.3	1.4	2.1	2.9	2.8	2.7	2.6	2.6	2.0	1.3	.9	.6	.3
AUG	8.4	10.2	9.1	5.9	3.2	1.4	1.1	1.5	2.3	2.6	2.6	2.6	2.5	1.9	1.3	.8	.5	.3
SEP	8.1	9.0	7.8	5.3	2.9	.8	-.5	-.4	.7	2.0	3.2	3.5	3.2	2.3	1.7	1.1	.6	.4
OCT	5.8	6.3	4.8	1.8	-.8	-1.9	-1.5	-.1	1.6	2.6	3.2	3.3	3.1	2.3	1.5	.8	.3	.1
NOV	2.6	2.3	-.3	-3.5	-6.0	-5.9	-3.2	-.1	2.3	3.3	3.4	3.3	2.8	2.1	1.5	.8	.4	.2
DEC	-.3	-2.1	-4.5	-6.6	-7.8	-5.9	-2.5	.8	3.1	3.8	3.4	3.1	2.5	1.8	1.2	.6	.3	.2
MEAN	4.1	3.2	.9	-1.5	-2.8	-2.2	-.4	1.4	2.8	3.3	3.2	2.9	2.5	1.8	1.2	.7	.4	.2
YEAR	3.9	3.2	.9	-1.5	-2.8	-2.2	-.4	1.4	2.8	3.4	3.3	3.0	2.5	1.8	1.2	.7	.4	.2

FLUX KINETIC ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	.01	.02	.04	.04	.03	.05	.11	.26	.35	.30	.15	.09	.09	.10	.05	-.00	-.01	.00
FEB	.01	.02	.05	.04	.02	.05	.17	.35	.38	.25	.10	.09	.16	.21	.14	.04	-.01	-.00
MAR	.01	.02	.03	.03	.03	.06	.11	.20	.27	.18	.03	.00	.04	.06	.04	.01	-.00	.00
APR	-.01	.00	.00	.01	.02	.05	.12	.19	.23	.16	.02	-.02	-.00	.01	-.00	-.01	-.00	-.00
MAY	-.02	-.01	-.01	-.00	.01	.02	.05	.10	.13	.11	.01	-.03	-.03	-.02	-.02	-.01	-.00	-.01
JUN	-.01	-.02	-.03	-.03	-.02	-.01	-.00	.02	.07	.09	.05	.05	.04	.01	-.01	-.01	.00	.00
JUL	-.02	-.04	-.05	-.04	-.02	-.01	-.02	-.01	.01	.03	.03	.02	.00	.00	-.00	-.01	-.01	-.02
AUG	-.02	-.04	-.05	-.04	-.02	-.01	-.01	-.00	.02	.05	.06	.05	.03	.01	.00	-.00	-.01	-.02
SEP	-.01	-.02	-.03	-.02	-.01	-.00	.00	.02	.06	.09	.07	.04	.01	.02	.02	.02	.01	.00
OCT	-.01	-.01	-.01	-.01	-.00	-.00	.02	.06	.12	.17	.17	.15	.10	.06	.03	.01	-.01	-.01
NOV	-.00	-.00	.01	.01	.01	.02	.06	.16	.26	.27	.20	.14	.10	.10	.09	.06	.03	.01
DEC	-.00	.01	.02	.02	.02	.05	.13	.23	.30	.26	.12	.04	.04	.07	.05	.01	-.00	-.01
MEAN	-.01	-.01	-.00	.00	.01	.02	.06	.13	.18	.16	.08	.05	.05	.05	.03	.01	-.00	-.00
YEAR	-.01	-.01	-.00	.00	.01	.02	.06	.12	.17	.15	.08	.05	.05	.05	.03	.01	-.00	-.00

FLUX TOTAL ENERGY

	10S	5S	EQ	5N	10N	15N	20N	25N	30N	35N	40N	45N	50N	55N	60N	65N	70N	75N
JAN	-.4	1.4	3.4	4.5	4.7	4.6	5.8	7.5	6.4	5.7	7.2	9.2	9.8	9.9	8.8	6.1	3.4	1.6
FEB	.0	1.8	4.3	5.3	5.0	4.7	5.7	7.0	6.0	4.8	5.1	6.9	7.5	8.1	7.5	5.1	2.6	2.5
MAR	-1.1	1.4	3.8	4.9	4.6	3.8	4.0	5.8	7.5	8.0	8.5	8.7	7.9	7.4	6.1	4.8	3.6	2.5
APR	-2.3	-.4	1.5	2.9	3.3	2.9	3.3	4.5	5.6	6.3	7.8	8.7	7.9	7.4	6.0	3.9	2.4	1.3
MAY	-3.7	-1.2	.3	1.5	2.2	2.5	2.4	2.7	3.5	4.3	4.5	5.6	5.9	5.4	4.8	4.3	3.5	1.8
JUN	-5.2	-2.6	-.6	.1	.7	.8	.2	.5	1.5	2.6	3.0	3.5	3.4	3.1	3.0	2.6	2.5	2.5
JUL	-6.4	-4.1	-1.6	.1	1.3	1.5	1.4	1.7	2.2	3.0	3.2	2.9	2.6	2.7	2.9	2.8	2.3	1.5
AUG	-6.6	-4.2	-1.9	-.3	.6	.5	.1	.6	1.3	2.4	3.4	3.7	2.9	2.7	2.9	2.7	2.7	2.5
SEP	-6.1	-3.4	-1.5	-.6	-.0	.3	.9	2.4	3.6	4.7	5.0	5.3	5.3	5.1	4.2	3.0	2.3	1.9
OCT	-4.4	-2.0	-.2	.6	.8	1.5	3.1	4.9	5.8	6.6	7.1	7.9	7.5	7.3	6.6	4.5	2.9	2.3
NOV	-2.6	-.6	1.8	2.8	2.5	2.7	3.9	5.9	6.7	7.0	7.4	8.4	8.3	7.8	6.9	5.1	3.3	1.9
DEC	-.8	1.5	3.5	4.4	4.6	4.8	5.3	6.2	6.8	6.9	7.4	9.3	9.9	9.1	7.6	6.0	4.0	1.7
MEAN	-3.3	-1.0	1.1	2.2	2.5	2.5	3.0	4.1	4.7	5.2	5.8	6.7	6.6	6.4	5.6	4.2	3.0	2.0
YEAR	-3.5	-1.1	1.1	2.2	2.5	2.6	3.0	4.1	4.9	5.6	6.1	6.7	6.5	6.1	5.4	4.1	2.8	1.8

constructed by Budyko (1964), zonal mean values were calculated for each season and for the year (curve 1, Fig. 10). The radiative heating in the shortwave part of the spectrum and the radiative cooling in the longwave part as given by London (1957) were used to calculate the net radiative cooling in the Northern Hemisphere (curve 2). The net change in energy (curve 3) and the energy convergence due to horizontal fluxes (curve 4) were evaluated from our data.

In view of the fact that many assumptions had to be made by Budyko and London in their calculations, the comparison with our results is perhaps encouraging. In winter the estimated convergence seems to be too large at 30N. The overestimation of the southward velocities at high levels in the Ferrel cell at about 35N seems to be the reason for the too strong convergence at 30N and the too strong divergence at 40N (compare Fig. 13 in ORa). In the other seasons (except at 15N in summer) there appears to be fair agreement between the different components in the heat balance. In general, our curves for the energy convergence are less smooth than either Budyko's or London's, but this does not mean that they are necessarily less accurate. For the annual mean conditions the agreement is even rather good.

An interesting effect in our data is the asymmetry with respect to the equator in all seasons. It seems that the energy divergence is always larger just south of the equator than north of it. The curves of Budyko tend to show a stronger upward flux of heat south of the equator which could balance this excess divergence. However, we cannot pursue this question further because London's radiative estimates only apply to the Northern Hemisphere. The asymmetry may well be connected with the asymmetry in ocean-continent distribution in the two hemispheres.

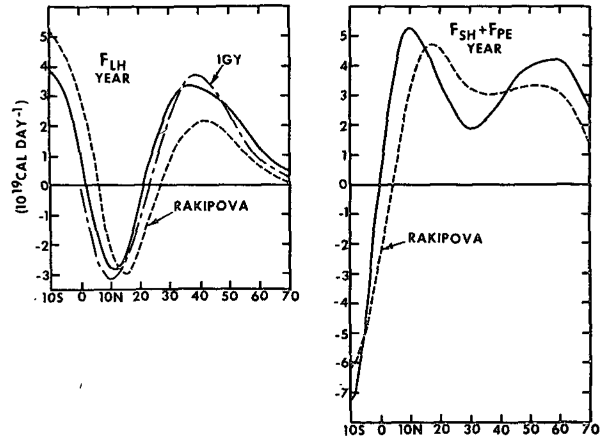

Fig. 9. The annual mean fluxes of latent heat and of sensible heat plus potential energy compared with indirect estimates by Rakipova (1966). Estimates of the latent heat flux for the IGY period are from Starr *et al.* (1965).

For the annual mean conditions Fig. 11 illustrates how the mean meridional and eddy circulations bring about the observed total energy convergence. At most latitudes (except in the equatorial region) the eddy cooling and heating tendencies seem to be partially compensated by the effects of the mean meridional circulation.

6. Summary and concluding remarks

1) The total atmospheric energy in the Northern Hemisphere appears to have a maximum value approximately 1.5 months following the summer solstice. The amplitude of the annual variation is 2.3% of the total energy content. During winter, uniform conditions seem to prevail for a longer period than during summer.

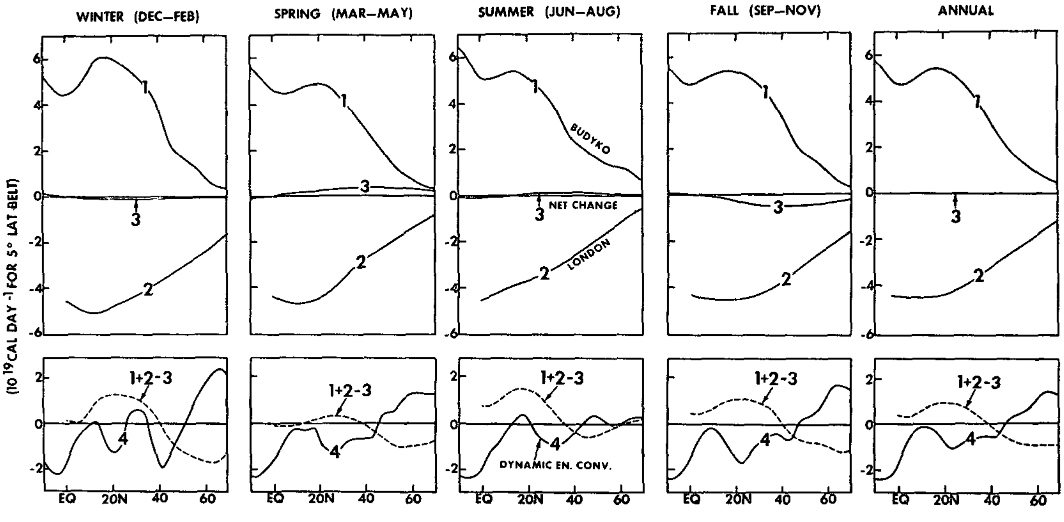

Fig. 10. Estimates of the heat balance components of the atmosphere: 1, upward flux of sensible plus latent heat at earth's surface from Budyko (1964); 2, net radiative cooling from London (1957); 3, change in total energy content; 4, energy flux convergence due to atmospheric motions. For perfect data, 1+2+4=3.

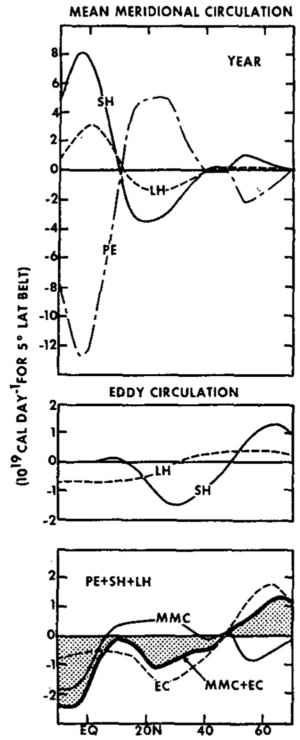

FIG. 11. Breakdown of the contributions by mean meridional (top) and eddy circulations (middle) to the total energy convergence (bottom) for the year.

2) The conversion from sensible plus latent heat to potential energy in the upward branch of the tropical Hadley cell and the opposite conversion in the downward branch lead to a significant cooling near the equator and heating in the subtropics. This direct action of cooling at low and heating at higher latitudes occurs in spite of the large observed transport of sensible plus latent heat by the Hadley cell toward the equator.

3) The energy flux due to both transient and standing eddies is practically negligible equatorward of 10 to 15° latitude. This is not because of a lack of disturbances in the tropics, but because of the horizontal homogeneity of the temperature and humidity around the equator. North of 20N the transient and standing eddies are of prime importance in transporting the necessary energy poleward. In contrast to the mean meridional circulation case, potential energy plays only a minor role and almost all the energy transport by the eddies is in the form of latent and sensible heat.

4) In midwinter (December–February) more than half of the sensible heat transfer is through the standing waves. The transient eddy fluxes do not peak in midwinter but in April and November. Earlier investigators have not noticed this interesting effect probably because they took averages over several calendar months.

5) The striking seasonal cycle in the strength and direction of the tropical Hadley circulation does not appear to contribute to the poleward transfer of energy for the year as a whole. On the other hand the seasonal cycle in the "standing" waves does contribute between 10–20% to the annual energy transport poleward. Thus, the remaining 80–90% of the eddy transport of energy is due to eddies with a period less than one month.

6) An important result of the present study is that it now appears possible to obtain meaningful estimates of the energy convergence by not only the eddy, but also the mean meridional circulations. The computed balance between independent estimates of the energy convergence by the atmospheric circulation, of the net radiative cooling rate and of the upward flux of latent and sensible heat at the earth's surface, as shown in Fig. 10, is not yet very satisfactory. However, the balance is probably as good as one may expect in view of the inaccuracies in evaluating each component. For further discussion of the energy balance components in both the atmosphere and the oceans, the reader is referred to a recent comprehensive study by Newell *et al.* (1969).

7) A further test will be to divide the atmosphere in layers and to compute the energy balance for each layer separately. Such studies have been attempted, but the accurate evaluation of an overall budget for individual layers has been made practically impossible because of the lack of knowledge about the vertical transfer of energy. The design of experiments to measure vertical fluxes should get first-order priority in future observational programs.

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