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AN OBSERVATIONAL STUDY OF THE MERIDIONAL FLUX OF ENERGY AND ANGULAR MOMENTUM IN THE TROPOSPHERE AND LOWER STRATOSPHERE AT LATITUDE 30° NORTH USING 1958 IGY DATA

BY

A. E. PARKER, B.Sc.

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AN OBSERVATIONAL STUDY OF THE MERIDIONAL FLUX OF ENERGY AND ANGULAR MOMENTUM IN THE TROPOSPHERE AND LOWER STRATOSPHERE AT LATITUDE 30°N USING 1958 IGY DATA

SUMMARY

During the International Geophysical Year much information was amassed about the atmosphere round the latitude circle 30°N. From this data extensive numerical calculations of the meridional flow, relative angular momentum and energy flux were made. March, June September and December 1958 were chosen as being the most representative months.

Most of the calculations were in broad agreement with the findings of previous workers although there are still uncertainties concerning the energy transports. The findings do, however, show the importance of the Hadley cell in transporting energy northwards.

§1 – INTRODUCTION

The extensive data contained in four volumes in *Daily aerological cross-sections at latitude* 30°N *during the International Geophysical Year period*[1*] afford a unique opportunity of calculating the values of the fluxes of various quantities across latitude 30°N and at the same time of verifying the results of earlier authors whose work had been based on comparatively few observations. The cross-sections mentioned above contained values of wind components, temperature, humidity mixing ratio and derived potential temperature, smoothed where necessary, round the latitude circle at 30°N from 1000 to 50 mb, and in some areas to 10 mb. However, the data for pressures less than 50 mb were too scanty in some areas to give reliable results so the calculations were restricted to the layer 1000 to 50 mb.

The sources of data for about 60 observing stations near latitude 30°N are quoted in *Daily aerological cross-sections at latitude 30° N.*[1] Temperature observations were corrected for the effect of solar radiation, where this had not already been done, and were then adjusted to allow for the latitude difference of the station from 30°N by means of a temperature gradient found either by estimation from the thermal wind or from the normal latitudinal temperature gradient, or by estimation from the temperature observations at nearby stations. Winds corrected to latitude 30°N were obtained by measuring gradient winds from constant-pressure charts or by interpolating between plotted wind values. Humidity mixing ratios were not corrected.

The results obtained in this study broadly confirm the results obtained by earlier workers notably those by White,[2] Starr and White,[3,4] and Priestley.[5] The computational procedures used were largely those of these earlier workers, the main difference being that these authors used actual observations from a few stations while grid-point values derived from carefully constructed cross-sections are used in the present study.

Some of the material used in the present Memoir has already been discussed elsewhere. (Murray, Parker and Collison.[6]) For various reasons SI units for heat have not been used.

§2 – FORMULAE FOR THE FLUX OF THE VARIOUS QUANTITIES

(i) *Flux of sensible heat*

If x is distance measured along a latitude circle and z distance measured vertically upwards then the flux of sensible heat in the atmosphere across an elementary area dxdz is $c_p \rho v T\, dx dz$ where c_p is the specific heat at constant pressure, ρ is the density of the air, T the absolute temperature and v the meridional wind component. If the hydrostatic equation is used to eliminate the variable ρ, then the rate of flux heat becomes $(-c_p/g)vT\, dx dp$ where p is the pressure. The

*The index numbers refer to the bibliography on p.55

mean rate of meridional flux of sensible heat $F(h)$ across an area bounded by x centimetres of the latitude circle and between pressure levels p_1 and p_0 is given by

$$F(h) = \frac{-c_p}{g} \int_0^x \int_{p_1}^{p_0} \overline{vT}\, dx dp \quad \text{calories per second}$$

where an overbar denotes a time mean: a month in the present work. Writing $v = \bar{v} + v'$ and $T = \overline{T} + T'$ where a prime denotes the departure from the monthly mean, then the flux of sensible heat can be written

$$F(h) = \frac{-c_p}{g} \int_0^x \int_{p_1}^{p_0} \left\{ \bar{v}\overline{T} + \overline{v'T'} \right\} dx dp \quad \text{cal/s}.$$

If square brackets [ ] denote a space mean (taken round the latitude circle), then the flux of sensible heat becomes

$$F(h) = -\frac{x}{g} c_p \int_{p_1}^{p_0} \left\{ [\bar{v}][\overline{T}] + \left[\overline{v'T'}\right] + \left[\bar{v}'_x\, \overline{T}'_x\right] \right\} dp \quad \text{cal/s} \qquad \ldots (1)$$

where the terms $\overline{T}'_x$ and $\bar{v}'_x$ denote space deviations from $\overline{T}$ and $\bar{v}$. The flux involving the term $[\overline{T}]\,[\bar{v}]$ is due to the mean flow and if the mass flow across the latitude circle during a month between pressure levels p_1 and p_0 (taken as 50 and 1000 mb in this Memoir) is zero, then $\int_{50}^{1000} [\bar{v}]\,[\overline{T}]\, d_p$ is different from zero only if circulations of the Hadley (see page 7) or reverse Hadley type are present. For this reason the flux due to the mean flow when integrated with respect to pressure (or height) is sometimes referred to as the cellular flux. The term in the flux involving $[\overline{v'T'}]$ is usually referred to as the local eddy flux, while the flux due to the term involving $\left[\bar{v}_x \overline{T}_x\right]$ is referred to as the standing eddy flux.

(ii) *Flux of latent heat*

The formula for the northward flux of latent heat can be developed on similar lines to that used for sensible heat (e.g. White[2]) and is

$$F(q) = \frac{Lx}{g} \int_{p_1}^{p_0} \left\{ [\bar{q}]\,[\bar{v}] + [\overline{q'v'}] + \left[\bar{q}'_x \bar{v}'_x\right] \right\} dp \quad \text{cal/s} \qquad \ldots (2)$$

where q is the humidity mixing ratio in grammes per kilogramme and L the latent heat of vaporization of water.

(iii) *Flux of potential energy*

The distance z in metres between two isobaric surfaces at pressures p_0 and p_1 is given by the formula

$$z = 29.289796\, T_v \log_e (p_0/p_1)$$

where T_v, in degrees absolute, is the mean virtual temperature of the air column from pressures p_1 to p_0. T_v is obtained from the formula

$T_v = T(1 + 0.00061q)$ where q is in grammes per kilogramme.

The potential energy (E_p) of a column of air having a horizontal cross-section of one square centimetre is

$$E_p = \int_0^z \rho\, gz\mathrm{d}z. = -\int_{p_1}^{p_0} z\mathrm{d}p.$$

The northward flux of potential energy across x centimetres of the latitude circle and between pressure levels p_1 and p_0 is

$$F(E_p) = \frac{1}{J} \int_0^x \int_{p_1}^{p_0} \overline{zv}\ \mathrm{d}p\mathrm{d}x \quad \text{cal/s}$$

in which J is the mechanical equivalent of heat 4.186×10^7 erg/cal. This formula, on expanding $\overline{zv}$ and taking means, may be written

$$F(E_p) = \frac{x}{J} \int_{p_1}^{p_0} \left\{ [\bar{z}]\,[\bar{v}] + [\overline{z'v'}] + \left[\bar{z}'_x \bar{v}'_x\right] \right\} \mathrm{d}p \quad \text{cal/s} \qquad \ldots (3)$$

(iv) *Northward flux of kinetic energy*

The instantaneous flux of horizontal kinetic energy (E_k) across x centimetres of a latitude circle and between height levels O and z is

$$F(E_k) = \int_0^x \int_0^z \tfrac{1}{2}\rho\, v\,(u^2 + v^2)\, \mathrm{d}x\mathrm{d}z \quad \text{cal/s}$$

On using the hydrostatic equation to eliminate ρ this becomes

$$F(E_k) = \frac{-1}{2gJ} \int_0^x \int_{p_0}^{p_1} \left\{ v(u^2 + v^2) \right\} \mathrm{d}x\mathrm{d}p \quad \text{cal/s} \qquad \ldots (4)$$

from which daily values and monthly means may be computed.

Since the flux of kinetic energy is very much smaller than the fluxes of sensible heat or latent heat, the total flux of kinetic energy will not be split up into components as was done when considering the other fluxes so far discussed.

(v) *Northward flux of angular momentum*

The absolute angular momentum (M) of unit mass of air is given by,

$$M = ua\cos\phi + \omega a^2\cos^2\phi$$

where u is the zonal wind component, a the earth's radius, ϕ the latitude and ω the earth's angular velocity. Hence the flux of angular momentum $F(M)$ per unit latitudinal distance is given by

$$F(M) = \frac{-a\cos\phi}{g} \int_{p_0}^{p_1} uv\mathrm{d}p \ \frac{-\omega a^2\cos^2\phi}{g} \int_{p_0}^{p_1} v\,\mathrm{d}p$$

The term involving $\int_{p_0}^{p_1} v\mathrm{d}p$ is very small or zero and in the present Memoir and most work (e.g. Tucker[11]) the values of v were adjusted to ensure this. The mean flux of angular momentum per second during a month across x centimetres of the latitude circle becomes

$$\text{mean } F(M) = \frac{xa \cos\phi}{g} \int_{p_1}^{p_0} \left\{ [\bar{u}]\,[\bar{v}] + [\overline{u'v'}] + \left[\acute{\bar{u}}_x \acute{\bar{v}}_x\right] \right\} \mathrm{d}p \quad \text{g cm}^2/\text{s}^2 \qquad \ldots (5)$$

(vi) *Adustment to the values of meridional wind components to obtain zero mass flow across the latitude circle*

In order to obtain zero mass flow across the latitude circle, $[\bar{v}]$ as defined by the quantity

$$[\bar{v}]_m = \frac{1}{p_0 - p_1} \int_{p_1}^{p_0} \bar{v}\, \mathrm{d}p$$

must be zero. Zero mass flow will be obtained if the actual value of $[\bar{v}]_m$ is subtracted from all the values of v. It is shown in section 4(c) that the mean value of $[\bar{v}]_m$ for a month is probably quite small.

§3 – COMPUTATIONAL PROCEDURE

Values of u the zonal wind component, v the meridional wind component, T the temperature and q the humidity mixing ratio were extracted from the *Daily aerological cross-sections* at five-degree longitude positions along latitude 30°N commencing at the Greenwich meridian. Data were extracted at the following pressure levels: 1000, 950, 900, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70 and 50 mb. Because of the presence of high ground the surface pressure was taken as having the following values at the given longitude positions:

0°	5°E	10°E	15°E	35°E	40°E	45°E	55°E	60°E	65°E	70°E	75°E	80°E
900	950	950	950	900	950	950	900	700	850	700	950	600 mb

85°E	90°E	95°E	100°E	105°E	110°E	120°E	115°W	110°W	105°W	100°W	5°W
400	500	500	500	950	850	950	850	850	850	900	850 mb

Values of $\bar{u}$, $\bar{v}$, $\bar{T}$ and $\bar{q}$ were readily computed and the values of u', v', T' and q' were then obtained by subtracting the values of $\bar{u}$, $\bar{v}$, $\bar{T}$ and $\bar{q}$ from the daily values of u, v, T and q. The values of v were then adjusted to make the mass flow across the latitude circle zero by subtracting $[\bar{v}]_m$ from all the values of v.

Mean values of the various fluxes during the month were then obtained using formulae (1) to (5). Integrations with respect to pressure were carried out using the trapezoidal rule as it was decided that the lack of accuracy inherent in some of the data did not justify the use of a more accurate method of integration.

§4 – ERRORS IN BASIC DATA

(i) *Random errors in measured winds*

Some of the winds used in the present study were estimated from constant-pressure charts and complex and subjective techniques entered into the drawing of the cross-sections. Because of this no numerical estimates of random error will be quoted.

(ii) *Estimation of systematic error in meridional wind*

If it is assumed that the mass of air above a polar cap north of latitude ϕ is proportional to the product of the mean sea-level pressure and the area, then

$$\text{mass} \propto p_0 \,(1\text{-}\sin\phi)$$

where p_0 is the mean pressure at sea level over the polar cap north of latitude ϕ. If the mass is concentrated into a smaller area by a mean northward wind $[\bar{v}]_m$ in the layer 1000-50 mb then

$$\frac{dp_0}{dt} = \frac{p_0 \cos\phi\,[\bar{v}]_m}{(1-\sin\phi)a}$$

where a is the earth's radius.

By integrating grid-point values of sea-level pressure it was found that mean sea-level pressure (i.e. p_0) over the polar cap north of latitude 30°N changed by about 2 mb or less during the months March, June, September and December 1958. The uncorrected values of $[\bar{v}]_m$ for March, June, September and December 1958 were 11.9, -7.9, 8.9 and 23.6 cm/s respectively giving a mean value of 13.1 cm/s for the four months. This is discussed in §6 and the values of $[\bar{v}]_m$ are taken from Table II. The value of $[\bar{v}]_m$ derived from the change in mean pressure at sea level over the polar cap was 0.24 cm/s so that the actual value of $[\bar{v}]_m$ appears to be in error by about 10 cm/s. An error of, say, 5 mb in p_0 would not affect this error significantly. This error in $[\bar{v}]_m$ is far too large to be attributed to random error, which was estimated using the probable error of a single observation and the number of observations but is not given here, and must be due to a systematic error.

Such a systematic error could arise in the following ways:

(a) Owing to lack of information the constant-pressure contours over an area could systematically have been drawn incorrectly.

(b) When a wind was estimated incorrectly at one level it was likely to be estimated incorrectly at levels above and below the original level. It was found when constructing the daily cross-sections that observations were sometimes consistent in groups but the groups were not consistent with each other so that it was difficult to decide which group contained the more accurate observations.

(c) Since the meridional wind component is usually much smaller than the zonal component the percentage error in meridional wind components is usually much greater than the percentage error in zonal wind components. In fact when daily components at 1200 GMT were worked out, a meridional component of less than 0.5 kt was ignored. Another factor is that when the wind is ageostrophic, the ageostrophic part of the wind forms a far larger percentage of the meridional component than it does of the zonal component, and this leads to large errors in meridional components estimated from contour charts.

(d) It is possible that there are regions of high wind speeds which are not revealed by the observational network but which nevertheless transfer a lot of air.

(iii) *Errors in temperature and humidity mixing ratio*

In practice it must be almost impossible to obtain firm estimates of the errors in temperature and humidity mixing ratio since complex and subjective procedures went into the construction of the cross-sections.

§5 – MEAN TEMPERATURES FOR MARCH, JUNE, SEPTEMBER AND DECEMBER 1958 ROUND THE 30°N LATITUDE CIRCLE

It will be convenient to consider the four months together. Table I and Figure 1 give mean monthly temperatures round the latitude circle at various pressure levels for the four months considered. A feature immediately obvious from Figure 1 is that the temperatures at the various pressure levels during March and December and during June and September were almost equal. From March to June the temperature at corresponding pressure levels in the troposphere increased by 6 to 7 degC and the height of the freezing-level rose from 675 to 575 mb. There was comparatively little change in tropospheric temperatures from June to September as mentioned earlier but from September to December 1958 temperatures in the troposphere fell by 6 to 8 degC and the freezing-level lowered

TABLE I – MEAN TEMPERATURES ROUND THE LATITUDE CIRCLE AT 30°N FOR 1958

Pressure level	March	June	September	December
millibars		*degrees Celsius*		
30	-55.6	-52.9	-53.5	-57.0
50	-62.9	-59.9	-60.5	-62.8
70	-66.7	-66.1	-66.3	-66.4
100	-67.7	-70.5	-71.5	-68.6
150	-60.9	-63.3	-62.2	-62.5
200	-54.8	-52.8	-52.3	-56.1
250	-48.1	-42.4	-41.6	-48.1
300	-40.5	-33.1	-32.9	-39.8
400	-26.2	-18.0	-17.8	-25.2
500	-14.7	-6.9	-6.5	-13.7
600	-5.8	2.0	2.2	-4.7
700	1.4	9.3	9.4	2.2
850	9.6	17.6	17.7	9.9
900	12.1	19.7	20.2	12.2
950	14.3	21.5	22.5	14.6
1000	16.4	22.4	24.7	17.2
Mean	-20.7	-14.7	-14.4	-20.4
Freezing-level (mb)	675	575	570	665
Tropopause level (mb)*	190	125	113	160

*The mean tropopause heights given in this table were obtained by averaging values obtained from daily aerological cross-sections at 5-degree longitude grid-points.

by just over 100 mb. In the stratosphere from 50 to 30 mb the mean temperature rose a few degrees Celsius from winter to summer, the smallest change occurring at 70 mb. During the four months considered the lowest mean monthly temperature of -71.5 °C occurred at about 100 mb in September.

§6 – MEAN MONTHLY MERIDIONAL FLOW

(i) *March 1958*

Figure 27 (*a* and *b*) gives cross-sections of south–north flow round the hemisphere at latitude 30°N. The main features of the monthly mean unadjusted meridional flow (adjusting the components would make very little difference to most of the S–N values) are the well-marked minimum at about 175°W and the well-marked maximum at about 100°E, both probably caused by radiation losses from land masses. The zero S–N component isotach marks the positions of the troughs and ridges and, for example, at 500 mb, this gives a trough at 115 °W and a ridge at 70°W. The meridional winds in the stratosphere are light and the zonal winds are mainly westerly. In the troposphere, owing to the progressive nature of synoptic disturbances in this month, the mean chart for March 1958 does not show such well-developed maxima in meridional wind components as those which occurred in June 1958 and which are shown in Figure 28.

Figure 2 shows the adjusted S–N wind components at various pressure levels meaned round the latitude circle, i.e. values of $[\bar{v}]$. In March 1958, the S–N component was southerly (i.e. positive) from 50 to 590 mb with a maximum at about 100 mb, and northerly (negative) from 590 to 1000 mb where the northerly maximum occurred. This system of winds, i.e. southerly in the upper troposphere and northerly in the lower troposphere, clearly indicates a type of circulation suggested by Hadley[7] and named after him. Evidence for such a circulation has been put forward by many workers, for example Mintz and Lang,[8] Palmén, Riehl and Vuorela,[9] Tucker,[10] Palmén and Vuorela,[11] Holopainen,[12] and Murray, Parker and Collison,[6] but there is probably still some uncertainty concerning the nature and strength of the Hadley cells and their location at different times of the year. It is generally thought that the maxima of meridional flow associated with the Hadley cell in the northern hemisphere are located between 10°N and 20°N in winter and between 20°N and 30°N in summer.

Table II gives values of S–N wind component ($[\bar{v}]$) at various pressure levels meaned round the latitude circle. The column headed 'U' gives the actual monthly mean S–N wind components as derived from grid points on the cross-sections while the mean winds adjusted for zero mass flow are given in the column denoted by 'A'. Part of the data given in Table II was used to construct Figure 2 which brings out the main features of the mean meridional flow more clearly than the table. The southward mass flow in the Hadley cell is given by $(2\pi a/g)\int_{590}^{1000}[\bar{v}]\,dp$ which works out to 32 x 10^6 tonnes per second and is equal of course to the mass flow in the upper part of the Hadley cell but opposite in sign.

(ii) *June 1958*

The main features of the mean meridional flow revealed by the cross-section, Figure 28, are the well-marked southerly maximum of 16 m/s at about 120°W, another well-marked southerly maximum of 12 m/s at 40°E and a strong northerly maximum of 12 m/s at 120°E. The upper ridge over the United States of America is undoubtedly a geographical feature and is probably due to intense solar heating over the land masses of the U.S.A. and Mexico. Similar ridging would be expected over the Afro-Asian land mass but this region is too large to contain just one ridge system. There are comparatively large northerly components at 120°E near the eastern seaboard of the land mass.

TABLE II – MEAN SOUTH–NORTH WIND COMPONENTS ([$\bar{v}$]) AT 30°N FOR 1958

Pressure	March		June		September		December	
	U	A	U	A	U	A	U	A
millibars	*centimetres per second*							
50	11.0	-0.9	-26.3	-18.4	-6.9	-15.7	28.3	4.7
70	40.1	28.2	-10.4	-2.5	-1.3	-10.1	40.1	16.4
100	52.6	40.7	6.8	14.7	11.4	2.5	52.5	28.9
150	41.1	29.2	-3.2	4.6	22.9	14.1	61.4	37.8
200	32.3	20.4	0.5	8.4	10.5	1.7	54.9	31.3
250	23.3	11.4	-3.4	4.5	19.8	10.9	47.0	23.4
300	21.7	9.8	-5.3	2.6	30.7	21.9	39.3	15.6
400	18.5	6.5	-7.4	0.5	36.0	27.2	43.4	19.8
500	21.0	9.0	-7.2	0.7	26.2	17.4	53.4	29.8
600	10.9	-1.0	-13.1	-5.3	18.8	10.0	30.4	6.7
700	0.9	-11.1	-10.6	-2.7	11.2	2.3	9.6	-14.0
850	-10.6	-22.5	-8.2	-0.3	-19.8	-28.7	-16.9	-40.6
900	-13.0	-25.0	-13.1	-5.2	-31.1	-39.9	-22.0	-45.7
950	-22.8	-34.7	-14.8	-6.9	-39.3	-48.2	-37.8	-61.5
1000	-23.7	-35.7	-9.4	-1.6	-36.3	-45.1	-51.1	-74.7
Mean ([$\bar{v}$]$_m$) 50 - 1000	11.9	0.0	-7.9	0.0	8.9	0.0	23.6	0.0

U = value of S–N wind component from actual observations.
A = adjusted value for zero mass flux.
The mean S–N wind component for the four months = 9.1 cm/s.

It will be seen from Table II and Figure 2 that values of [$\bar{v}$] were much less in June than they were in March although the cross-section, Figure 28, shows that maximum values of $\bar{v}$ were larger in June than in March. The southerly jet at about 120°W is one example. This is because, in the summer months, the neighbourhood of latitude 30°N is a baroclinically stable zone with rather pronounced stable troughs and ridges.

Considering the variation of [$\bar{v}$] with pressure shown in Figure 2 it will be seen that the adjusted wind component is southerly from about 520 to 70 mb, northerly from 520 to 1000 mb, and northerly again from 70 mb to pressures less than 50 mb. The distribution of adjusted values of S–N wind components in the troposphere and lower stratosphere support the hypothesis of the existence of a Hadley-type cell in the troposphere and the northerly components at 50 mb suggest the possibility of another Hadley-type cell in the lower stratosphere. The northward mass flow in the Hadley cell using adjusted winds is 7 x 10^6 tonnes per second which is, of course, equal to the southwards mass flow in the northerlies.

(iii) *September 1958*

Values of $\bar{v}$ are depicted on the cross-section, Figure 29. The pattern of S–N wind component resembles that for June but the strong northerly jet present in June at 120°E had disappeared from the September cross-section. However, the southerly jet at 40°E in June had strengthened slightly in September and moved westwards to about 33°E. Also the strong southerly jet just over the west coast of the U.S.A. in June – a maximum of 16 m/s – had decreased markedly in speed in September – a maximum of 10 m/s – and moved about 10 degrees of longitude to the east of its June position.

Table II and Figure 2 show that quite a strong mean Hadley cell occurred in September 1958, the S–N component being southerly from about 710 to 95 mb, northerly from 710 to 1000 mb, and northerly again from 95 to 50 mb.

The mass flow in the Hadley cell was 31 x 10^6 tonnes per second.

(iv) *December 1958*

The cross-section, Figure 30, gives mean S–N wind components for December 1958. The main features of the S–N wind component-pattern (i.e. $\bar{v}$) in the western hemisphere are the northerly maximum at about 180°W (this maximum was at 175°W in March), a weaker southerly maximum at about 145°W, a northerly maximum at about 115°W, a southerly maximum at about 85°W and a northerly maximum at 110°W. It will be noticed that the ridge which was present over the U.S.A. in June and September has been replaced by a trough in the upper atmosphere due no doubt to radiative cooling over a large land mass. In the eastern hemisphere the main feature is the well-marked southerly wind maximum at 145°E probably due to the combined effects of the oceanic heat source and the Asian heat sink. Referring to Table II and Figure 2 it will be seen that S–N wind components were positive from about 640 to 50 mb and negative from about 640 to 1000 mb, giving a more vigorous Hadley cell than had occurred in September. Another feature of note is the southerly component at 50 mb; in June and September the component at 50 mb was northerly. The Hadley cell was a strong one with a mass flow of 51 x 10^6 tonnes per second.

(v) *Relative strengths of the mean Hadley cells*

The mass flows in the Hadley cells at latitude 30°N using adjusted winds are given as follows:

Month	Mass flow 10^6 *tonnes per second*
March	32
June	7
September	31
December	51

The strongest Hadley circulation was clearly in December, although March had rather stronger average westerlies, and the weakest Hadley circulation occurred in June. Vernekar[13] found that the mass circulation in January 1962 was three times as intense as that in July 1962, while the circulations in April and October were almost equal but about twice that for July.

§7 – MEAN MONTHLY ZONAL FLOW

(i) *March 1958*

The cross-section of mean monthly zonal wind components for March 1958 are given in Figure 31. The main features are well-marked maxima at about the 200-mb level near 100°W, 85°W, 15°E and 125°E, and well-marked minima at 20°W and 75°E. It should also be noted that the winds in the stratosphere were mainly westerly and rather light at the 30-mb level.

The graph of the variation of monthly mean zonal wind component with pressure is shown in Figure 3. This figure indicates that the zonal wind components were stronger in March than in any of the other three months considered.

(ii) *June 1958*

Cross-sections of mean monthly zonal winds are presented in Figure 32. The main features are well-marked wind maxima at the 250 to 200-mb levels at 120°W, 35°E and 130°E. Another feature to be noted is that winds in the stratosphere changed from mainly westerly in March to easterly in June. The graph of mean zonal winds at various pressure levels given in Figure 3 shows that mean winds in June were lighter than in March and the change to summer easterlies in the stratosphere was clearly complete.

(iii) *September 1958*

Table III and the graph in Figure 3 show that between June and September, mean zonal winds decreased and in fact the September zonal components were the lightest of the four months considered. On the cross-section, Figure 33, the main features are wind maxima at 110°W, 25°E and 115°E with ill-defined subsidiary maxima between the main maxima.

As was mentioned previously the graph of mean west wind components (Figure 3) shows that the west winds were lighter in this month than in any of the other three months. Figure 3 and the cross-sections show east winds at 50 and 30 mb.

(iv) *December 1958*

The most striking change in mean zonal winds from September to December shown in the cross-section, Figure 34, was a large increase in these components (but in fact they were not as strong as they were in March) and the winds in the stratosphere had become mainly westerly reaching a mean value at 90°W over the U.S.A. of 28 m/s at 10 mb. In rather more detail well-marked W–E wind maxima occurred at 85°W and 125°E with subsidiary maxima. These two maxima occurred near the eastern coasts of America and of Asia. The variation of monthly mean zonal wind with pressure is shown in Figure 3 and it is apparent that the winds in December were somewhat lighter than they were in March which may thus be considered a winter month in the subtropics.

TABLE III – MEAN W–E WIND COMPONENTS AT 30°N IN 1958

Pressure	March	June	September	December
millibars	*metres per second*			
30	–	–12.4	–10.7	6.9
50	7.9	–8.2	–7.4	9.4
70	10.0	–1.3	–2.0	15.3
100	30.3	7.6	2.9	23.3
150	40.7	14.6	8.6	31.5
200	43.6	16.5	10.7	35.2
250	39.9	15.2	10.0	33.3
300	34.7	13.5	8.6	29.7
400	26.1	10.3	6.2	22.7
500	19.5	7.7	4.0	17.1
600	14.5	5.9	2.6	12.9
700	10.4	4.2	1.5	9.1
850	5.4	1.9	–0.2	4.5
900	3.8	1.3	–0.7	3.4
950	2.4	0.7	–1.1	2.2
1000	1.1	0.0	–1.6	0.8

Mean winds

March	50-190 mb	31.68 m/s	September	50-113 mb	2.49 m/s
	190-500	31.31		113-500	7.72
	500-1000	9.21		500-1000	1.11
	50-1000	19.73		50-1000	3.79
June	50-125 mb	6.39 m/s	December	50-160 mb	22.86 m/s
	125-500	12.45		160-500	27.23
	500-1000	3.75		500-1000	8.42
	50-1000	7.38		50-1000	17.34

(v) *Mean monthly zonal winds in various layers of the atmosphere (calculated from the data in Table III)*

TABLE IV – MEAN MONTHLY ZONAL WINDS

Layer	March	June	September	December
		metres per second		
50 mb – tropopause	31.68	6.39	2.49	22.86
Tropopause – 500 mb	31.31	12.45	7.72	27.23
500 – 1000 mb	9.21	3.75	1.11	8.42
50 – 1000 mb	19.73	7.38	3.79	17.34
Level of tropopause (mb)	190	125	113	160

(vi) *Mean monthly north to south temperature gradient at the various pressure levels*

Considering the variation of mean wind with pressure as depicted in Figure 3 it is obvious that the mean horizontal north to south temperature gradient must change sign at about 200 mb in all months. Furthermore, this reversed temperature gradient must be less in June and September than in March and December.

§8 – MEAN MONTHLY VALUES OF HUMIDITY MIXING RATIO

Values of monthly mean humidity mixing ratio (in grammes per kilogramme) round the latitude circle at various pressure levels are given in Table V. Values of humidity mixing ratio increased at all pressure levels from March to June 1958. From June to September the values of humidity mixing ratio increased further in the layer 1000-600 mb but decreased somewhat for pressures less than 600 mb. The values of humidity mixing ratio decreased considerably from September to December as might have been expected. The mean values of humidity mixing ratio for the latitude circle at 30°N for September 1958 are given in Figure 4, curve a. In order to show the variability of mean monthly humidity mixing ratio with longitude, curve b gives mean values for September at longitude 35°E and curve c gives corresponding values at 78°E where high values of humidity mixing ratio occurred.

§ 9 – FLUX OF RELATIVE ANGULAR MOMENTUM

Before considering the flux of angular momentum across latitude 30°N during 1958 it should be noted that cross-sections of flux of a quantity for a month must resemble rather closely monthly mean cross-sections of meridional wind, mainly because the meridional wind speed is a factor entering into all such calculations. The regions of maximum flux should therefore occur at or near the region of maximum meridional wind unless modified markedly by the value of the quantity whose flux is being considered. This applies both to the flux due to the total flow and to the flux due to the mean flow, since the flux due to the mean flow at individual pressure levels is usually much larger than that due to the eddies although the flux due to the mean flow, integrated through the depth of the atmosphere (i.e. from 1000 to 50 mb), may be small.

In order to reduce the number of large diagrams, cross-sections of flux of angular momentum for March and September are not reproduced, since broadly speaking the results for these two

TABLE V – MEAN HEMISPHERIC HUMIDITY MIXING RATIO

Pressure	March	June	September	December
millibars		*grammes per kilogramme*		
200	0.00	0.16	0.09	0.00
250	0.01	0.32	0.08	0.01
300	0.13	0.30	0.24	0.12
400	0.38	0.79	0.75	0.37
500	0.86	1.63	1.54	0.79
600	1.54	2.62	2.68	1.49
700	2.41	4.04	4.26	2.41
850	4.78	7.50	8.36	4.93
900	5.83	9.06	10.22	6.22
950	6.93	10.81	12.20	7.45
1000	8.27	13.05	14.73	8.98

HMR values at 150 mb and above are zero.

months resemble those for December and June respectively. However, the calculated values of flux of angular momentum across latitude 30°N at various pressure levels for March and September are given in graphical form.

(i) *June 1958*

(a) Total flux. The cross-section of total flux of angular momentum is given in Figure 35. There was a maximum of transport at 200 mb just off the west coast of the U.S.A., another at 35°E and another at about 115°E. These maxima were associated with, but not coincident with, the S–N jets.

The flux of total angular momentum with pressure is depicted in Figure 5 and it is evident that the flux was positive at all pressure levels with the maximum value occurring at about 200 mb. The total flux for the layer 50-1000 mb across the 30°N latitude circle was 19.2×10^{25} g cm^2/s^2.

(b) Local eddy flux. The cross-section of local eddy flux of angular momentum is given in Figure 36 and the patterns of the isopleths are necessarily more complicated than those of total flux. It is immediately obvious from the cross-sections that the transport of momentum due to local eddies was overwhelmingly positive. Figure 5 shows that the local eddy flux of angular momentum was positive at all pressure levels yielding a total local eddy flux for the layer 50-1000 mb across the latitude circle of 10.4×10^{25} g cm^2/s^2.

(c) Standing eddy flux. The cross-section of standing eddy flux is given in Figure 37. There were large positive standing eddies at 120°W, at about 90°W and near 40°E, all associated

with maxima in the meridional wind components (see Figure 28) but the meridional wind maximum at about 120°E and at about 175 mb (Figure 28(*b*)) was associated with rather a weak standing eddy in the flux of angular momentum.

The variation of pressure with the mean flux due to the standing eddies, round the hemisphere at 30°N is given in Figure 5 from which it is evident that the fluxes due to the local and standing eddies were rather similar. The flux due to the standing eddies for the layer 50-1000 mb was 8.5 x 10^{25} g cm^2/s^2.

(d) Flux due to the mean flow (cellular flux). This was very small indeed because the Hadley circulation in the month was very weak. The cross-sections resemble those due to the total flow very closely and so have not been given.

(e) Daily values of total flux of relative angular momentum in June 1958. Table VI gives daily values for various layers of the atmosphere. Table VI shows that in the layer 50-1000 mb quite large changes in total flux of total angular momentum can occur in one day and that a negative value occurred on only one day – 12 June. The table also indicates a period when a four-day oscillation occurred, with maxima of total flux of angular momentum occurring on the 2nd, 6th, 10th and 14th, but thereafter the four-day oscillation ceased. This rather short-period oscillation might suggest that the driving force maintaining the general circulation stems from large synoptic-type eddies having a period of a few days although of course Table V does not prove this. Without the evidence contained in this table one might have expected a more gradual daily variation in total flux of angular momentum than actually seemed to occur.

(ii) *December 1958*

(a) Total flux. The total northward flux of angular momentum is given in the cross-section Figure 38. It is apparent that the maxima of total flux are largely determined by the maxima in $\bar{v}$. The large positive values over the U.S.A. at about 85°W and again over the Pacific Ocean between 130°E and 155°E are noteworthy. The graph given in Figure 5 shows that the total flux of angular momentum across the latitude circle at 30°N was positive at all pressure levels and that the bulk of the transfer of angular momentum occurred between 600 and 100 mb. The total flux from 50 to 100 mb was 35.6 x 10^{25} g cm^2/s^2.

(b) Local eddy flux. Values of local eddy flux of angular momentum for December 1958 are given in the cross-section, Figure 39. The large values at about 100°W and 5°W indicate a fairly high degree of correlation in these two areas between the zonal and meridional winds. It is obvious from the cross-section that the local eddy flux of angular momentum had a preponderance of positive values, and calculations show that by far the greater part of the total flux came from the eddy terms.

The graph of the variation of local eddy flux with pressure given in Figure 6 shows that the local eddy flux was positive at all pressure levels and that the maximum flux occurred at about 250 mb. The total local eddy flux for the layer 50-1000 mb across the latitude circle was 16.2 x 10^{25} g cm^2/s^2.

(c) Standing eddy flux. The cross-section giving values of standing eddy flux for December 1958 is given in Figure 40. Standing eddies were present at 175°W, 140°W, 115°W, 85°W, 25°W, 130°E and 150°E, all associated with, but not necessarily coincident with, maxima in the mean meridional wind (see Figure 30). The atmosphere over the land mass of Afro-Asia appears to have been characterized by an absence of standing eddies of flux of angular momentum in this month. Comparing cross-sections of standing eddy flux for December (Figure 40) with those for June 1958 (Figure 37), it can be seen that the standing eddy present in June at about 120°W, which had disappeared by September, had re-formed by December at 115°W, and

TABLE VI – DAILY VALUES OF TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N IN JUNE 1958

Day	Layers (mb)			
	50–125	125–500	500–1000	50–1000
	10^{21} $g\ cm^2/s^2$			
1	3950	123 000	55 000	182 000
2	29 300	286 000	134 000	450 000
3	22 500	249 000	23 300	295 000
4	9530	121 000	44 200	174 000
5	11 000	229 000	46 100	286 000
6	7760	274 000	62 700	345 000
7	3430	115 000	6190	125 000
8	5620	108 000	-5630	108 000
9	4870	159 000	48 000	212 000
10	9540	271 000	54 600	336 000
11	10 500	120 000	40 600	171 000
12	9080	-44 100	19 000	-16 000
13	10 800	102 000	29 900	143 000
14	9630	218 000	68 700	297 000
15	2850	161 000	28 400	192 000
16	13 000	221 000	19 300	253 000
17	-1560	194 000	71 300	264 000
18	10 000	93 300	26 700	130 000
19	10 500	172 000	-43 400	139 000
20	33 800	139 000	2230	175 000
21	3490	165 000	7560	176 000
22	2230	186 000	59 300	248 000
23	-1840	109 000	104 000	210 000
24	14 800	125 000	85 800	225 000
25	7400	46 900	24 800	79 100
26	18 800	80 300	38 400	137 000
27	15 800	143 000	47 100	206 000
28	4240	30 100	44 900	79 300
29	9700	22 500	37 700	69 900
30	14 000	57 900	9580	81 500

another strong negative standing eddy formed at about 175°W. The intense standing eddy present in June at about 40°E moved westwards to 25°E in September but was not evident at all in December.

The variation of standing eddy flux of angular momentum with pressure, averaged round the latitude circle for December 1958, is given in Figure 6. The maximum flux occurred at about 150 mb and values became small for pressures greater than 600 mb.

(d) Flux due to the mean flow. The flux at the various pressure levels is given in graphical form in Figure 6. Values became small and negative for pressures greater than 650 mb and the maximum positive value occurred at 150 mb. The total flux due to the mean flow for the layer 50-1000 mb was 5.5×10^{25} g cm^2/s^2.

(e) Daily values of total flux of relative angular momentum in December 1958. These are given in Table VII. The values are larger, on the average, than those for June and there are no negative values.

(iii) *March 1958*

(a) Total flux. Cross-sections of total northward flux of angular momentum (not reproduced) show that the total flux reached a maximum at about the levels of the wind maxima and the pattern of the isopleths followed broadly the pattern of the S–N wind components but were not entirely determined by it since the west wind component also entered into the calculations. The largest values of flux of angular momentum occurred over the U.S.A. at about 95°W and over the Pacific at 155°E with subsidiary maxima occurring between the main maxima.

Figure 7 depicts the variation of total flux of angular momentum with pressure. It will be seen that the flux is very definitely northwards, except for negligible negative flux in the layer 950-1000 mb, and the bulk of the transport took place in the layer 600-100 mb. The total flux in the layer 50-1000 mb due to the total flow was 34.3×10^{25} g cm^2/s^2.

(b) Local eddy flux. The variation of local eddy flux with pressure is given in Figure 7. The local eddies transported angular momentum northwards for the most part, but there was small negative transport from 850 to 1000 mb. The total local eddy flux across the latitude circle for the layer 50-1000 mb was 15.2×10^{25} g cm^2/s^2, a value very close to that due to the standing eddies.

(c) Standing eddy flux. Figure 7 shows that the flux due to the standing eddies was positive at all pressures and the total for the layer 50-1000 was 15×10^{25} g cm^2/s^2. Cross-sections of standing eddy flux for March (not reproduced) reveal an intense standing eddy at 175°W and another of less than half its intensity at 100°W. Between March and June, strong standing eddies formed at about 120°W, 95°W and 40°E, but the eddy at 175°W almost vanished.

(d) Flux due to the mean flow. This was comparatively small but with a maximum positive value at about 100 mb. From 600 to 1000 mb the flux was small and negative (see Figure 7). The total flux in the layer 50-1000 mb was 4.1×10^{25} g cm^2/s^2. Cross-sections of flux of angular momentum due to the mean flow would resemble the cross-sections of flux due to the total flow.

TABLE VII – DAILY VALUES OF TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N IN DECEMBER 1958

Day	Layers (mb)			
	50–160	160–500	500–1000	50–1000
	$10^{21}\ g\ cm^2/s^2$			
1	79 900	393 000	55 700	528 000
2	63 900	244 000	50 100	358 000
3	15 100	89 300	2390	107 000
4	36 000	3740	77 000	117 000
5	85 200	380 000	21 100	487 000
6	43 700	114 000	32 000	189 000
7	70 600	147 000	40 000	258 000
8	42 700	104 000	55 300	202 000
9	86 300	602 000	76 800	765 000
10	22 600	106 000	26 600	155 000
11	99 500	677 000	94 500	871 000
12	118 000	584 000	171 000	873 000
13	89 200	374 000	45 500	508 000
14	60 400	161 000	-11 900	209 000
15	22 800	127 000	-13 500	136 000
16	94 500	25 200	-6560	113 000
17	73 500	279 000	-1380	351 000
18	20 700	-20 700	15 800	15 900
19	46 400	404 000	79 200	529 000
20	87 100	490 000	81 100	658 000
21	14 400	313 000	58 400	386 000
22	12 600	24 100	15 200	51 900
23	73 500	308 000	92 000	474 000
24	27 500	9380	74 200	111 000
25	89 400	271 000	86 400	447 000
26	-240	101 000	125 500	226 000
27	62 300	392 000	188 000	643 000
28	49 000	181 000	135 000	365 000
29	13 100	73 100	102 000	188 000
30	72 900	320 000	59 700	453 000
31	49 200	210 000	3230	262 000

(e) Daily values of total flux of relative angular momentum in March 1958. These are given in Table VIII. The average value of daily flux of total angular momentum was large, in fact the largest daily total flux during the four months considered occurred on 7 March. In spite of the large daily mean positive value of total flux during March 1958, daily values were negative on four days.

(iv) *September 1958*

(a) Total flux. Cross-sections of northward transport of total angular momentum (not reproduced) show that most of the flux was associated with the S–N jets at about 110°W over the U.S.A. and at 25°E over Libya. The graph given in Figure 8 shows that the pattern of total flux transport with pressure followed broadly the pattern of the standing eddy flux. The integrated value of the flux due to the total flow was 8.75×10^{25} g cm^2/s^2.

(b) Local eddy flux of angular momentum. The graph given in Figure 8 shows that the local eddies made only a minor contribution to the total flux of angular momentum at all pressure levels, the maximum positive value occurring at about 300 mb with small values from 600 to 1000 mb. The total flux due to local eddies for the layer 50-1000 mb was 1.39×10^{25} g cm^2/s^2.

(c) Standing eddy flux. It will be clear from the graph given in Figure 8 that the greater part of the total flux of momentum was contributed by the standing eddies. This is to be expected in a summer-type month when synoptic disturbances are feeble but seasonal patterns are strong. The total standing eddy flux from 50 to 1000 mb across the latitude circle was 6.16×10^{25} g cm^2/s^2.

Cross-sections of standing eddy flux of angular momentum for September 1958 (not reproduced) show that the intense positive standing eddy at about 45°E in June moved westwards to 25°E in September, while the standing eddies at 120°W and 95°W, present in June, had almost disappeared in September. Between September and December, large standing eddies formed in the western hemisphere and in the western Pacific in the eastern hemisphere.

(d) Flux due to the mean flow. Figure 8 shows this to be small at all pressure levels; the total for the layer 50-1000 mb was 1.2×10^{21} g cm^2/s^2 across the latitude circle. This small total occurred because the mean latitudinal Hadley cell was weak.

(e) Daily values of total flux of relative angular momentum in September 1958. These values are presented in Table IX. The daily values were, on average, smaller than any of the other months and negative values occurred on several days.

(v) *Values of total flux of relative angular momentum for March, June, September and December 1958*

The values of flux of angular momentum for the layer 50-1000 mb for the four months considered are plotted on a graph and the points joined by a reasonable curve as shown in Figure 9, in order to exhibit the seasonal changes in the various fluxes.

The flux due to the mean flow, i.e. the cellular flux, was at a maximum about January and at a minimum about July when the values were small compared with those for the winter.

The flux due to the local eddies was at a maximum in January and decreased to a rather sharp minimum in September. Values of the flux due to the standing eddies, which reached a

TABLE VIII – DAILY VALUES OF TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N IN MARCH 1958

Day	Layers (mb)			
	50-190	190-500	500-1000	50-1000
	$10^{21}\ g\ cm^2/s^2$			
1	225 000	387 000	117 000	729 000
2	117 000	708 000	17 000	841 000
3	131 000	486 000	89 600	707 000
4	59 800	263 000	132 000	455 000
5	88 800	41 900	84 400	215 000
6	74 800	-147 000	-73 600	-146 000
7	159 000	624 000	141 000	924 000
8	69 700	296 000	28 200	394 000
9	146 000	374 000	64 800	584 000
10	52 200	182 000	-9490	225 000
11	161 000	479 000	69 200	709 000
12	-19 100	68 800	-27 700	22 000
13	8250	6990	4700	19 900
14	34 200	304 000	38 300	376 000
15	-26 000	26 600	-12 000	-11 300
16	48 500	129 000	36 000	213 000
17	-59 800	87 800	-50 300	-22 300
18	32 200	207 000	63 000	303 000
19	78 700	206 000	80 700	365 000
20	104 000	202 000	144 000	450 000
21	50 200	242 000	-740	291 000
22	4410	55 000	4720	64 100
23	110 000	293 000	65 900	469 000
24	101 000	80 500	88 300	270 000
25	107 000	348 000	142 000	596 000
26	-141 000	-185 000	26 200	-300 000
27	61 400	63 700	121 000	246 000
28	107 000	285 000	48 000	440 000
29	40 700	252 000	43 500	336 000
30	156 000	296 000	69 300	521 000
31	127 000	207 000	3580	338 000

TABLE IX – DAILY VALUES OF TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N IN SEPTEMBER 1958

Day	Layers (mb)			
	50-113	113-500	500-1000	50-1000
	10^{21} $g\ cm^2/s^2$			
1	4970	105 000	-10 100	99 700
2	3880	130 000	-20 700	114 000
3	14 100	146 000	-6540	153 000
4	8030	173 000	9480	190 000
5	4040	105 000	4010	113 000
6	5280	113 000	4070	122 000
7	4950	58 200	10 100	73 300
8	4520	124 000	16 400	145 000
9	520	99 700	-32 300	67 800
10	7450	97 000	-18 000	86 500
11	1320	15 800	-27 900	-10 800
12	-2720	15 900	-24 700	-11 500
13	240	-24 200	-15 900	-39 800
14	-2190	65 200	3260	59 800
15	110	-26 500	-6220	-32 600
16	3630	73 600	-47 600	29 600
17	-1780	5320	-8440	-4900
18	5580	-1310	-5020	-750
19	11 100	174 000	15 300	200 000
20	-120	79 100	-3870	75 100
21	5360	76 300	46 200	128 000
22	10 400	184 000	16 400	211 000
23	14 700	159 000	29 000	203 000
24	13 000	190 000	20 100	223 000
25	6910	102 000	52 200	161 000
26	5620	91 300	40 600	138 000
27	50	4180	-40 500	-36 300
28	-2220	58 200	2210	58 200
29	180	-13 300	3110	-10 000
30	-3580	74 100	52 600	123 000

maximum in February and a minimum in August, exceeded that due to the local eddies from about August to November. The maximum in local eddy flux in January presumably corresponded to the winter maximum in the subtropical jet, while the standing eddy flux maximum which occurred in February suggested that considerable blocking occurred in the subtropics in winter.

(vi) *The northward flux of omega angular momentum*

The omega angular momentum of a parcel of air is that part of the absolute angular momentum due to the earth's rotation; the numerical value of its flux at any pressure level can be obtained by multiplying the S–N wind component by a suitable constant. This has been done in Figure 2 by adding a suitable scale at the top of the diagram so that the value of omega angular momentum is obtained from the corresponding value of mean monthly latitudinal meridional wind component $[\bar{v}]$. Broadly speaking, the flux of omega momentum is positive in the upper troposphere and negative in the lower troposphere in all months. The effect of the Hadley circulation is, therefore, to cause an increase in *relative* angular momentum as air moves northwards in the upper troposphere and to decrease relative angular momentum as air moves southwards in the lower troposphere. This increase in relative angular momentum which occurs when air moves northwards could be one of the causes of the subtropical jet stream.

At 50 millibars in June and September the flux of omega momentum is southwards and it would be expected, from the conservation of absolute angular momentum, that the zonal wind would become less westerly, or more easterly, to the south of latitude 30°N. In fact, in June and September the zonal wind is easterly, but it would be wrong to invoke the principle of the conservation of absolute angular momentum to explain entirely the existence of jet streams or other winds as in the troposphere; frontogenetic processes must play an important part. The integrated flux of omega angular momentum throughout the atmosphere is zero so that the Hadley cells merely transfer relative angular momentum from one level of the atmosphere to another.

(vii) *Summary and discussion of main results obtained for the flux of angular momentum in the layer 50-1000 mb*

Before leaving this discussion of flux of angular momentum it will be instructive to collect the main results in Table X.

TABLE X – FLUX OF RELATIVE ANGULAR MOMENTUM IN THE LAYER 50-1000 mb FOR JUNE 1958

Month	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
		10^{25} $g\ cm^2/s^2$		
March	34.3	4.1	15.1	15.0
June	19.2	0.3	10.4	8.5
September	8.7	1.2	1.4	6.2
December	35.6	5.5	16.2	13.8
Mean	24.5	2.8	10.8	10.9

Considering the means for the four months it will be clear that the mean or cellular flow made only a small contribution to the flux of angular momentum (but it was seen earlier that the mean flow was important at individual pressure levels), the main transporting agents being the two types of eddy which appear equally important. In most months too, both types of eddy made equal contributions to the flux but in September the standing eddy flux was considerably greater than the local eddy flux.

§10 – FLUX OF SENSIBLE HEAT

(i) *Flux of sensible heat during June 1958*

(a) Total flux. Figure 41 gives cross-sections of the flux of total sensible heat across latitude 30°N during June 1958. Well-defined maxima of total flux occurred at about 200 mb and 120°W, 200 mb and 40°E and 180 mb and 120°E. The general pattern of the isopleths of total flux resembles the pattern of the meridional wind isopleths and the cross-sections suggest that the integrated south to north total flux could have been negative.

(b) Local eddy flux. Values of local eddy flux of sensible heat (i.e. due to the term involving $\overline{v'T'}$) are presented in the cross-section, Figure 42. The patterns are more complex than those of total flux, with the largest values in some places occurring near the maximum S–N wind component, but this was not always so. It is noteworthy that the large values of local eddy flux of sensible heat at 135°E are not associated with the S–N jet.

Figure 10 depicts the variation with pressure of local eddy flux and standing eddy flux for June 1958. The heat flux due to the local eddies is positive in the upper troposphere, negative in the middle troposphere and positive in the lower troposphere giving a positive total flux from 50 to 1000 mb of 176 x 10^{11} cal/s.

(c) Standing eddy flux. Figure 43 is a cross-section of standing eddy flux of sensible heat for June 1958, from which it is seen that quite pronounced patterns of standing eddy flux occur. For example, the large positive values at about 93°E at 200-250 mb were probably connected with the monsoon. There are also some large low-level seasonal features such as that at about 50°E due to the Shamal, a north-westerly wind which blows in summer over Iraq and the Persian Gulf, and that at about 136°W due to rather marked and persistent low-level northerlies in this area.

The variation of standing eddy flux with pressure is given in Figure 10. The standing eddy flux is large and positive in the upper troposphere and lower stratosphere, becomes zero at about 525 mb, is negative from 525 to 960 mb and is again positive from 960 to 1000 mb. The total standing eddy flux for the layer 50-1000 mb was 410 x 10^{11} cal/s, a value more than twice that due to the local eddies. This result might have been expected since the summer months in the neighbourhood of latitude 30°N are characterized by marked seasonal features which are perturbed from time to time by feeble synoptic disturbances thus giving rise to large standing eddy flux and small local eddy flux.

(d) Total eddy flux. Figure 10 shows the variation of total eddy flux of sensible heat with pressure. The flux was positive from 1000 to 820 mb, negative from 820 to 470 mb (largely due to negative flux from the standing eddies), and positive from 470 to about 60 mb, the maximum value occurring at about 100 mb. The total eddy flux for the layer 50-1000 mb was 586 x 10^{11} cal/s.

(e) Flux due to the mean flow. The flux of sensible heat with pressure due to the mean flow is depicted in Figure 11. It is seen that the flux was small and negative in the lower troposphere because of small negative values of $[\overline{v}]$, small and positive in the upper troposphere because of small positive values of $[\overline{v}]$ and small and negative at 50 mb.

The total flux from 50 to 1000 mb due to the mean flow was -1910 x 10^{11} cal/s. Thus a Hadley cell transports sensible heat southwards but it will be shown later that if the potential energy transported by the Hadley cell is included then a Hadley cell transports *energy* northwards. It is of interest that although the mean Hadley circulation during June 1958 was weak, the flux of sensible heat transported southwards by the Hadley cell was of the same order of magnitude as that transported during the other three months when the Hadley circulations were much stronger.

(f) Daily values of total flux of sensible heat during June 1958. These are given in Table XI. The daily values of total flux of sensible heat which seem more erratic than the daily values of total flux of angular momentum, have an irregular periodicity of a few days again suggesting that possibly the driving force behind the general circulation stems from large synoptic-type eddies.

(ii) *Flux of sensible heat during December 1958*

(a) Total flux. The total flux of sensible heat is given in the cross-section, Figure 44. It is clear on comparing this figure with the cross-section of S–N wind component (Figure 30) that the pattern of total flux is determined mainly by the pattern of S–N wind component.

(b) Local eddy flux. Figure 45 is a cross-section of local eddy flux of sensible heat. The largest fluxes were at 5°W at 400 mb and 150 mb, and in the central and eastern Pacific. The comparative smallness of values at about 145°E was no doubt due to the steadiness of the S–N wind components.

The variation of local eddy flux with pressure for December 1958 is given in Figure 12. Values were positive at all pressure levels and yielded a total flux from 50 to 1000 mb of 1490×10^{11} cal/s.

(c) Standing eddy flux. The cross-section of values of standing eddy flux, Figure 46, shows that quite large values occurred, for example over the Pacific at 150°E and 180 mb. Referring to Figure 12 again it will be noticed that the flux due to the standing eddies was small in the lower stratosphere but became positive in the upper troposphere, assumed small negative values in the middle troposphere and then became positive from 600 to 1000 mb. The total flux from 50 to 1000 mb due to the standing eddies was 337×10^{11} cal/s, a value much less than that due to the local eddies but a result to be expected in a winter month.

(d) Total eddy flux. Figure 12 gives the variation of total eddy flux of sensible heat with pressure. The total eddy flux is positive at all pressure levels, with the maximum occurring at about 950 and 300 mb and giving a total eddy flux for the layer 50-1000 mb of 1830×10^{11} cal/s.

(e) Flux due to the mean flow. The flux of sensible heat with pressure due to the mean flow is given in Figure 11 from which it will be seen that the flux was large and negative in the lower troposphere, became zero at about 640 mb and remained positive to 50 mb. The total flux for the layer 50-1000 mb due to the mean flow was -2510×10^{11} cal/s, which was the largest value for the four months considered.

(f) Daily values of the total flux of sensible heat during December 1958. These are given in Table XII. The daily values vary in an irregular manner with periodicities of a few days. It is noteworthy that the daily values were negative on more than half the days in the month.

(iii) *Flux of sensible heat during March 1958*

(a) Total flux. Cross-sections of total northward flux of sensible heat (not reproduced) for March 1958 show that the largest fluxes occurred, for the most part, between 250 and 150 mb and were associated with the S–N jets. The largest S–N transports occurred over the eastern Pacific at about 130°W, over the U.S.A. at about 100°W, over China at about 100°E, over the western Pacific at 152°E and again at 176°W where the largest value of all occurred. One might have expected large values of total flux of sensible heat in the longitude of Japan in association with the jet there (Figure 31(*b*)) but in fact the winds were presumably too westerly and too steady for this to have occurred.

(b) Local eddy flux. Cross-sections of values of local eddy flux of sensible heat (not reproduced) showed a complicated pattern of isopleths with positive and negative maxima occurring

TABLE XI – DAILY VALUES OF TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N IN JUNE 1958

Day	Layers (mb)			
	50-125	125-500	500-1000	50-1000
	10^{11} *cal/s*			
1	-100	4100	-9240	-5240
2	2630	43 600	50 500	96 700
3	7330	3970	4140	15 400
4	1670	3930	59 900	65 500
5	503	42 900	66 300	110 000
6	-620	84 200	16 600	100 000
7	6420	-450	-24 300	-18 300
8	890	35 500	-54 500	-18 100
9	-1370	-62 300	13 000	-50 600
10	-4310	13 700	-47 600	-38 200
11	-4300	-28 200	51 900	19 300
12	6070	-99 400	-50	-93 400
13	-1840	-15 800	3650	-14 000
14	2090	50 300	-43 900	8480
15	-830	10 600	-85 800	-76 000
16	6290	1140	-74 300	-66 800
17	-5870	-16 000	-2310	-24 200
18	-6310	-52 200	-48 900	-107 000
19	-1460	24 800	-64 400	-41 100
20	3320	-39 300	-33 900	-69 900
21	2720	51 000	800	54 500
22	-2290	-35 200	-50 300	-87 800
23	-3320	21 800	28 000	46 600
24	-3780	-18 600	-18 200	-40 700
25	3570	-22 900	-580	-19 900
26	2890	-37 100	3750	-30 500
27	-2200	57 400	57 600	113 000
28	1610	-2240	44 900	44 300
29	300	43 300	25 800	69 400
30	6290	23 800	-8110	22 000

TABLE XII – DAILY VALUES OF TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N IN DECEMBER 1958

Day	Layers (mb)			
	50-160	160-500	500-1000	50-1000
	10^{11} cal/s			
1	8060	36 200	-80 500	-36 200
2	7100	-1230	-50 000	-44 200
3	-5970	-13 500	-59 600	-79 000
4	5790	-17 700	-26 700	-38 600
5	18 700	123 000	-39 900	102 000
6	11 100	35 400	-37 000	9590
7	9450	26 600	-36 300	-300
8	1530	-4990	-5150	-8620
9	6630	76 200	42 700	126 000
10	-9880	-31 400	-25 400	-66 700
11	9280	105 000	-29 600	84 700
12	12 800	89 600	2930	105 000
13	19 900	41 800	-11 100	50 500
14	1620	-7840	-44 200	-50 500
15	-14 700	-41 300	-76 100	-132 000
16	17 200	-51 500	-34 800	-69 100
17	11 100	49 700	-48 400	12 400
18	-2490	-26 800	-32 100	-61 300
19	4130	53 300	23 700	81 200
20	17 400	120 000	3570	141 000
21	7510	81 900	71 900	161 000
22	-5820	-44 300	-23 300	-73 400
23	14 200	65 700	7210	87 100
24	-5210	-65 900	1430	-69 700
25	7700	12 500	22 900	43 200
26	-6620	-52 200	-18 800	-77 600
27	11 100	57 500	-17 100	51 500
28	5090	-50 000	-21 700	-66 600
29	-660	-14 700	-13 600	-29 000
30	3980	380	-91 200	-86 900
31	2640	-35 800	-52 700	-85 800

almost vertically above each other especially in the western hemisphere. The largest values of local eddy flux occurred at 20°E at 200 mb. These large values may have been partly due to errors in estimating high-level winds at 30°N 10°E owing to lack of wind information south of 30°N in this area.

The variation of local eddy flux of sensible heat with pressure is given in Figure 13). The local eddy flux is mainly positive but small negative values occurred at about 100 mb. The total local eddy flux of sensible heat in the layer 50-1000 mb was 1820 x 10^{11} cal/s.

(c) Standing eddy flux. Cross-sections giving values of standing eddy flux of sensible heat (not reproduced) show that, on the whole, the standing eddies were rather weak in March 1958: a result to be expected since March that year was a winter-type month in the subtropics.

The variation of standing eddy flux with pressure is given in Figure 13. The flux is negative from 50 to 170 mb and positive from 170 to 1000 mb. The total standing eddy flux from 1000 to 50 mb was 404 x 10^{11} cal/s, a value much less than the flux due to the local eddies but consistent with the fact that March 1958 was a winter-type month at latitude 30°N.

(d) Total eddy flux. The variation with pressure of total eddy flux of sensible heat is shown in Figure 13. The values were mainly positive, the maximum occurred at about 850 mb, but negative values occurred from about 140 to 60 mb. The local eddies made the greater contribution to the total eddy flux of sensible heat, which for the layer 50-1000 mb amounted to 2220 x 10^{11} cal/s.

(e) Flux due to the mean flow. Figure 11 depicts the variation of flux of sensible heat with pressure for March 1958. The flux was large and negative at 1000 mb, decreased almost linearly with pressure to become zero at about 600 mb and then remained positive in the upper troposphere but decreased to almost zero at 50 mb. The total flux due to the mean flow was -2420 x 10^{11} cal/s.

(f) Daily values of total flux of sensible heat for March 1958. These are given in Table XIII from which it is seen that there were quite large day-to-day variations in total flux.

(iv) *Flux of sensible heat during September 1958*

(a) Total flux. Cross-sections of total flux of sensible heat (not reproduced) showed that the main regions of flux of total sensible heat corresponded closely to the S–N wind maxima. The largest value occurred at about 35°E.

(b) Local eddy flux. Cross-sections giving values of local eddy flux of sensible heat show that the patterns formed by the isopleths of local eddy flux of sensible heat were more complicated than those of total flux of sensible heat. One noteworthy feature was that the local eddy flux of sensible heat near the region of large total flux at about longitude 30°E was comparatively small presumably because of rather steady winds in this area.

The variation of monthly mean local eddy flux with pressure is given in Figure 14. The flux is small and positive from 1000 to 220 mb and small and variable from 220 to 50 mb. The total local eddy flux of sensible heat from 50 to 1000 mb was 190 x 10^{11} cal/s.

(c) Standing eddy flux. Cross-sections of standing eddy flux of sensible heat (not reproduced) showed that the absolute values of the maxima of the standing eddy fluxes were larger than those of the local eddies and the patterns formed by the standing eddy isopleths were more pronounced than those for the local eddies. The main seasonal features present in June were still present in September.

The variation of standing eddy flux of sensible heat with pressure is given in Figure 14. The flux was negative from 50 to 115 mb, positive from 115 to 590 mb, negative from 590 to

TABLE XIII – DAILY VALUES OF TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N IN MARCH 1958

Day	Layers (mb)			
	50-190	190-500	500-1000	50-1000
		10^{11} *cal/s*		
1	39 900	25 700	13 600	79 100
2	19 800	156 000	-40 800	135 000
3	14 500	48 700	-4750	58 400
4	4860	18 800	-26 700	-3040
5	-5380	-97 900	-81 700	-185 000
6	17 400	-2700	-35 800	-21 100
7	18 900	50 000	-49 200	19 700
8	8660	29 100	31 400	69 100
9	23 600	38 500	560	62 600
10	7410	1000	-11 000	-2630
11	35 500	147 000	5820	189 000
12	-6290	-5670	-56 200	-68 200
13	3200	-27 700	-67 600	-92 100
14	-170	17 000	-40 600	-23 800
15	-3880	-47 000	-85 800	-137 000
16	3810	-19 600	-23 500	-39 300
17	-17 400	-5780	-30 500	-53 700
18	-2890	-5890	-21 900	-30 700
19	10 600	16 200	-26 500	240
20	12 000	200	29 700	41 900
21	1080	740	600	2420
22	-8980	-17 100	-18 000	-44 100
23	19 700	-30 800	-31 700	-42 800
24	21 100	16 000	95 200	132 000
25	17 800	53 800	62 900	134 000
26	-32 400	-98 100	-45 300	-176 000
27	2500	-12 300	45 400	35 600
28	10 300	15 800	28 100	54 200
29	-13 800	-14 300	-9360	-37 500
30	9170	-31 000	-66 500	-88 300
31	13 600	-8100	19 800	25 400

975 mb and positive from 975 to 1000 mb. The total standing eddy flux from 50 to 1000 mb was -7 x 10^{11} cal/s, a very small value. This was not due to an absence of standing eddies, but rather to positive and negative standing eddies cancelling each other out. This result was different from the result for June in which the local eddy flux was much smaller than the standing eddy flux.

(d) Total eddy flux. Figure 14 shows the variation of total eddy flux of sensible heat with pressure. The flux was positive from 1000 to 950 mb, negative from 950 to about 640 mb, positive from 640 to about 110 mb and negative from 110 to 50 mb. The total eddy flux for the layer 50-1000 mb was 184 x 10^{11} cal/s, a value less than one-tenth of the corresponding values for March and December.

(e) Flux due to the mean flow. The flux shown in Figure 11 was large in the lower troposphere, became zero at about 715 mb, remained positive to the upper troposphere and then became negative in the upper troposphere and lower stratosphere. The total flux from 50 to 1000 mb due to the mean flow was -1660 x 10^{11} cal/s. It will be seen from Figure 11 that the variation of flux of sensible heat with pressure due to the mean flow during September 1958 resembled those for March and December rather than that for June even though in some respects September 1958 was a summer-type month. The flux of sensible heat for September 1958 due to the mean flow mostly resembled that for June in the upper troposphere and lower stratosphere.

(f) Daily values of total flux of sensible heat for September 1958. These are given in Table XIV. It is seen that the flux was negative on 15 of the 30 days and the difference in fluxes on consecutive days could be large, as on the 18th and 19th.

(v) *Mean values of eddy fluxes of sensible heat for March, June, September and December 1958*

In order to exhibit the monthly variation in the eddy flux of sensible heat for the layer 50-1000 mb for the four months considered, the monthly values of the various fluxes were plotted and reasonable curves drawn to fit the points as shown in Figure 15. The curve for total eddy flux suggests that values were small and possibly negative (i.e. southwards) from the middle of July to early in September. Values of local eddy flux were large in the winter months but possibly became small and negative late in June until the end of August. Standing eddy fluxes, which were small and rather constant from January to June, probably assumed small negative values from early August to mid-September and became positive thereafter. It is of interest to note too that from early June to late August the standing eddy flux exceeded the local eddy flux.

(vi) *Summary of results obtained for the flux of sensible heat in the layer 50-1000 mb*

At this stage it seems appropriate and of interest to discuss and summarize the main results obtained for the flux of sensible heat. These results are given in Table XV.

TABLE XIV – DAILY VALUES OF TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N IN SEPTEMBER 1958

Day	Layers (mb)			
	50-113	113-500	500-1000	50-1000
	10^{11} *cal/s*			
1	1320	-1150	-38 900	-38 800
2	-2490	-8920	-25 700	-37 100
3	-1850	11 590	10 600	20 300
4	450	42 900	-14 200	29 200
5	-3660	71 400	42 400	110 000
6	4620	60 500	-2790	62 300
7	-700	36 700	4180	40 100
8	-480	7900	3580	11 000
9	-2980	-39 600	1390	-41 200
10	1760	47 600	27 200	76 600
11	-5270	-64 300	13 400	-56 200
12	770	25 300	17 000	43 000
13	-3370	50 700	-61 700	-14 400
14	-1410	43 700	-86 400	-44 100
15	270	41 500	-2870	38 900
16	1700	51 900	-58 300	-4720
17	-5840	-20 700	-60 100	-86 600
18	2080	-55 000	-16 200	-69 100
19	1280	63 700	-8190	56 800
20	2410	20 500	20 500	43 400
21	-2610	26 000	-34 500	-11 000
22	-4440	-32 400	-9300	-46 100
23	880	-16 000	-19 600	-34 800
24	2510	-13 100	11 300	700
25	-3480	-1540	-58 400	-63 400
26	1800	-3230	25 100	23 600
27	-4350	-40 300	-110 000	-155 000
28	-160	56 300	15 400	71 500
29	570	55 400	560	56 500
30	3050	910	-30 500	-26 500

TABLE XV – FLUX OF SENSIBLE HEAT IN THE LAYER 50–1000 mb IN 1958

Month	Flux due to total flow	Flux due to mean flow	Local eddy flux	Standing eddy flux
		10^{11} *cal/s*		
March	-199	-2420	1820	404
June	-1330	-1910	176	410
September	-1470	-1660	191	-7
December	-689	-2510	1490	337
Mean	-926	-2130	918	286

In every month:

(*a*) the total flux of sensible heat was southwards;

(*b*) the cellular flux of sensible heat was southwards;

(*c*) the local eddy flux was northwards;

(*d*) the standing eddy flux was northwards except in September when the value was so small that the actual value could have been positive.

In the winter months March and December the local eddy flux was greater than the standing eddy flux while in June the standing eddy flux exceeded the local eddy flux. The standing eddy flux in September was so small that its sign cannot be relied upon.

The foregoing results show that in every month sensible heat was transported southwards but it will be shown later that the flux of energy from the total and mean flows was northwards.

§11 – FLUX OF LATENT HEAT

(i) *June 1958*

(*a*) *Total flux.* Figure 47 gives cross-sections of values of total flux of latent heat across latitude 30°N during June 1958. The largest values occurred near the surface and mainly over the sea, such as those from 90°W to 100°W which were due to moist southerly winds from the Gulf of Mexico. Large positive values also occurred over the Pacific at 150°E associated with southerly winds. The variation of total flux of latent heat with pressure is given in Figure 16. This flux was positive at all pressure levels with the maximum at about 850 mb. It decreased above 850 mb to become comparatively small at 300 mb. The total flux due to the total flow was 3130 x 10^{11} cal/s, a value greater than the corresponding flux of sensible heat, which was negative

(*b*) *Local eddy flux.* Values of local eddy flux of latent heat are shown in the cross-section, Figure 48. The large values over the Rockies were presumably due to seasonal and orographic effects. The mean cross-sections for June 1958[1] show that values of humidity mixing ratio increased in the layer 1000-400 mb east of the Rockies, compared with the value to the west of the Rockies, and part of this increase may have been due to lifting of air by the Rockies, the lifted air having largely retained its value of humidity mixing ratio. Weak fronts and tropical storms no doubt account for the large values at 135°E in the longitude of Japan. However, calculations show that the greater part of the total flux of latent heat over the hemisphere was due to the standing eddies. Figure 16 shows the variation of local eddy flux of latent heat with pressure and it is apparent that values were positive at all pressure levels. The total local eddy flux of latent heat across latitude 30°N in the layer 300-1000 mb was 1170 x 10^{11} cal/s.

(c) Standing eddy flux. Cross-sections of standing eddy flux of latent heat across latitude 30°N for June 1958 are given in Figure 49. Large standing eddies in the flux of latent heat occurred in the western hemisphere at 125°W and 100°W (the latter probably an orographic effect), each being associated with rather strong low-level mean winds (see Figure 26(*a*)). In the eastern hemisphere the most intense standing eddies in the flux of latent heat occurred at about 10°E, 18°E, 45°E and 150°E and all were associated with comparatively strong low-level mean winds (Figure 28(*b*)). Figure 16 shows the monthly variation of standing eddy flux of latent heat with pressure. The main feature of interest from the graph is that the standing eddy flux was larger than the local eddy flux from about 660 to 1000 mb, giving a total standing eddy flux across latitude 30°N for the layer 300-1000 mb of 2230 x 10^{11} cal/s, a value almost twice that due to the local eddies. This result is to be expected since in summer the standing eddies are stronger than the local eddies.

(d) Flux due to the mean flow. The variation of flux of latent heat with pressure is given in Figure 16. This flux was southwards in the lower troposphere but decreased with decreasing pressure to become very small at 500 mb. The total flux of latent heat due to the mean flow for the layer 300-1000 mb was -268 x 10^{11} cal/s. It is clear that in June 1958 the mean flow played a minor role in the transport of latent heat, the main transporting agent being the standing eddies.

(e) Daily values of total flux. Daily values of total flux of latent heat for June 1958 are given in Table XVI. Layer 50-1000 mb showed that the daily values of total flux were mainly positive and fluctuated with varying periodicities of two to eight days no doubt because of the effect of synoptic-type eddies.

(ii) *December 1958*

(a) Total flux. The cross-section of total flux of latent heat in December 1958 is given in Figure 50. The largest values of total flux mostly occurred near sea level in association with southerly winds. It appears from the cross-sections that the integrated flux round the latitude circle would have been positive. The variation of total flux of latent heat with pressure due to the total flow is given in Figure 17. The flux was negative in the lower troposphere, became zero at about 865 mb and then remained positive to 250 mb where it became very small. The total flux due to the total flow in the layer 250-1000 mb was 521 x 10^{11} cal/s, a value much smaller than the corresponding flux for June.

(b) Local eddy flux. The cross-section of local eddy flux of latent heat is given in Figure 51. It is seen that the largest values occurred near sea level and that positive values predominated. The variation of local eddy flux of latent heat with pressure is given in graphical form in Figure 17. The flux due to the local eddies was very small in the upper troposphere and positive in the middle and lower troposphere giving a total local eddy flux for the layer 250-1000 mb of 1530 x 10^{11} cal/s.

(c) Standing eddy flux. The cross-section of the standing eddy flux of latent heat in December 1958 is given in Figure 52. In both hemispheres the standing eddies were not very intense but the main centres were at 140°W, 120°W, 50°W and 135°E and all were associated with comparatively strong mean low-level meridional winds (Figure 30).

The variation with pressure of the standing eddy flux of latent heat is given in Figure 17. The flux due to the standing eddies was small and positive at all pressure levels and yielded

TABLE XVI – DAILY VALUES OF TOTAL FLUX OF LATENT HEAT ACROSS LATITUDE 30°N IN JUNE 1958

Day	Layers (mb)			
	50-300	300-500	500-1000	50-1000
	10^{11} *cal/s*			
1	0	276	1090	1370
2	0	747	4330	5080
3	0	-0.76	1730	1720
4	0	23.9	4660	4680
5	0	343	2735	3080
6	0	-3.53	3700	3700
7	0	-89	-222	-311
8	0	458	450	908
9	0	358	802	1160
10	0	573	3690	4270
11	0	136	6920	7060
12	0	-511	3980	3470
13	0	150	2970	3120
14	0	451	-127	324
15	0	260	-1350	-1090
16	0	9.26	2820	2830
17	0	304	3730	4030
18	0	-121	-192	-313
19	0	486	-603	-117
20	0	-41.4	1370	1320
21	0	-15.4	2830	2810
22	0	-212	3340	3130
23	0	604	7750	8360
24	0	673	3430	4110
25	0	107	4690	4800
26	0	-38.5	5590	5550
27	0	290	3830	4120
28	0	563	6720	7280
29	0	545	4821	5370
30	0	107	912	1020

a total for the layer 250-1000 mb of 388 x 10^{11} cal/s, a value much less than that due to the local eddies, but a result to be expected in winter.

(d) Flux due to the mean flow. Figure 17 shows the variation of flux of latent heat with pressure due to the mean flow. The flux was large and negative at 1000 mb but decreased rather sharply at first with decreasing pressure to become zero at about 620 mb. From 620 to 300 mb the flux was very small and positive. The total flux of latent heat due to the mean flow for the layer 300-1000 mb was -1390 x 10^{11} cal/s, a not insignificant value and numerically nearly equal to the positive flux due to the local eddies.

(e) Daily values of total flux. Table XVII gives daily values of total flux of latent heat for December 1958. The daily values vary in an irregular manner with varying periodicities of a few days. It is noteworthy that the daily values were negative for more than half of the days in the month.

(iii) *March 1958*

(a) Total flux. Cross-sections of total transport of latent heat for March 1958 (not reproduced) show that owing to the rapid decrease of humidity mixing ratio with height in the atmosphere, the main transport of latent heat at latitude 30°N occurred for the most part in the lowest 10 000 ft of the atmosphere and mostly over the oceans where, from the cross-sections, values were up to seven times the values which occurred over land.

The variation of flux of latent heat with pressure due to the total flow is given in Figure 18. The flux was positive at all pressures, reached a maximum around 850 mb and decreased rather rapidly with decreasing pressure above 700 mb to become almost zero at 250 mb. The total flux for the layer 250-1000 mb was 1490 x 10^{11} cal/s.

(b) Local eddy flux. Cross-sections of local eddy flux of latent heat showed that the largest values occurred over the oceans, the large values at about longitude 90°W presumably being due to the proximity of the warm and moist air over the Gulf of Mexico.

The variation of local eddy flux of latent heat with pressure is given in graphical form in Figure 18. The local eddies gave a positive transport of latent heat at all pressures but the largest values occurred in the lower troposphere from 700 to 1000 mb. The total local eddy flux of latent heat in the layer 250-1000 mb was 2620 x 10^{11} cal/s.

(c) Standing eddy flux. Cross-sections of standing eddy flux of latent heat (not reproduced) showed that the standing eddies were rather weak in March, with the main eddies occurring at about 160°W, 35°W, 120°E and 165°E (at 700 mb), and all were associated with rather strong monthly mean low-level winds.

(d) Flux due to the mean flow. The variation of flux of latent heat with pressure due to the mean flow is presented in Figure 18. This flux was large and negative at 1000 mb, decreased with decreasing pressure to become zero at 600 mb and remained small and positive from 600 to 250 mb. The total flux due to the mean flow for the layer 250-1000 mb was -770 x 10^{11} cal/s, a rather small value when compared with that due to the local eddies of 2620 x 10^{11} cal/s.

(e) Daily values of total flux. These values for the layer 250-1000 mb are given in Table XVIII. These were positive for the most part with maximum values occurring about every three or four days.

(iv) *September 1958*

(a) Total flux. Cross-sections of total flux of latent heat for September 1958 (not reproduced) showed large values of flux over the U.S.A. at about 95°W and over the Pacific at about 140°E.

TABLE XVII – DAILY VALUES OF TOTAL FLUX OF LATENT HEAT ACROSS LATITUDE 30°N IN DECEMBER 1958

Day	Layers (mb)			
	50-250	250-500	500-1000	250-1000
	10^{11} *cal/s*			
1	0	169	-1670	-1500
2	0	292	-698	-406
3	0	-146	-962	-1110
4	0	-312	490	178
5	0	-132	-105	-238
6	0	37	296	333
7	0	226	159	384
8	0	482	2650	3130
9	0	492	3860	4350
10	0	20	806	826
11	0	683	3510	4190
12	0	728	2090	2820
13	0	-156	-1180	-1340
14	0	-17	-1840	-1850
15	0	370	-558	-188
16	0	273	-1710	-1430
17	0	185	-2570	-2380
18	0	268	-392	-124
19	0	209	639	848
20	0	208	-1740	-1540
21	0	364	1640	2010
22	0	121	-797	-676
23	0	249	1980	2230
24	0	238	799	1040
25	0	294	1650	1940
26	0	175	3250	3430
27	0	227	787	1010
28	0	-119	252	134
29	0	137	1550	1690
30	0	-143	-1870	-2010
31	0	369	53.9	422

TABLE XVIII – DAILY VALUES OF THE TOTAL FLUX OF LATENT HEAT ACROSS LATITUDE 30°N IN MARCH 1958

Day	Layers (mb)			
	50-250	250-500	500-1000	50-1000
	10^{11} *cal/s*			
1	0	64.7	1920	1980
2	0	469	543	1010
3	0	38.6	1800	1840
4	0	63.4	-945	-882
5	0	-98.1	-337	-435
6	0	147	1600	1750
7	0	63.2	295	358
8	0	120	5530	5650
9	0	76.0	1310	1390
10	0	48.0	1290	1340
11	0	428	790	1220
12	0	-41.8	906	864
13	0	98.9	-659	-560
14	0	259	245	503
15	0	-132	-1460	-1590
16	0	228	2.9	231
17	0	93.5	876	969
18	0	-27.6	-729	-757
19	0	335	-381	-46.3
20	0	387	2320	2710
21	0	384	2750	3130
22	0	-110	1100	985
23	0	-18.7	1140	1120
24	0	284	5040	5330
25	0	315	4160	4480
26	0	272	1170	1450
27	0	230	2790	3020
28	0	240	3310	3550
29	0	279	3100	3370
30	0	145	678	823
31	0	-82.0	1620	1540

The variation of total flux of latent heat with pressure is presented graphically in Figure 19. The flux was negative at 1000 mb, became zero at about 910 mb and positive from 900 to 300 mb where it became almost zero. The total flux of latent heat due to the total flow in the layer 250-1000 mb was 951×10^{11} cal/s.

(b) Local eddy flux. Cross-sections of local eddy flux of latent heat (not reproduced) showed rather weak flux patterns, but the largest values occurred at about 120°E. The variation of local eddy flux of latent heat with pressure is given in Figure 19. The flux due to the local eddies was small and positive at all pressure levels with a total flux of 522×10^{11} cal/s in the layer 250-1000 mb.

(c) Standing eddy flux. The September cross-sections of standing eddy flux (not reproduced) show that there were intense standing eddies in the flux of latent heat in both hemispheres; the eddies were located at about 120°W, 100°W, 10°W, 25°E, 50°E and 140°E and all were associated with rather large mean low-level meridional winds.

The variation of pressure with flux of latent heat due to the standing eddies is presented graphically in Figure 19 from which it is apparent that the flux had a small negative value in the upper troposphere, became zero at 420 mb and positive at greater pressures, reaching large positive values in the lower troposphere. The total standing eddy flux of latent heat from 250 to 1000 mb was large, 2030×10^{11} cal/s. Large values would be expected in September, a summer-type month, but the total flux of latent heat was small owing to a large negative contribution from the mean flow.

(d) Flux due to the mean flow. Figure 19 shows the variation of flux of latent heat with pressure due to the mean flow. This flux was large and negative at 1000 mb but became zero at about 710 mb and was small and positive from 710 to 250 mb. The total flux of latent heat across latitude 30°N due to the mean flow in the layer 250-1000 mb was -1600×10^{11} cal/s, a value which cancelled out about 75 per cent of the positive flux due to the standing eddies.

(e) Daily values of total flux. Table XIX gives daily values of total flux of latent heat. Values were negative on 6 of the 30 days and the values fluctuated with a periodicity of a few days.

(v) *Mean values of eddy flux of latent heat for March, June, September and December 1958*

Values of eddy flux of latent heat for the four months considered are plotted in Figure 20 and reasonable curves are drawn through the points. The total eddy flux of latent heat was probably a maximum in June and a minimum in December. The local eddy flux was a maximum in March and a minimum in August, a result which might have been expected since local eddies are more pronounced than standing eddies in winter-type months.

The standing eddy flux, which was a maximum in July and a minimum (actually negative) in February, exceeded the local eddy flux from about May to November.

TABLE XIX – DAILY VALUES OF TOTAL FLUX OF LATENT HEAT ACROSS LATITUDE 30°N IN SEPTEMBER 1958

Day	Layers (mb)			
	50-250	250-500	500-1000	250-1000
	10^{11} cal/s			
1	0	208	-2300	-2090
2	0	21.2	534	555
3	0	170	1900	2070
4	0	147	1230	1380
5	0	216	4010	4220
6	0	208	317	525
7	0	111	1420	1530
8	0	-373	1030	660
9	0	-334	826	491
10	0	94.3	3300	3400
11	0	30.0	2360	2390
12	0	88.3	2640	2720
13	0	-255	-4760	-5010
14	0	-138	-3400	-3840
15	0	-31.1	761	730
16	0	117	-2010	-1890
17	0	-11.5	-2130	-2150
18	0	-379	3030	2650
19	0	424	2800	3230
20	0	400	3170	3560
21	0	296	382	677
22	0	156	1450	1610
23	0	345	917	1260
24	0	456	3520	3970
25	0	857	1000	1860
26	0	378	5110	5490
27	0	34.4	-4010	-3970
28	0	567	123	691
29	0	303	1040	1340
30	0	-48.2	576	528

(vi) *Summary of results obtained for the flux of latent heat in the layer 50-1000 mb*

The main results for the flux of latent heat are given in Table XX.

TABLE XX – TOTAL FLUX OF LATENT HEAT IN THE LAYER 50-1000 mb IN 1958

Month	Flux due to total flow	Flux due to mean flow	Local eddy flux	Standing eddy flux
		10^{11} *cal/s*		
March	1490	-770	2620	-355
June	3130	-269	1170	2230
September	951	-1600	522	2030
December	521	-1390	1530	388
Mean	1520	-1010	1460	1070

In all months:

(a) The total flux of latent heat was northwards which clearly indicated a northward flux of moisture;

(b) The cellular flux was negative because of a mean northerly wind at low levels associated with maximum moisture content;

(c) The local eddy flux of latent heat was positive;

(d) The standing eddy flux of latent heat was positive except in March when it was negative, but since the value was small its sign is probably uncertain.

In the two winter-type months March and December the local eddy flux of latent heat was appreciably greater than the standing eddy flux with a reversal of these values in the summer months June and September.

§12 – FLUX OF POTENTIAL ENERGY

It will be convenient to discuss the results for all four months together. Cross-sections of total flux of potential energy were drawn but are not reproduced. They are characterized by strong patterns resembling the patterns of the isopleths of S–N wind component which contributed very largely to the flux of total potential energy. Tables XXI–XXIV give monthly mean values of flux of potential energy at various pressure levels and total fluxes for the layer 50-1000 mb. It will be noticed that the fluxes of potential energy due to the eddies are small, thus the Hadley cells or other circulations play a major role in the transport of potential energy.

Figure 21 gives the variation of total flux of potential energy with pressure across latitude 30°N during the four months, March, June, September and December 1958 and it should be noted that a diagram giving the flux due to the mean flow would be very similar. For all months the flux was small and negative in the lower troposphere and, broadly speaking, became zero in the middle troposphere and reached a maximum positive value at about the 100-mb level. At 50 mb

TABLE XXI – FLUX OF POTENTIAL ENERGY VALUES AT VARIOUS PRESSURE LEVELS, AND INTEGRATED VALUES FOR THE LAYER 50-1000 mb FOR MARCH 1958

Pressure	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
millibars	10^{11} *cal/s per mb*			
30	-105	25.5	-130	-0.33
50	-1.61	-2.02	0.62	-0.21
70	56.2	56.0	0.42	-0.21
100	71.9	71.3	0.66	-0.04
150	43.9	43.3	0.58	0.08
200	27.2	26.2	0.86	0.13
250	14.5	12.9	1.49	0. 07
300	11.1	9.79	1.34	-0.03
400	6.25	5.10	1.15	0.00
500	6.64	5.55	1.00	0.09
600	0.73	-0.15	0.75	0.13
700	-2.60	-3.28	0.53	0.14
850	-2.84	-3.16	0.27	0.05
900	-2.00	-2.20	0.16	0.03
950	-1.41	-1.50	0.07	0.02
1000	0.00	0.00	0.00	0.00
	10^{11} *cal/s*			
Total 50-1000	9960	9220	687	50

TABLE XXII – FLUX OF POTENTIAL ENERGY VALUES AT VARIOUS PRESSURE LEVELS, AND INTEGRATED VALUES FOR THE LAYER 50-1000 mb FOR JUNE 1958

Pressure	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
millibars		10^{11} *cal/s per mb*		
50	-39.9	-41.2	1.13	0.17
70	-4.36	-5.1	0.38	0.36
100	27.6	26.2	0.81	0.62
150	8.81	7.07	0.38	1.36
200	12.2	11.1	-0.11	1.20
250	5.97	5.21	-0.13	0.89
300	3.02	2.64	-0.15	0.53
400	0.34	0.42	-0.07	-0.02
500	0.21	0.37	0.05	-0.22
600	-2.75	-2.65	0.17	-0.27
700	-1.05	-1.06	0.18	-0.17
850	-0.11	-0.17	0.09	-0.04
900	-0.64	-0.66	0.03	-0.01
950	-0.40	-0.42	0.02	0.01
1000	0.0	0.0	0.0	0.0
		10^{11} *cal/s*		
Total 50-1000	1760	1490	99	172

TABLE XXIII – FLUX OF POTENTIAL ENERGY VALUES AT VARIOUS PRESSURE LEVELS, AND INTEGRATED VALUES FOR THE LAYER 50-1000 mb FOR SEPTEMBER 1958

Pressure	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
millibars	10^{11} *cal/s per mb*			
30	-103	-76.6	-26.5	0.03
50	-34.1	-35.3	0.99	0.14
70	-19.9	-20.5	0.75	-0.13
100	4.86	4.53	0.76	-0.43
150	21.1	21.4	0.20	-0.48
200	2.94	2.2	1.13	-0.39
250	13.5	12.7	0.97	-0.20
300	23.3	22.5	0.86	-0.12
400	22.4	21.9	0.53	-0.01
500	11.0	10.9	0.15	-0.04
600	4.98	4.86	0.19	-0.07
700	1.02	0.96	0.15	-0.09
850	-4.21	-4.25	0.06	-0.03
900	-3.78	-3.81	0.04	-0.01
950	-2.22	-2.24	0.02	0.01
1000	0.0	0.0	0.0	0.0
	10^{11} *cal/s*			
Total 50-1000	6230	5980	354	-109

TABLE XXIV – FLUX OF POTENTIAL ENERGY VALUES AT VARIOUS PRESSURE LEVELS, AND INTEGRATED VALUES FOR THE LAYER 50-1000 mb FOR DECEMBER 1958

Pressure	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
millibars		10^{11} *cal/s per mb*		
30	-2.37	-108	106	0.17
50	9.82	10.3	-0.35	-0.15
70	31.9	32.6	-0.34	-0.27
100	49.5	50.5	-0.63	-0.47
150	55.5	56.1	-0.06	-0.52
200	40.4	40.4	0.53	-0.51
250	26.2	26.5	0.18	-0.44
300	15.7	15.7	0.40	-0.32
400	15.9	15.5	0.48	-0.12
500	18.7	18.2	0.46	0.04
600	4.13	3.64	0.41	0.08
700	-3.56	-3.96	0.32	0.08
850	-5.45	-5.66	0.16	0.05
900	-3.85	-3.98	0.10	0.03
950	-2.56	-2.63	0.05	0.02
1000	0.0	0.0	0.0	0.0
		10^{11} *cal/s*		
Total 50-1000	12 700	12 600	223	-107

in June and September the flux became negative, but in March the flux was very small and negative while in December it was small and positive. The largest total flux of potential energy for the layer 50-1000 mb occurred in December (12 720.5 x 10^{11} cal/s) and the smallest in June (1759.1 x 10^{11} cal/s), a value much less than that for September.

§13 – FLUX OF KINETIC ENERGY

(i) *March 1958*

Cross-sections of total flux of kinetic energy are given in Figure 53. Eddy fluxes were not computed since the energy transported in the form of kinetic energy is small compared with that transported in other forms. Clearly, most of the flux takes place in the jets and reaches a maximum at about the level of the maximum wind. It is obvious from the cross-sections that there is more positive than negative flux, i.e. the net flux round the latitude circle is probably northwards. Figure 22 shows the variation of total flux of kinetic energy with pressure.

(ii) *June 1958*

Cross-sections of total flux of kinetic energy are given in Figure 54. These sections bring out in a striking manner the way in which the flux of total kinetic energy is concentrated in or near the jets. Particularly noteworthy are the small values over most of the western hemisphere except over the west coast of the U.S.A. It is clear even from the cross-sections that there is a preponderance of positive over negative total flux.

The variation of total flux of kinetic energy with pressure is given in Figure 22. The values at the various pressure levels are smaller than those for March with the maximum occurring at about 200 mb.

(iii) *September 1958*

Figure 55 is a cross-section of total flux of kinetic energy for September 1958. As is well known the main transport of kinetic energy occurs near the S–N wind maxima. Of particular interest are the large values over the U.S.A. and at longitude 26°E, which were associated with meridional wind maxima. Referring to Figure 22 again it will be apparent that the total flux during September was smaller than it was in any of the other months considered.

(iv) *December 1958*

Cross-sections giving the total flux of kinetic energy are given in Figure 56. The usual large fluxes occur near the jets and there is clearly a preponderance of positive over negative flux.

The graph, Figure 22, shows the variation of total flux of kinetic energy with pressure. Large values of flux occurred near the level of maximum wind but the total flux from 50 to 1000 mb was less in December than in March.

(v) *Daily values of flux of kinetic energy for March, June, September and December 1958*

These daily values, given in Tables XXV-XXVIII, are mostly positive and have variable periodicities of a few days suggesting the influence of large-scale synoptic eddies.

§14 – FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY

The sum of the fluxes of sensible heat and potential energy are required when considering the flux of energy necessary to balance radiation losses. It has already been shown that in the layer 50-1000 mb there is a northward flux of potential energy across latitude 30°N in all the months considered. Therefore, unless there is a conversion of potential energy into another form of energy,

TABLE XXV – DAILY VALUES OF FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N IN MARCH 1958

Day	Layers (mb)			
	50-190	190-500	500-1000	50-1000
	10^{11} *cal/s*			
1	13.5	32.7	4.63	50.8
2	6.39	44.0	2.05	52.4
3	5.70	20.7	1.26	27.7
4	0.37	4.62	0.46	5.44
5	4.77	-1.87	-2.26	0.64
6	4.57	-5.27	-1.99	-2.68
7	11.6	42.0	3.34	56.9
8	4.33	20.3	1.74	26.4
9	7.89	22.3	3.25	33.4
10	3.66	12.8	0.75	17.3
11	6.68	18.7	1.26	26.6
12	-1.59	4.42	-1.59	1.24
13	0.83	2.95	0.37	4.15
14	2.52	16.4	0.21	19.1
15	-3.41	2.60	-1.13	-1.95
16	1.58	8.14	0.14	9.86
17	-3.53	5.61	-0.97	0.11
18	2.40	11.8	1.33	15.6
19	4.09	11.6	1.59	17.3
20	5.31	9.73	4.13	19.2
21	2.74	15.2	-1.13	16.8
22	1.92	6.68	0.95	9.55
23	7.28	19.0	1.22	27.5
24	5.44	6.4	3.96	15.8
25	6.47	18.2	3.74	28.4
26	-6.35	-3.92	1.05	-9.03
27	2.82	1.36	2.69	6.87
28	4.74	16.7	0.91	22.4
29	3.01	12.2	2.08	17.3
30	9.16	18.7	3.55	31.4
31	6.56	12.9	1.15	20.6

TABLE XXVI – DAILY VALUES OF FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N IN JUNE 1958

Day	Layers (mb)			
	50-125	125-500	500-1000	50-1000
	10^{11} cal/s			
1	-0.01	3.90	0.06	3.94
2	0.09	3.46	2.37	5.92
3	0.41	8.56	0.65	9.63
4	0.16	4.17	0.41	4.73
5	0.14	7.32	1.33	8.79
6	0.10	8.29	1.40	9.80
7	0.05	5.28	0.10	5.43
8	-0.04	2.83	-0.30	2.48
9	0.03	2.07	0.86	2.96
10	0.15	7.12	-0.41	6.87
11	0.12	6.78	0.72	7.62
12	0.22	-1.42	0.15	-1.06
13	0.18	3.32	0.41	3.91
14	0.18	7.20	0.30	7.69
15	-0.04	4.31	-0.27	4.01
16	0.35	6.75	-0.54	6.55
17	-0.19	6.32	1.41	7.54
18	0.09	4.45	-0.17	4.36
19	0.17	6.89	-0.87	6.20
20	1.99	6.25	-0.25	7.98
21	0.15	3.08	-0.28	2.96
22	-0.02	0.73	-0.86	-0.15
23	-0.24	1.65	2.17	3.59
24	-0.22	1.12	0.73	1.63
25	-0.07	-0.36	0.50	0.07
26	-0.05	0.87	0.23	1.05
27	-0.03	2.71	0.43	3.11
28	0.08	0.03	0.55	0.66
29	0.03	1.47	0.25	1.75
30	-0.09	0.05	-0.07	-0.10

TABLE XXVII – DAILY VALUES OF FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N IN SEPTEMBER 1958

Day	Layers (mb)			
	50-113	113-500	500-1000	50-1000
	10^{11} *cal/s*			
1	0.10	2.79	-0.33	2.55
2	-0.01	1.96	-0.31	1.63
3	0.19	2.69	-0.15	2.73
4	0.22	7.01	-0.42	6.80
5	-0.01	4.13	-0.06	4.05
6	0.03	3.93	-0.01	3.95
7	0.03	3.52	0.65	4.20
8	0.07	4.13	0.34	4.54
9	0.01	2.62	-0.08	2.55
10	0.11	4.41	1.95	6.47
11	0.00	-0.85	0.08	-0.77
12	0.07	1.85	0.45	2.37
13	-0.00	-0.58	-0.53	-1.11
14	-0.00	3.57	-0.40	3.17
15	0.09	3.27	0.30	3.65
16	0.13	3.44	-0.15	3.41
17	-0.02	1.28	0.36	1.61
18	-0.06	-0.80	-0.17	-1.03
19	-0.08	4.32	0.24	4.47
20	0.06	1.89	1.14	3.09
21	-0.05	0.67	0.01	0.62
22	-0.04	2.58	0.04	2.58
23	0.12	5.00	0.18	5.30
24	-0.03	1.29	0.48	1.73
25	0.01	4.03	1.36	5.40
26	0.04	1.12	1.67	2.83
27	-0.04	-0.42	-0.71	-1.17
28	-0.06	2.21	0.45	2.60
29	-0.00	0.30	0.28	0.57
30	-0.01	2.42	-0.03	2.37

TABLE XXVIII – DAILY VALUES OF FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N IN DECEMBER 1958

Day	Layers (mb)			
	50-160	160-500	500-1000	50-1000
	10^{11} *cal/s*			
1	2.03	14.4	0.21	16.7
2	2.68	11.4	0.60	14.7
3	0.36	0.97	0.70	2.02
4	1.65	-5.09	1.26	-2.18
5	3.62	14.1	0.46	18.2
6	0.43	4.15	0.44	5.01
7	3.45	10.8	1.76	16.0
8	1.78	4.34	0.93	7.05
9	4.47	28.9	0.77	34.2
10	1.48	8.15	0.25	9.89
11	3.20	33.1	0.89	37.2
12	5.67	28.6	5.14	39.4
13	3.34	21.7	3.03	28.1
14	2.62	8.17	-0.31	10.5
15	0.55	6.79	-0.10	7.25
16	3.81	2.51	-0.85	5.47
17	2.83	9.54	0.18	12.5
18	1.05	0.1	0.28	1.43
19	2.66	28.1	2.36	33.2
20	3.74	21.8	2.09	27.7
21	1.74	15.7	1.60	19.1
22	1.15	6.07	0.46	7.67
23	2.69	16.2	2.59	21.5
24	0.94	-0.11	1.66	2.49
25	4.31	14.3	1.10	19.7
26	-0.77	-0.49	0.33	-0.94
27	0.82	10.2	2.01	13.0
28	0.37	-8.04	0.64	-7.03
29	-0.07	-5.40	0.36	-5.11
30	2.90	17.2	-1.10	19.0
31	1.94	4.31	-0.41	5.85

the atmosphere north of 30°N would constantly acquire potential energy. Since this does not happen it follows that this northward flux of potential energy, plus the energy supplied by the fluxes of sensible heat and latent heat, just balances the radiation losses. The flux of kinetic energy is ignored since it has been shown that it is very small in all months.

Cross-sections of total flux of sensible heat plus potential energy due to the total flow will be presented for the four months considered but cross-sections of flux of sensible heat plus potential energy due to the mean flow would resemble the former very markedly so have not been given. Cross-sections of eddy flux of sensible heat plus potential energy have not been given since:

(a) The total flux of potential energy due to the total flow is largely controlled by the mean meridional wind and the eddies make a minor contribution.

(b) Cross-sections of the eddy fluxes of sensible heat have already been given.

(c) Some authorities suggest that the eddy fluxes of potential energy should be zero but be this as it may the eddy fluxes of potential energy found in this study were small compared with the flux of potential energy due to the mean flow.

(i) *March 1958*

(a) Total flux. In order to illustrate the longitudinal distribution of northward flux of energy, cross-sections of total flux of sensible heat plus potential energy are given in Figure 57. It will be seen, on comparing Figure 57 with the cross-sections of meridional wind given in Figure 27, that the maxima of total flux of sensible heat plus potential energy occurred at or near the maxima in meridional wind component. This is because the flux of both quantities was determined largely by the value of $\bar{v}$. There might be expected to be large values of flux of sensible heat plus potential energy at high levels, as at 10 mb, due mainly to the large potential energy at this level, but on the whole larger values do not occur because $\bar{v}$ at this level is usually small. However, the large values of flux at 10 mb and 15°W shown in Figure 57*(a)* are of interest.

The variation with pressure of flux of sensible heat plus potential energy, which may be termed flux of potential heat due to the total flow, is given in Figure 23 (lower scale). The flux was negative at 1000 mb and varied more or less linearly with pressure to become zero at about 610 mb. From 610 to 50 mb the flux was positive, the maximum occurring at about 100 mb with a rapid decrease to almost zero at 50 mb. The total flux across latitude 30°N due to the total flow was 9761.8×10^{11} cal/s.

(b) Flux due to the mean flow. The variation of flux of potential heat with pressure due to the mean flow has not been depicted on Figure 23 as it would resemble that due to the total flow very closely. The total flux (cellular flux) in the layer 50-1000 mb due to the mean flow was 6800×10^{11} cal/s. It will thus be realized that the Hadley cells transport a considerable quantity of energy northwards.

(c) Local eddy flux. Figure 23 (upper scale) shows that the flux is positive at all pressures, the maximum occurring at about 850 mb and the minimum at about 100 mb. The total flux in the layer 50-1000 mb due to the local eddies was 2500×10^{11} cal/s. It is of interest that, although individual values of local eddy flux at given pressures were almost two orders of magnitude smaller than those for total flux, nevertheless the flux in the layer 50-1000 mb due to the local eddies was comparable with that due to the total flow, because the large negative flux due to the total flow at low levels largely cancels the positive flux in the upper troposphere.

(d) Standing eddy flux. From Figure 23 it will be seen that the flux was positive for the most part but became negative from about 150 to 50 mb. The total flux in the layer 50-1000 mb was 454 x 10^{11} cal/s which is less than a quarter of the flux due to the local eddies, but a result to be expected in a winter-type month.

(ii) *June 1958*

(a) Total flux. Figure 58 is a cross-section of total flux of potential heat due to the total flow. The northward and southward maxima were stronger than those which occurred in March because of the presence of large standing eddies in the flow, as will be seen on referring to Figure 28.

Figure 24 (lower scale) gives the variation of flux of potential heat with pressure due to the total flow. The flux was negative from 1000 to about 510 mb, positive from 510 to about 75 mb and negative from 70 to 50 mb. The total flux in the layer 50-1000 mb from the total flow was 433 x 10^{11} cal/s, a value much smaller than that for March 1958.

(b) Flux due to the mean flow. In June 1958 the flux due to the mean flow resembled that due to the total flow very closely so is not reproduced on Figure 24. The total cellular flux for the layer 50-1000 mb was -425 x 10^{11} cal/s.

(c) Local eddy flux. This flux, given in Figure 24 (upper scale), was positive in the lower troposphere, became zero at about 600 mb, assumed small negative values from 600 to 350 mb and positive values from 350 to 50 mb where it became a maximum. The total flux in the layer 50-1000 mb due to the local eddies was 275 x 10^{11} cal/s, a value having an order of magnitude lower than the corresponding value in March 1958.

(d) Standing eddy flux. This flux, given in Figure 24 (upper scale), was positive at 1000 mb, became negative from 760 to 480 mb and positive from 480 to 50 mb, the maximum positive flux occurring at 150 mb. The total flux of potential heat due to the standing eddies in the layer 50-1000 mb was 582 x 10^{11} cal/s, a value more than double that due to the local eddies but a result to be expected in a summer month.

(iii) *September 1958*

(a) Total flux. Cross-sections of total flux of potential heat are given in Figure 59 and, on referring to the cross-section,Figure 29, it will be seen that the flux maxima coincided closely with the positions of the meridional wind maxima. The largest contribution to the total northward flux appears to have come from the large flux maximum located at about 30°E which was about 10° longitude further east in June 1958.

Figure 25 (lower scale) gives the variation of flux of potential heat with pressure due to the total flow. The flux was large and negative in the low troposphere, became zero at about 720 mb, assumed positive values from 720 to 95 mb and then became negative from 95 to 50 mb. The total flux for the layer 50-1000 mb was 4750 x 10^{11} cal/s, a value more than 10 times greater than that for June which is rather a surprising result since both are summer-type months.

(b) Flux due to the mean flow. This has not been depicted on Figure 25 as the values would almost coincide with those for total flux. The total flux of potential heat due to the mean flow in the layer 50-1000 mb was 4320 x 10^{11} cal/s, a value which differs considerably from that for June 1958 and illustrates that fluxes can vary considerably from month to month.

(c) Local eddy flux. The variation with pressure is given in Figure 25 (upper scale). The flux, which was positive at all pressures and reached a maximum at about 400 mb, yielded a total for the layer 50-1000 mb of 545 x 10^{11} cal/s.

(d) Standing eddy flux. Figure 25 (upper scale) shows that the flux was positive at 1000 mb, became negative from 975 to 580 mb, positive from 580 to 130 mb apart from some small negative values around 300 mb, and negative from 130 to 50 mb. The total flux due to the standing eddies in the layer 50-1000 mb was -116 x 10^{11} cal/s, a value much less than that due to the local eddies and rather unexpected since September 1958 was a summer-type month in other respects.

(iv) *December 1958*

(a) Total flux. Cross-sections of total flux of potential heat are given in Figure 60. It will be seen on referring to the cross-sections giving meridional winds, Figure 30, that the total flux is determined largely by the meridional wind component. In general, although the cross-sections show up the effect of standing eddies, the flux maxima for December (Figure 60) were not as marked as those which occurred in June and September 1958 because in winter months local eddies are stronger than standing eddies. The variation of total flux of potential heat with pressure due to the total flow is depicted in Figure 26 (lower scale). The flux was large and negative at 1000 mb and decreased almost linearly with decrease of pressure to become zero at about 640 mb, and was then positive from 640 to 50 mb with the maximum value at about 150 mb. The total flux in the layer 50-1000 mb due to the total flow was 12 000 x 10^{11} cal/s, a value greater than that for any other month considered.

(b) Flux due to the mean flow. A diagram giving the variation of flux of potential heat with pressure due to the mean flow would resemble that for total flux rather closely, so has not been reproduced on Figure 26. The total flux of potential heat across latitude 30°N due to the mean flow in the layer 50-1000 mb was 10 100 x 10^{11} cal/s, a value much greater than that due to the eddies.

(c) Local eddy flux. The flux, given in Figure 26 (upper scale), was mainly positive apart from some small negative values in the lower stratosphere. The total flux of potential heat due to the local eddies in the layer 50-1000 mb was 1710 x 10^{11} cal/s.

(d) Standing eddy flux. The values for the standing eddy flux are also given in Figure 26 (upper scale). The flux was positive from 1000 to 580 mb, became small and negative from 580 to 360 mb, positive from 360 to 120 mb and negative or small from 120 to 50 mb. The total flux in the layer 50-1000 mb due to standing eddies was 230 x 10^{11} cal/s, a value much less than that due to the local eddies but a result to be expected for December, a winter month.

(v) *Summary of main results for the flux of potential heat in the layer 50-1000 mb*

The main results obtained for the flux of potential heat in 1958 are summarized in Table XXIX.

TABLE XXIX – FLUX OF POTENTIAL HEAT IN THE LAYER 50-1000 mb IN 1958

Month	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
	10^{11} *cal/s*			
March	9760	6800	2500	454
June	432	-425	275	582
September	4750	4330	545	-116
December	12 000	10 100	1710	230
Mean	6740	5200	1260	286

The total flux was positive in all four months, but that for June was very small – in fact less than 10 per cent of that for any other month. The cellular fluxes were mainly large and positive but June proved an apparent exception with a small negative value. The eddy fluxes were mostly positive but September provided the exception with a small negative standing eddy flux. The mean values at the bottom of each column show clearly that the largest contribution to the total flux came from the mean flow. In the winter months the local eddy flux of potential heat,which was much greater than the standing eddy flux, was larger than the summer values. In June the standing eddy flux was larger than the local eddy flux, a result to be expected in a summer month, but September results proved rather surprising by having a negative standing eddy flux. However, the value was small and could be due to errors in the data.

§15 – DISCUSSION OF MAIN RESULTS GIVEN IN TABLE XXX

The fluxes obtained in the present study for the layer 50-1000 mb are summarized in Table XXX.

TABLE XXX – FLUX OF RELATIVE ANGULAR MOMENTUM AND ENERGY ACROSS 30°N FOR THE LAYER 50–1000 mb DURING MARCH, JUNE, SEPTEMBER AND DECEMBER 1958

Month	Quantity	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
			$10^{21} g\ cm^2/s^2$		
	Angular momentum	278 000(H) 343 000	-900(H) 41 000	229 000(H) 152 000	58 000(H) 150 000
			$10^{11}\ cal/s$		
	Kinetic energy	18.29	–	–	–
March	Sensible heat	-199	-2420	1820	404
	Latent heat	1490	-770	2620	-355
	Potential energy	9960	92 200	687 (7.4%)	50 (0.5%)
	Potential heat	9760	6800	2500	454
			$10^{21} g\ cm^2/s^2$		
	Angular momentum	127 000(H) 192 000	5000(H) 3390	100 000(H) 104 000	22 000(H) 84 700
			$10^{11}\ cal/s$		
	Kinetic energy	4.3	–	–	–
June	Sensible heat	-1330	-1910	176	410
	Latent heat	3130	-269	1170	2230
	Potential energy	1760	1490	99 (6.6%)	172 (11.6%)
	Potential heat	432	-425	275	582

TABLE XXX *(contd)*

Month	Quantity	Total flux	Flux due to mean flow	Local eddy flux	Standing eddy flux
September			$10^{21} g\ cm^2/s^2$		
	Angular momentum	266 000(H) 87 500	11 000(H) 12 100	205 000(H) 13 900	50 000(H) 61 600
			$10^{11}\ cal/s$		
	Kinetic energy	2.7	-	-	-
	Sensible heat	-1480	-1660	191	-7.1
	Latent heat	951	-1600	522	2030
	Potential energy	6230	5980	354 (5.9%)	-109 (1.8%)
	Potential heat	4750	4320	545	-116
December			$10^{21} g\ cm^2/s^2$		
	Angular momentum	150 000(H) 356 000	-30 000 55 200	325 000(H) 163 000	125 000(H) 138 000
			$10^{11}\ cal/s$		
	Kinetic energy	13.5	-	-	-
	Sensible heat	-689	-2510	1490	336
	Latent heat	521	-1390	1530	388
	Potential energy	12 700	12 600	223 (1.8%)	-107 (0.85%)
	Potential heat	12 000	10 100	1710	230

The values of the fluxes have been rounded off and so may not balance exactly.
The values according to Holopainen[12] are denoted by (H).

The figures given under flux of angular momentum denoted by (H) are Holopainen's[12] results using upper air data for several years published by Crutcher.[14] The values of total flux of angular momentum obtained in the present study agree reasonably well with those quoted by Holopainen although the flux in September 1958 obtained in the present study appears to have been much lower than that for the several Septembers studied by Holopainen.

It can be noticed that the total flux of potential energy was large in all months except in June when it was rather small. The eddy fluxes of potential energy were small,as suggested earlier, the mean eddy flux of potential energy amounting to 4.6 per cent of the total flux with extremes of 11.6 and 0.5 per cent.

The average local eddy flux of sensible heat for the four months (present study) was 918.5 x 10^{11} cal/s compared with a value of 2700 x 10^{11} cal/s quoted by Starr and White.[4] The average local eddy flux of latent heat for the four months (present study) was 1460 units compared with 3100 units quoted by Starr and White.[4] Peixoto[15] gives a mean local eddy flux of sensible heat in the layer 1000-30 mb of 1850 x 10^{11} cal/s for the year 1950. The values of local eddy flux of sensible heat for March, June, September and December 1958 (Table XXV) were approximately 1820, 176, 191 and 1490 units (10^{11} cal/s), giving an average for the four months of 918 x 10^{11} cal/s, which is about half of the value quoted by Peixoto for the year 1950. The values of local eddy flux of sensible heat and of latent heat obtained in the present study seem rather smaller but of the same order of magnitude as values obtained by other workers.

Table XXX shows that the total flux of sensible heat was negative in each month.

The mean total flux of moisture across latitude 30°N for the four months was 2.61 x 10^{11} g/s compared with Peixoto's[16] value of 4.19 x 10^{11} g/s for all months of 1958. The mean local eddy transport of water vapour for the four months, obtained in the present study, was 2.44 x 10^{11} g/s which is about a half of Peixoto's value of 5.58 x 10^{11} g/s for the whole year. The difference between these results could be due to the use of data for only four months in the present study but is more likely to have been brought about by over-smoothing in the original cross-sections. This seems confirmed by the fact that the local eddy flux of moisture in the present study is rather less than a half of that obtained by Peixoto. The mean total northward transport of potential heat for 1950 quoted by Lorenz[17] was about 1400 x 10^{11} cal/s, a value which is less than 25 per cent of 6700 x 10^{11} cal/s, the value obtained in the present study. Thus although various writers agree as to order of magnitude of the various fluxes, their individual values differ considerably. This is mainly because the calculated value of mean wind $[\bar{v}]_m$ is probably not very accurate and the total cellular flux of sensible heat, for example, which consists of a small residual between large positive flux in the upper troposphere and large negative flux in the lower troposphere, is consequently not very accurate.

§16 – FLUX OF ENERGY ACROSS LATITUDE 30°N COMPARED WITH THE FLUX REQUIRED TO BALANCE RADIATION LOSSES

At the end of this Memoir it will be of interest to compare the total flux of potential heat (i.e. the sum of sensible heat and potential energy) obtained in the present study with that required to balance radiation losses as estimated by London.[18] The mean total northward flux of potential heat (present study) was 6700 x 10^{11} cal/s while London's estimate of the flux of sensible heat required to balance radiation losses was 7160 x 10^{11} cal/s, thus the value obtained in the present study falls short of London's estimate by 460 x 10^{11} cal/s; but so far no account has been taken of the northward flux of latent heat. If the total flux of latent heat is realized as sensible heat, as it must be, then the total northward flux of energy becomes (6700 + 1500) x 10^{11} cal/s, equal to 8200 x 10^{11} cal/s, a value which would easily compensate for radiation losses.

§17 – SUMMARY OF THE MAIN RESULTS OBTAINED IN THE PRESENT STUDY

(i) *Flux of angular momentum*

The flux of angular momentum across latitude 30°N from 1000 to 50 mb was positive in all months and reached a maximum in the winter months and a minimum in the summer months. In the lower troposphere the flux of angular momentum was small but increased markedly with height to reach a maximum at about the level of the maximum wind. The mean flow contributled little to the flux of angular momentum, (but as was shown earlier, was important at individual pressure-levels) most of the flux being due to the eddies. The cross-sections show that there are preferred regions at latitude 30°N where the transport of angular momentum reached large values but the regions were not necessarily the same in all months and seasons.

(ii) *Flux of sensible heat*

The total eddy flux of sensible heat for the layer 1000-50 mb was positive in all months but the total flux was small and negative. The pattern of total eddy flux of sensible heat with pressure could vary widely from month to month. For example, in June and September 1958, negative values of total eddy flux of sensible heat occurred in the layer 800-700 mb, but in March and December 1958 values were positive throughout the troposphere.

(iii) *Flux of latent heat*

The total flux of latent heat for the layer 1000-50 mb was positive in all four months, with the largest value occurring in June, when moisture content was high, and the smallest in December, when moisture content was low. The maximum flux of latent heat occurred in the lower troposphere and values decreased with height to become quite small at about 300 mb. The entire positive flux of latent heat across latitude 30°N was contributed by the eddies since the flux due to the mean flow was negative. However, the flux of moisture across the latitude was positive, the eddies more than compensating for the negative flux due to the mean flow.

(iv) *Flux of kinetic energy*

The cross-sections of total flux of kinetic energy for March, June, September and December 1958 showed that this flux was a maximum at or near the meridional wind maxima. The maximum flux in each month occurred near the level of the maximum wind at between 250 and 150 mb and the total flux in the layer 50-1000 mb was positive in each month. As might have been expected the fluxes in the winter months were considerably larger than those which occurred in the summer months but the flux of kinetic energy was trivial when compared with the flux of potential heat or sensible heat.

(v) *Flux of potential energy*

In the four months considered, the total flux of potential energy in the layer 50-1000 mb was positive, the largest value occurring in December and the smallest in June. In general the flux of potential energy was small and negative in the lower troposphere, large and positive in the upper troposphere and in the summer months the values in the lower stratosphere became negative.

The cellular flux contributed by far the largest proportion of the total flux thus emphasizing the importance of Hadley circulations in transporting potential energy northwards.

(vi) *Flux of potential heat*

The flux of potential heat obtained in the present study, due mainly to the cellular component, largely balanced the loss of sensible heat due to radiation as estimated by London.[18] Since, as already mentioned, the main contribution arose from the cellular term, the importance of Hadley circulations in transporting energy northwards becomes apparent.

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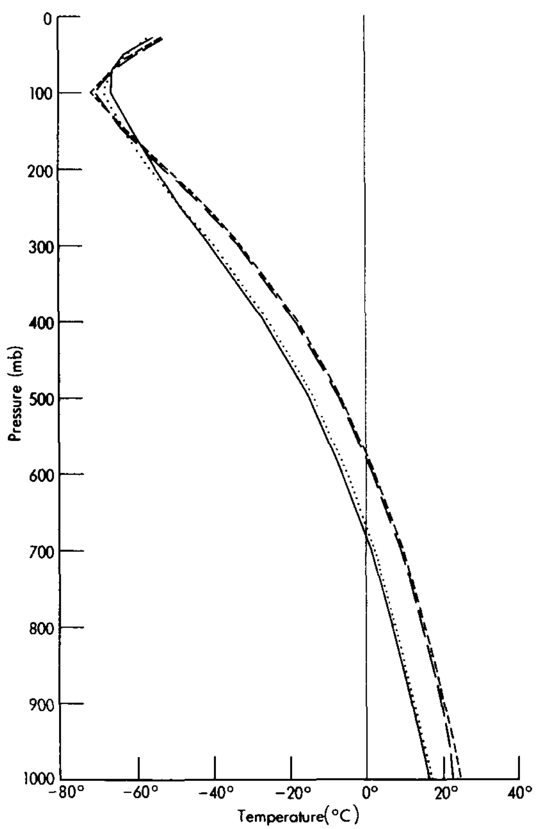


FIGURE 1. VARIATION OF MEAN TEMPERATURE WITH PRESSURE

——— March — — June - - - - - September ..... December 1958

The tropopause heights are given in Table I

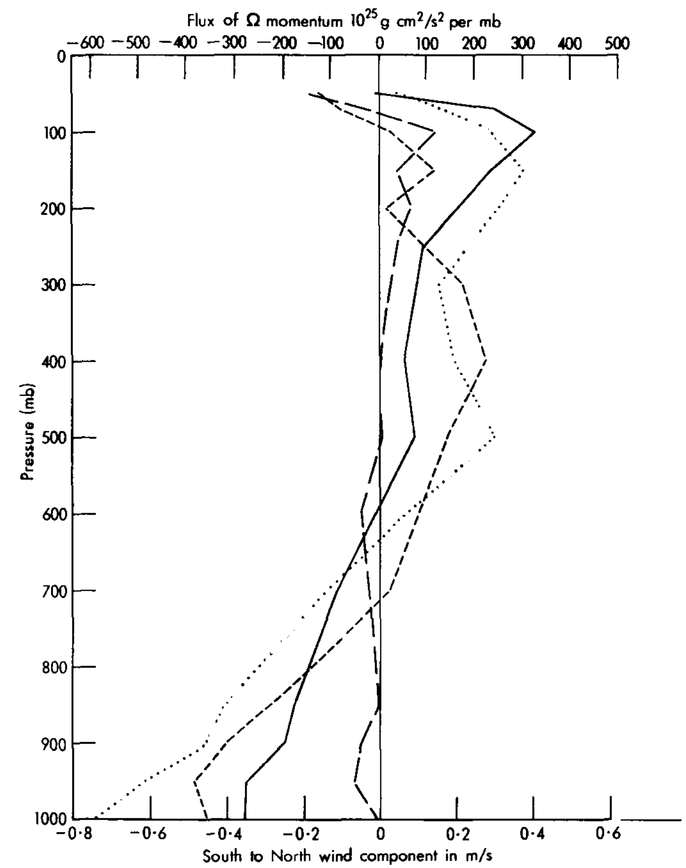


FIGURE 2. VARIATION OF MEAN MERIDIONAL WIND WITH PRESSURE AND THE VARIATION OF FLUX OF OMEGA MOMENTUM WITH PRESSURE

——— March — — June - - - - - September ..... December 1958

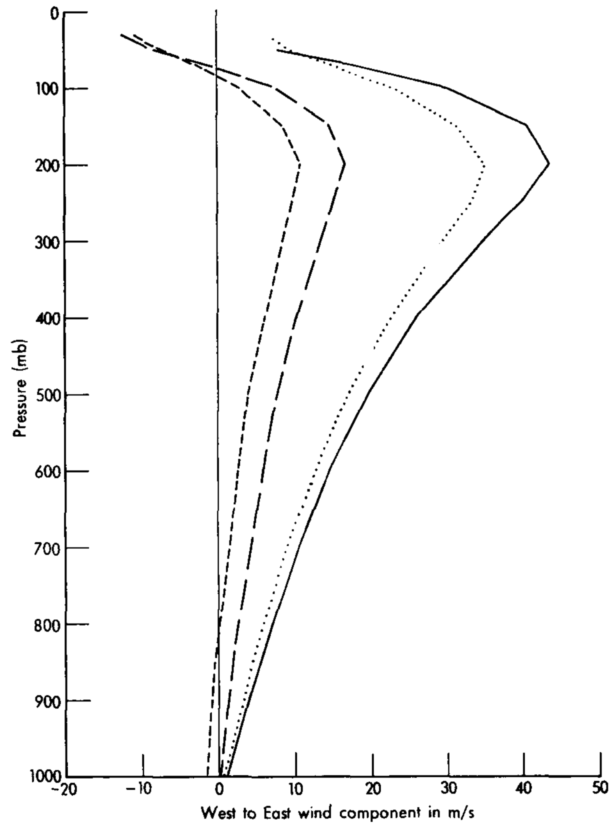


FIGURE 3. VARIATION OF MEAN ZONAL WIND WITH PRESSURE

——— March — — June – – – – September ····· December 1958

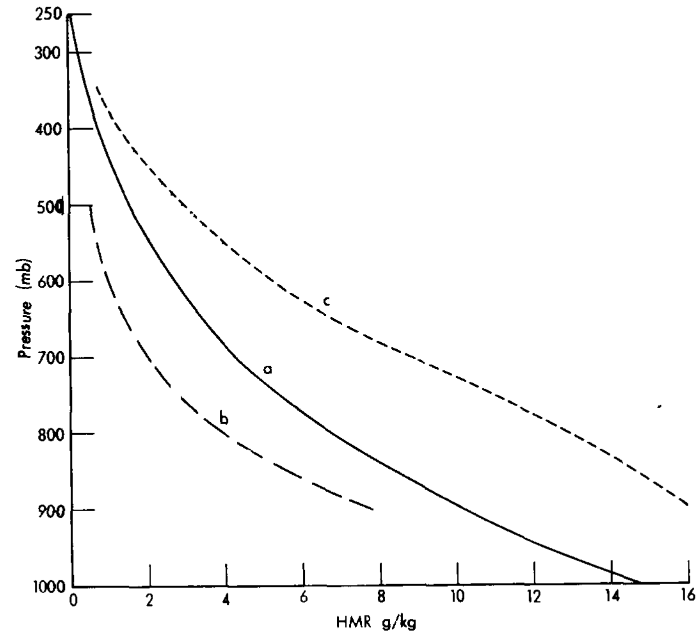


FIGURE 4. MEAN HUMIDITY MIXING RATIO FOR SEPTEMBER 1958

a = Mean HMR round latitude circle 30°N
b = Mean HMR at 35°E
c = Mean HMR at 78°E

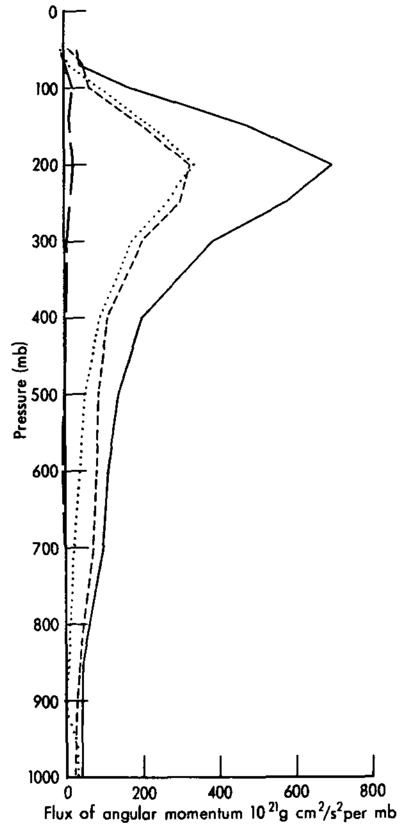


FIGURE 5. VARIATION OF FLUX OF RELATIVE ANGULAR MOMENTUM WITH PRESSURE FOR JUNE 1958

——— total flow, – – – local eddy flow, ... standing eddy flow, — — mean flow

Total flux 50-1000 mb (10^{21}g cm^2/s^2)	
due to mean flow	3 386
due to local eddy flow	104 344
due to standing eddy flow	84 672
due to total flow	192 408

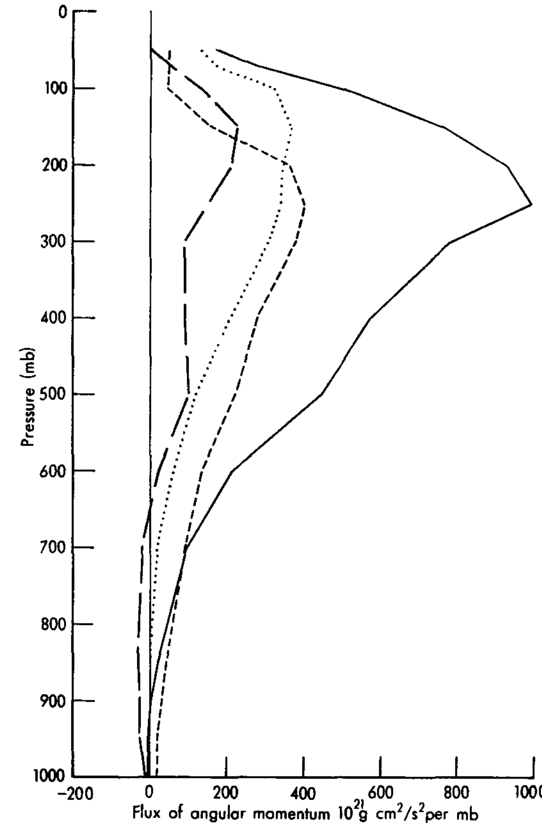


FIGURE 6. VARIATION OF FLUX OF RELATIVE ANGULAR MOMENTUM WITH PRESSURE FOR DECEMBER 1958

——— total flow, – – – local eddy flow, ... standing eddy flow, — — mean flow

Total flux 50-1000 mb (10^{21}g cm^2/s^2)	
due to mean flow	55 204
due to local eddy flow	162 536
due to standing eddy flow	138 328
due to total flow	356 064

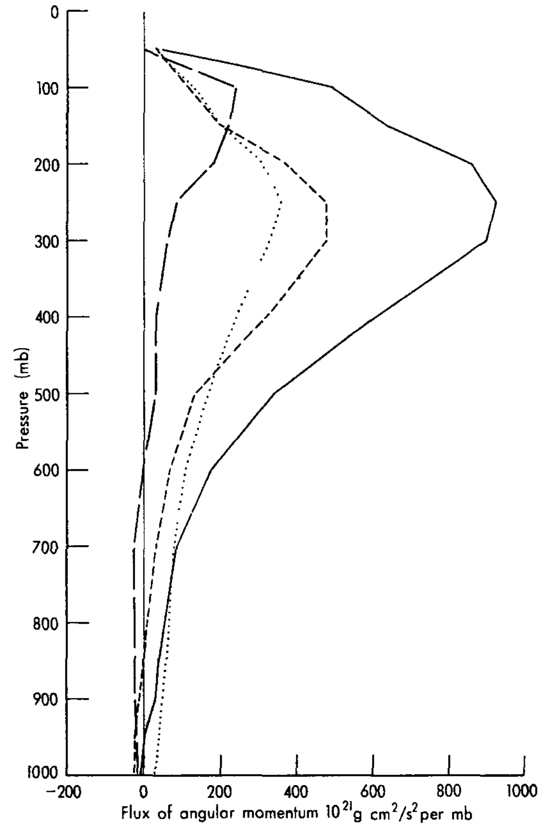


FIGURE 7. VARIATION OF FLUX OF RELATIVE ANGULAR MOMENTUM WITH PRESSURE FOR MARCH 1958

——— total flow, – – – local eddy flow, ... standing eddy flow, — — mean flow

Total flux 50-1000 mb (10^{21}g cm^2/s^2)	
due to mean flow	40 966
due to local eddy flow	151 552
due to standing eddy flow	150 280
due to total flow	342 784

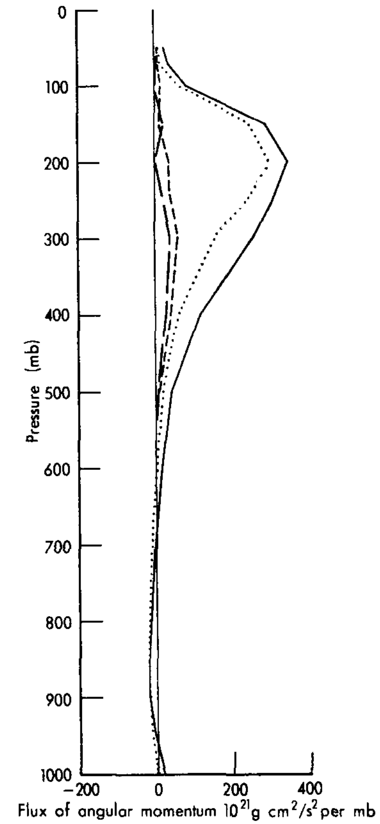


FIGURE 8. VARIATION OF FLUX OF RELATIVE ANGULAR MOMENTUM WITH PRESSURE FOR SEPTEMBER 1958

——— total flow, – – – local eddy flow, ... standing eddy flow, — — mean flow

Total flux 50-1000 mb (10^{11}g cm^2/s^2)	
due to mean flow	12 063.5
due to local eddy flow	13 853.5
due to standing eddy flow	61 630
due to total flow	87 544

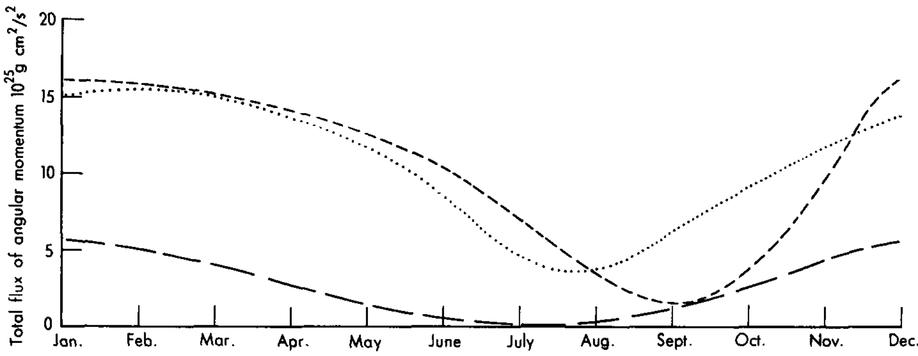


FIGURE 9. MONTHLY VARIATION OF TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM FOR 1958

– – – local eddy flow, ... standing eddy flow, —— —— mean flow

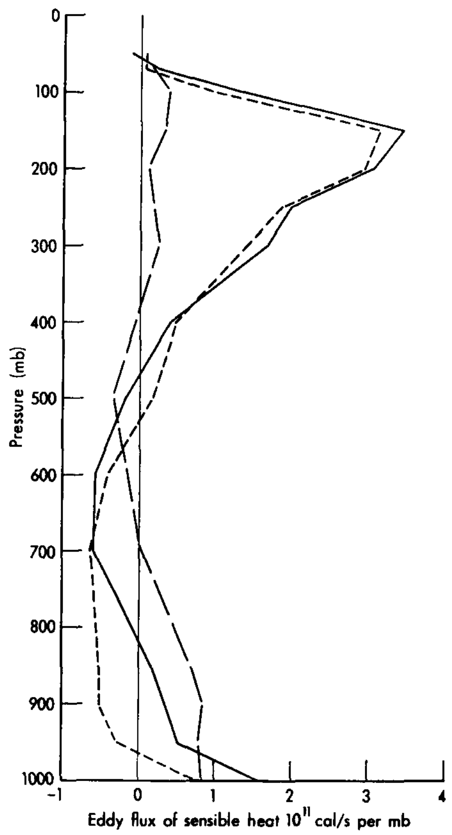


FIGURE 10. VARIATION OF EDDY FLUX OF SENSIBLE HEAT WITH PRESSURE FOR JUNE 1958

—— —— local eddy flow, – – – standing eddy flow.
———— total eddy flow

Eddy flux 50-1000 mb (10^{11} cal/s)	
due to local eddy flow	175.87
due to standing eddy flow	409.96
due to total eddy flow	585.83

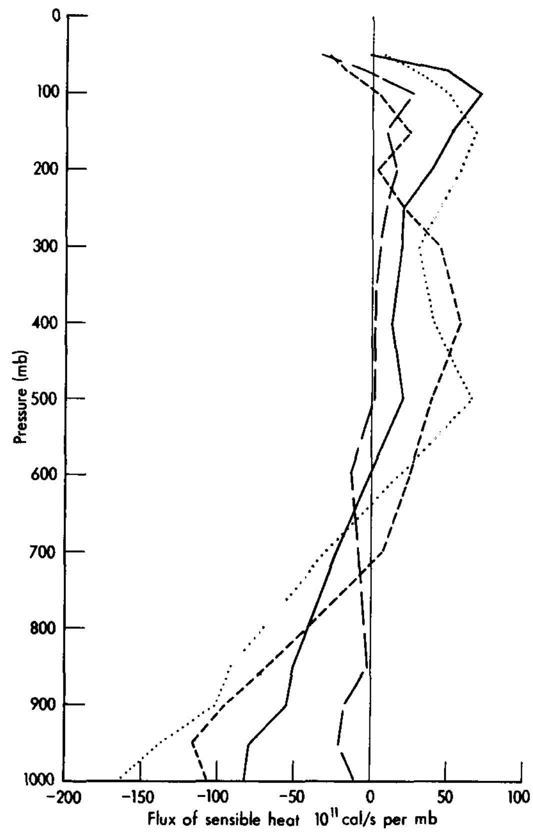


FIGURE 11. VARIATION OF FLUX OF SENSIBLE HEAT DUE TO THE MEAN FLOW WITH PRESSURE

———— March, —— —— June, – – – September, ... December

Total flux 50-1000 mb (10^{11} cal/s)	
March	−2 420.3
June	−1 912.4
September	−1 658.9
December	−2 515.0

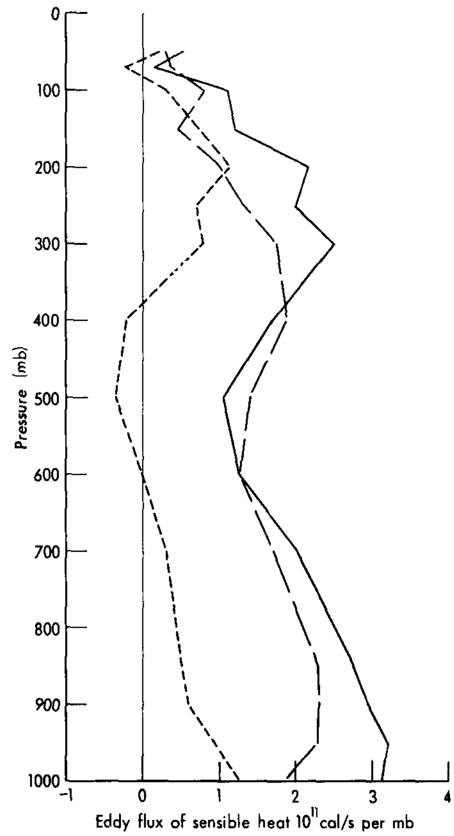


FIGURE 12. VARIATION OF EDDY FLUX OF SENSIBLE HEAT WITH PRESSURE FOR DECEMBER 1958

Total flux 50-1000 mb (10^{11} cal/s)	
due to local eddy flow	1 489.56
due to standing eddy flow	336.66
due to total eddy flow	1 826.22

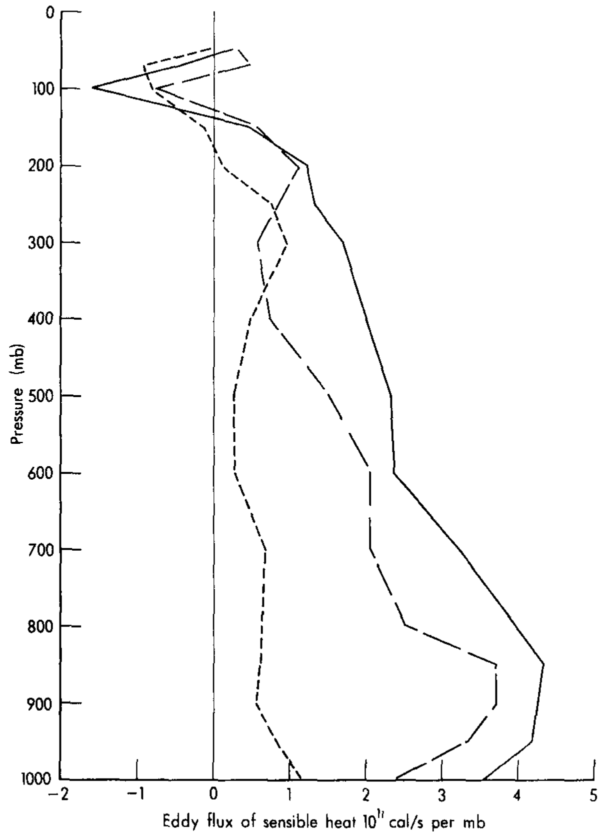


FIGURE 13. VARIATION OF EDDY FLUX OF SENSIBLE HEAT WITH PRESSURE FOR MARCH 1958

Total flux 50-1000 mb (10^{11} cal/s)	
due to local eddy flow	1 817.50
due to standing eddy flow	404.08
due to total eddy flow	2 221.58

— — local eddy flow
..... *standing eddy flow*
——— total eddy flow

(key for Figs. 12-14)

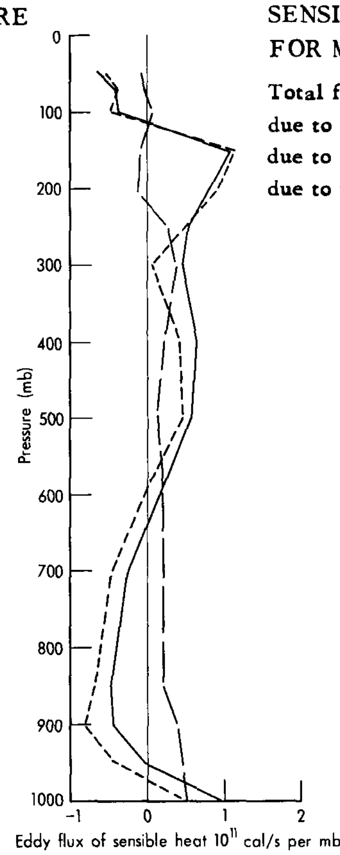


FIGURE 14. VARIATION OF EDDY FLUX OF SENSIBLE HEAT WITH PRESSURE FOR SEPTEMBER 1958

Total flux 50-1000 mb (10^{11} cal/s)	
due to local eddy flow	190.86
due to standing eddy flow	−7.11
due to total eddy flow	183.75

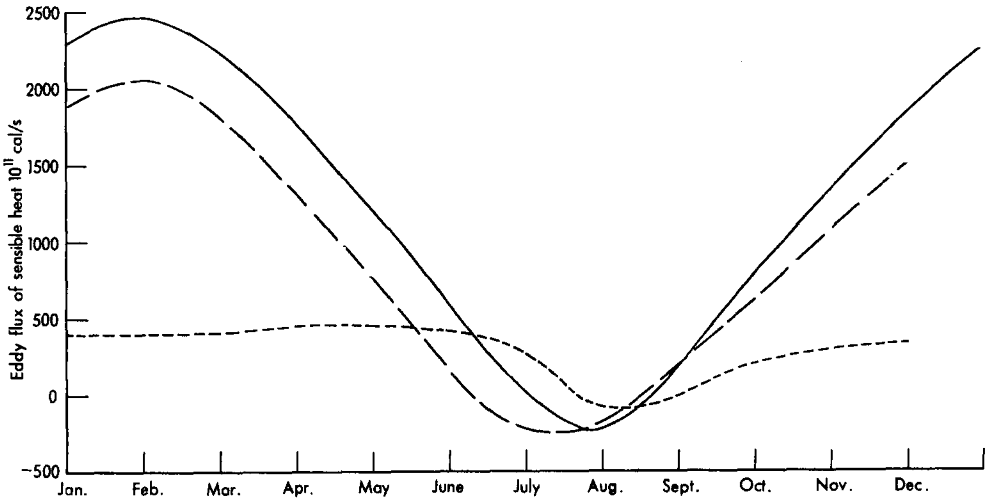


FIGURE 15. MONTHLY VARIATION OF EDDY FLUX OF SENSIBLE HEAT FOR 1958

——— total eddy flow, — — local eddy flow, - - - standing eddy flow

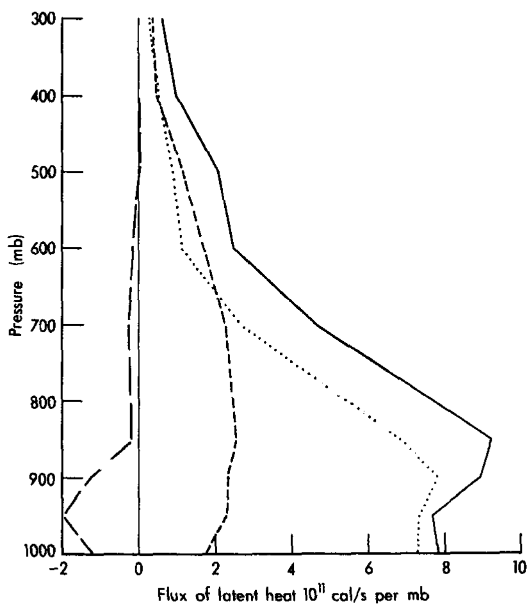


FIGURE 16. VARIATION OF FLUX OF LATENT HEAT WITH PRESSURE FOR JUNE 1958

——— total flow, — — mean flow, - - - local eddy flow. ..... standing eddy flow

Total flux 50-1000 mb (10^{11} cal/s)	
due to mean flow (cellular)	−268.7
due to local eddy flow	1 166.1
due to standing eddy flow	2 231.9
due to total flow	3 129.4

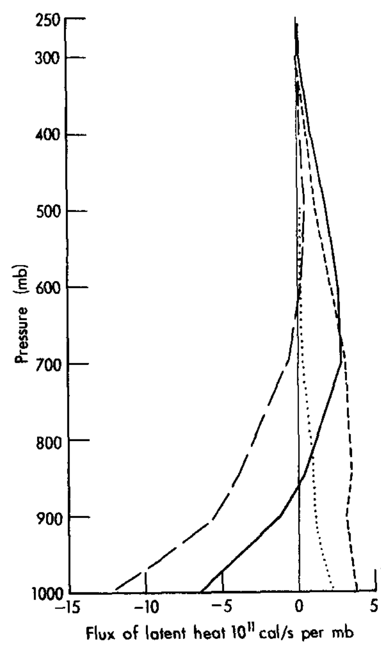


FIGURE 17. VARIATION OF FLUX OF LATENT HEAT WITH PRESSURE FOR DECEMBER 1958

——— total flow, — — mean flow, - - - local eddy flow, ... standing eddy flow

Total flux 50-1000 mb (10^{11} cal/s)	
due to mean flow (cellular)	−1 393.9
due to local eddy flow	1 527.4
due to standing eddy flow	387.6
due to total flow	521.2

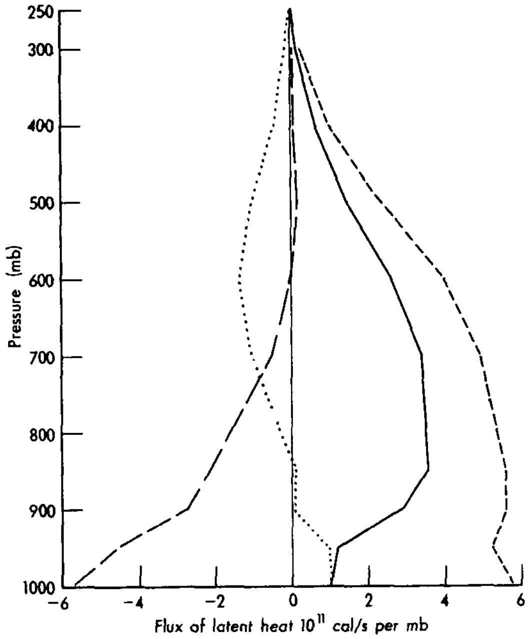


FIGURE 18. VARIATION OF FLUX OF LATENT HEAT WITH PRESSURE FOR MARCH 1958

——— total flow, — — mean flow, - - - local eddy flow, ... standing eddy flow

Total flux 50-1000 mb (10^{11} cal/s)

due to mean flow (cellular)	−769.6
due to local eddy flow	2 619.1
due to standing eddy flow	−354.7
due to total flow	1 494.9

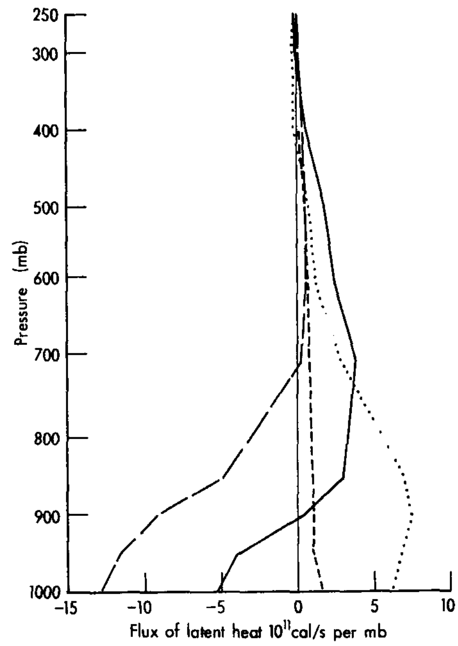


FIGURE 19. VARIATION OF FLUX OF LATENT HEAT WITH PRESSURE FOR SEPTEMBER 1958

——— total flow, — — mean flow, - - - local eddy flow, ... standing eddy flow

Total flux 50-1000 mb (10^{11} cal/s)

due to mean flow (cellular)	−1 604.9
due to local eddy flow	522.0
due to standing eddy flow	2 033.9
due to total flow	951.2

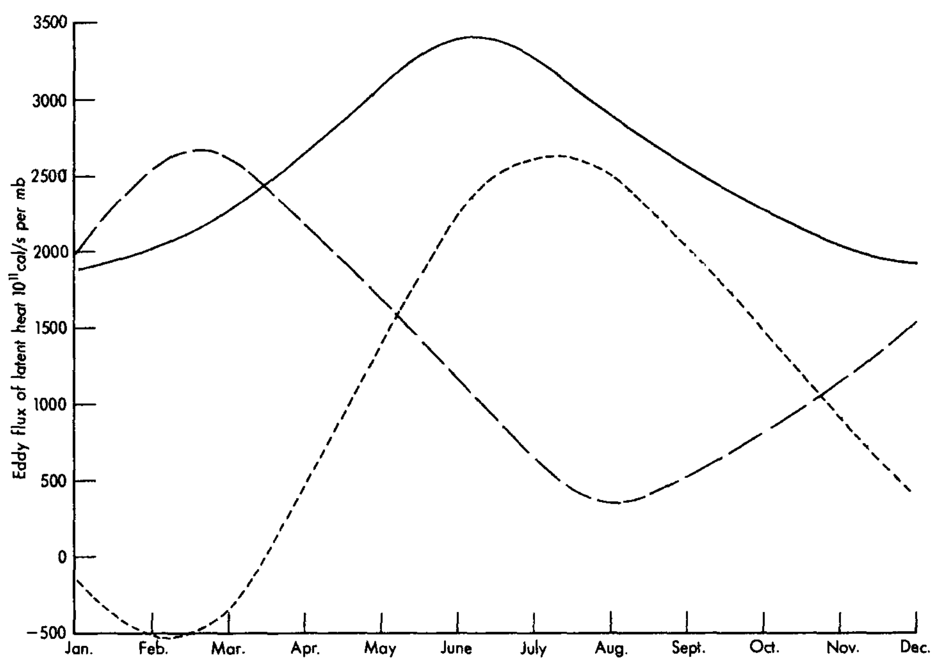


FIGURE 20. MONTHLY VARIATION OF EDDY FLUX OF LATENT HEAT FOR 1958

——— total eddy flow, — — local eddy flow, - - - standing eddy flow

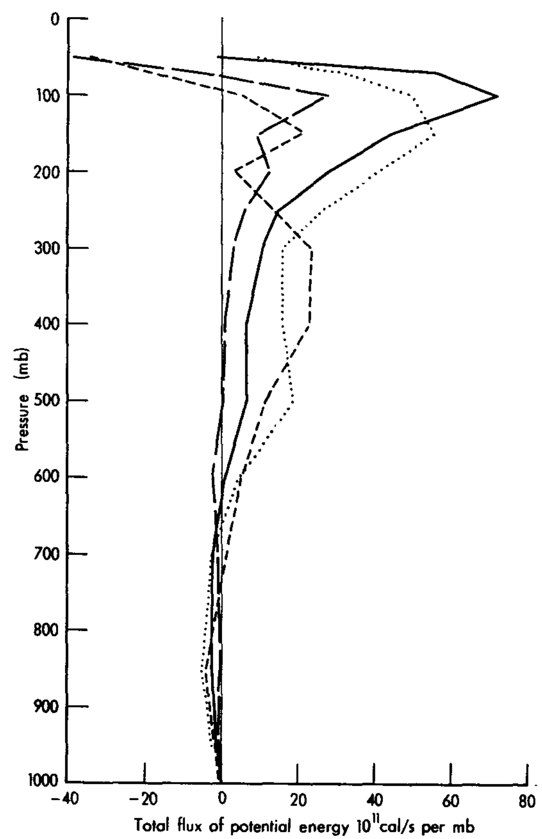


FIGURE 21. VARIATION OF TOTAL FLUX OF POTENTIAL ENERGY WITH PRESSURE FOR 1958

——— March, — — June, - - - September, ... December

Total flux 50-1000 mb (10^{11}cal/s)

March	9 960.5
June	1 759.1
September	6 229.0
December	12 720.5

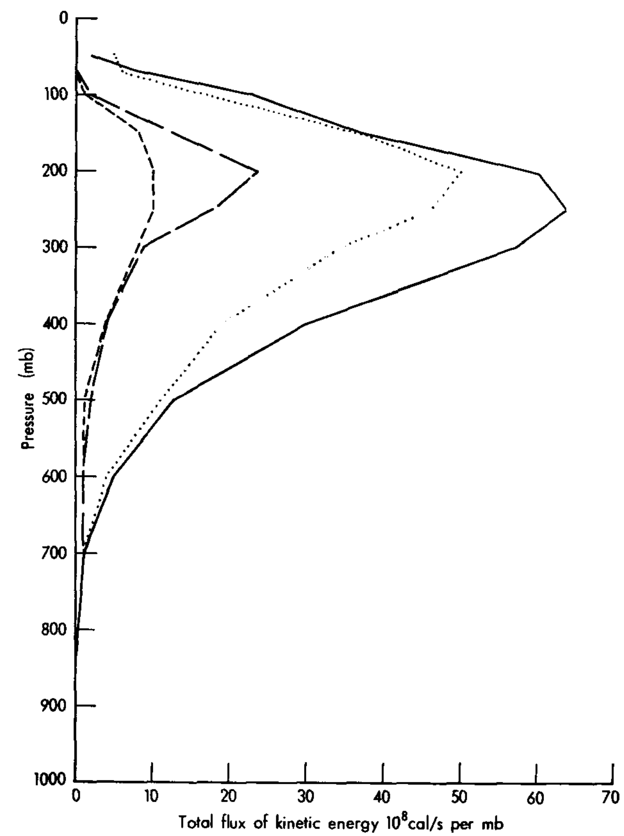


FIGURE 22. VARIATION OF TOTAL FLUX OF KINETIC ENERGY WITH PRESSURE FOR 1958

——— March, — — June, - - - September, ... December

Total flux 50-1000 mb (10^{11} cal/s)

March	18.3
June	4.3
September	2.7
December	13.5

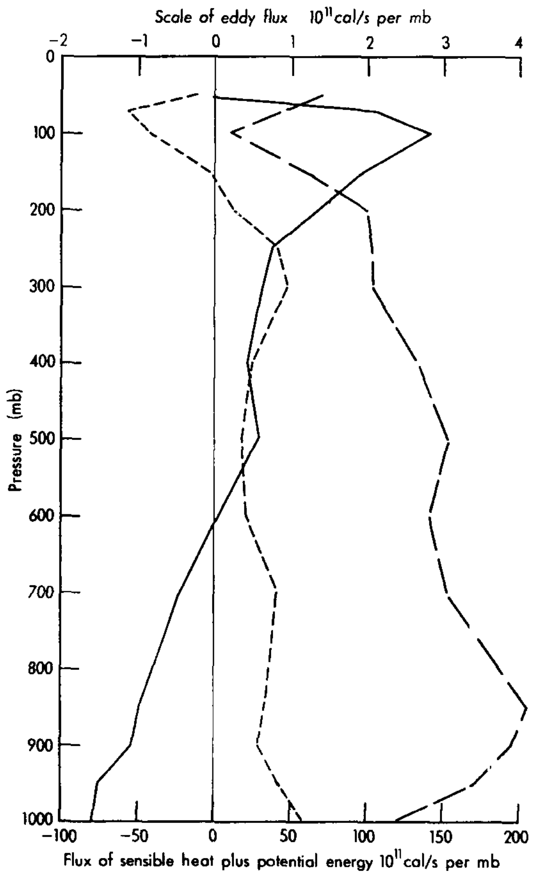


FIGURE 23. VARIATION OF FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY WITH PRESSURE FOR MARCH 1958

——— total flow (lower scale), — — local eddy flow (upper scale), - - - standing eddy flow (upper scale)

due to total flow	9 761.8
due to local eddy flow	2 504.1
due to standing eddy flow	453.7
due to mean (cellular) flow	6 803.7

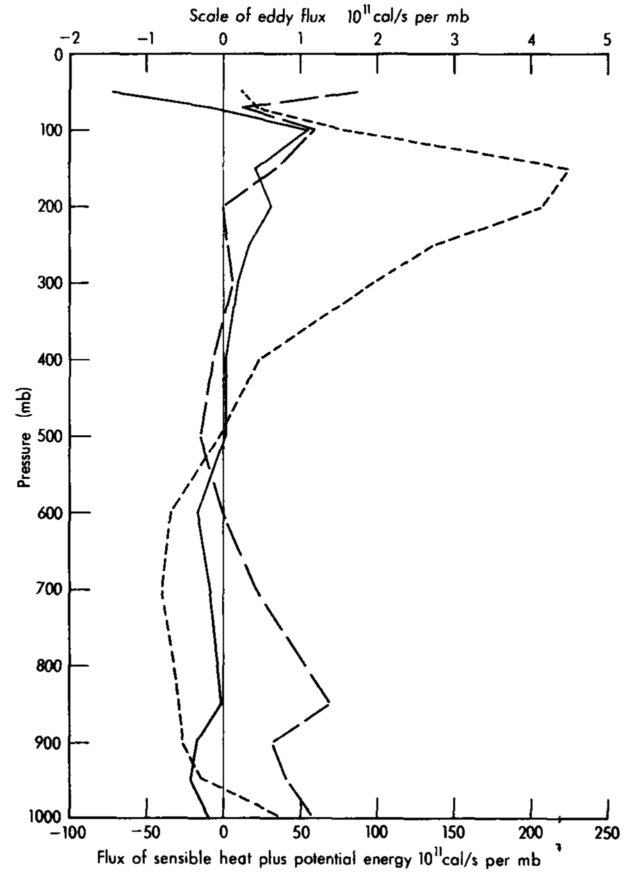


FIGURE 24. VARIATION OF FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY WITH PRESSURE FOR JUNE 1958

——— total flow (lower scale), — — local eddy flow (upper scale), - - - standing eddy flow (upper scale)

due to total flow	432.5
due to local eddy flow	274.9
due to standing eddy flow	582.4
due to mean (cellular) flow	−424.8

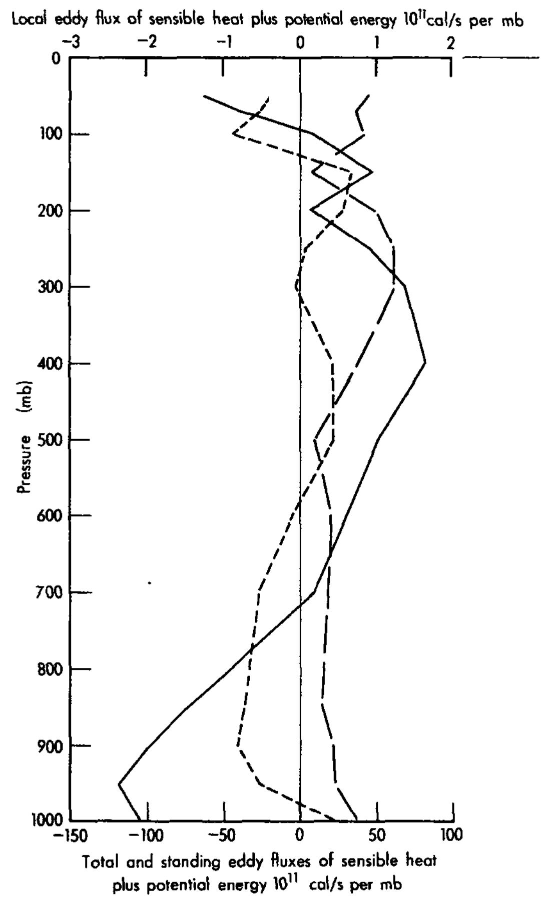


FIGURE 25. VARIATION OF FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY WITH PRESSURE FOR SEPTEMBER 1958

—— total flow (lower scale), — — local eddy flow (upper scale), - - - standing eddy flow (upper scale)

due to total flow	4 753.9
due to local eddy flow	544.7
due to standing eddy flow	−115.7
due to mean (cellular) flow	4 324.8

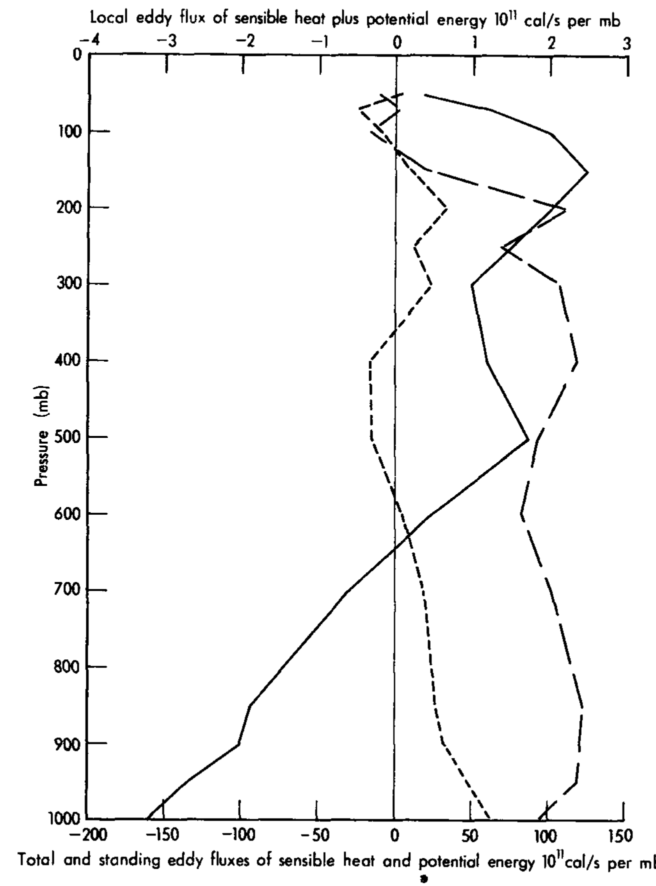


FIGURE 26. VARIATION OF FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY WITH PRESSURE FOR DECEMBER 1958

—— total flow (lower scale), — — local eddy flow (upper scale), - - - standing eddy flow (upper scale)

due to total flow	12 031.7
due to local eddy flow	1 712.6
due to standing eddy flow	229.6
due to mean (cellular) flow	10 090.0

AEROLOGICAL CROSS-SECTIONS

AT 30°NORTH

The following cross-sections are so constructed that the isopleths are not necessarily at constant intervals. The reader should look carefully at the magnitude of the units employed and the value assigned to each isopleth.

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (WESTERN HEMISPHERE)

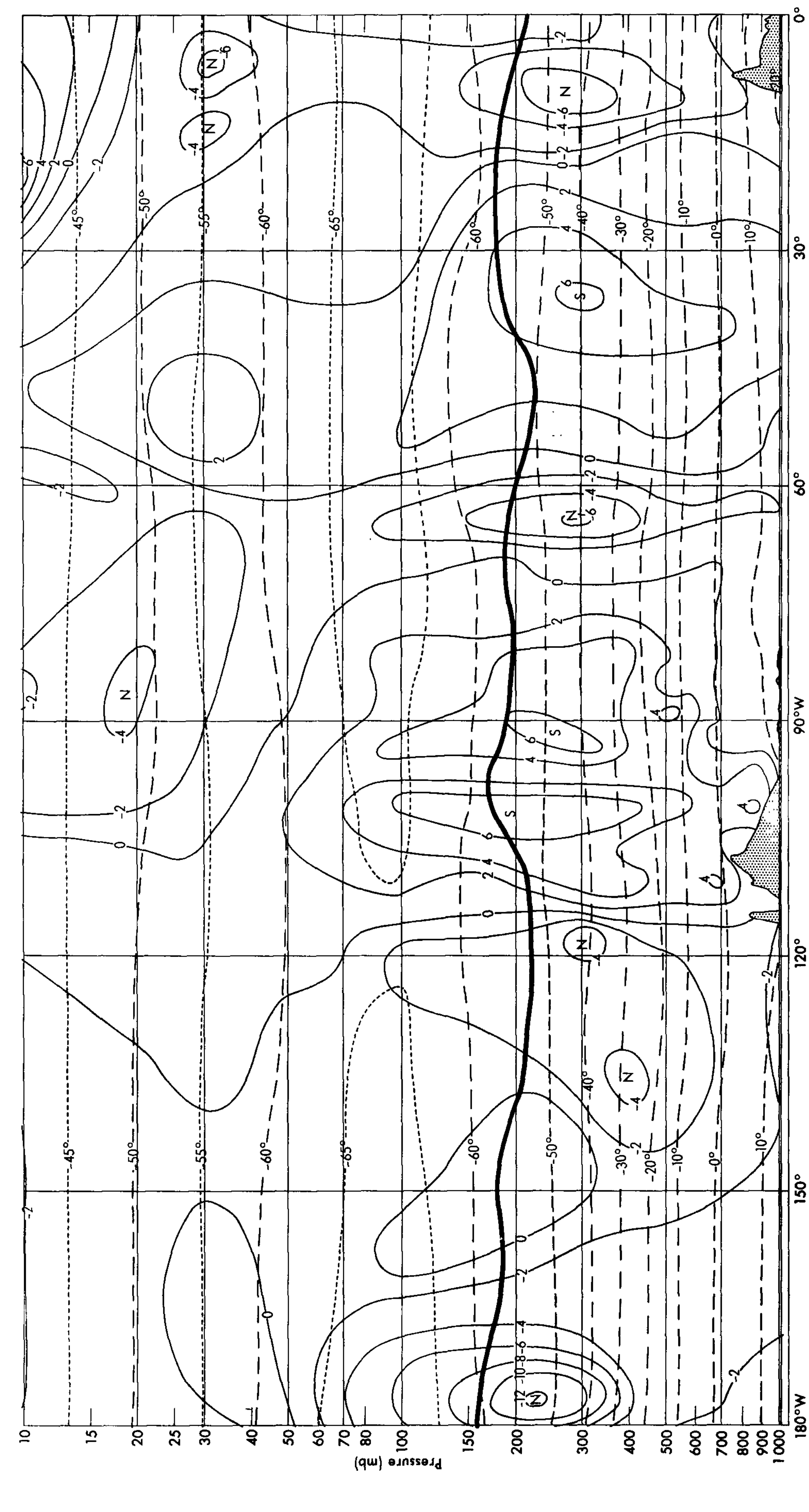


FIGURE 27 (a). MEAN FOR MARCH 1958

—— south to north wind component in m/s. ▬▬ tropopause. – – – temperature in °C.

..... intermediate temperature values

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

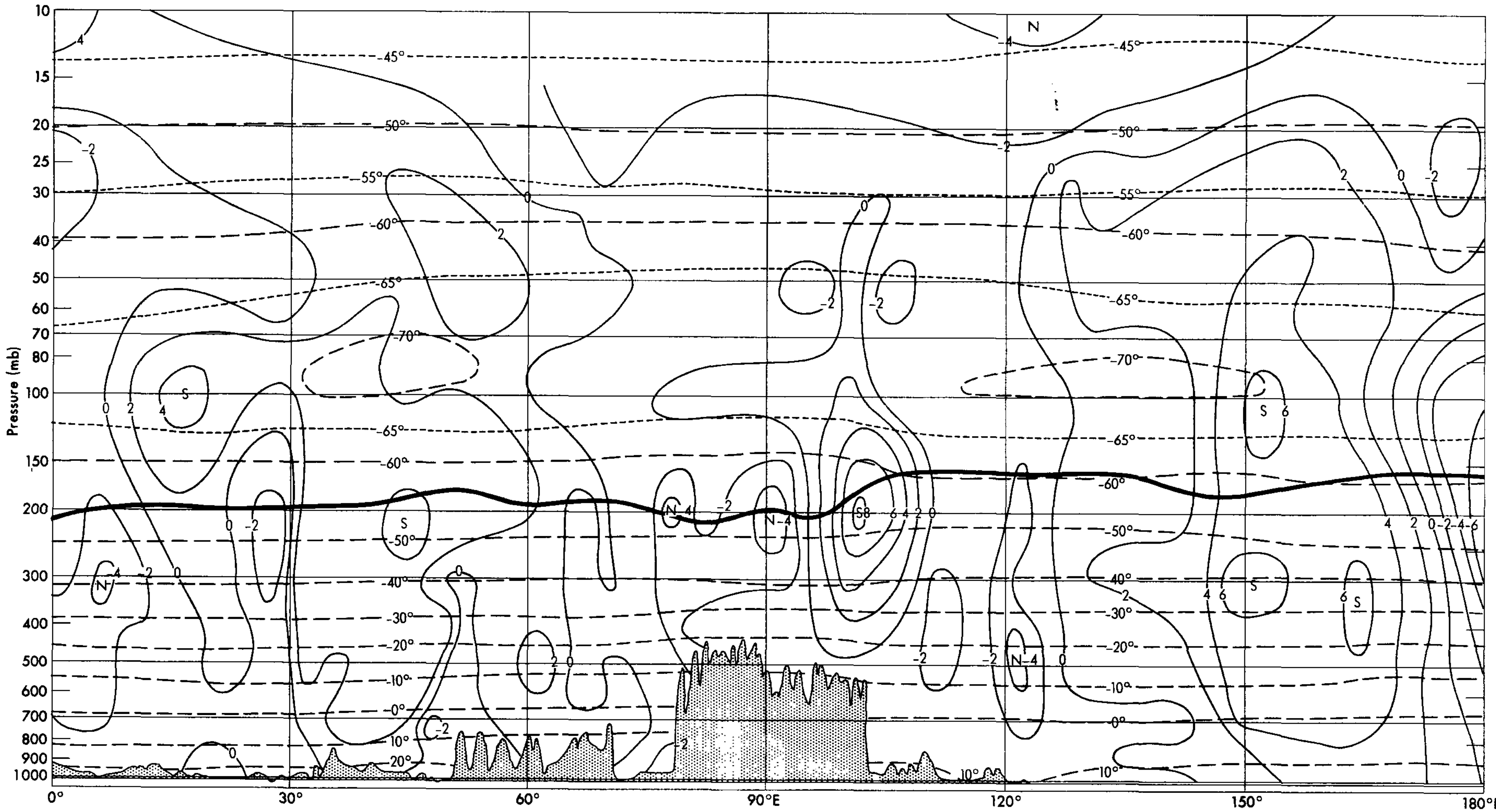


FIGURE 27 (b). MEAN FOR MARCH 1958

——— south to north wind component in m/s. ▬▬ tropopause. – – – – temperature in °C

..... intermediate temperature values

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

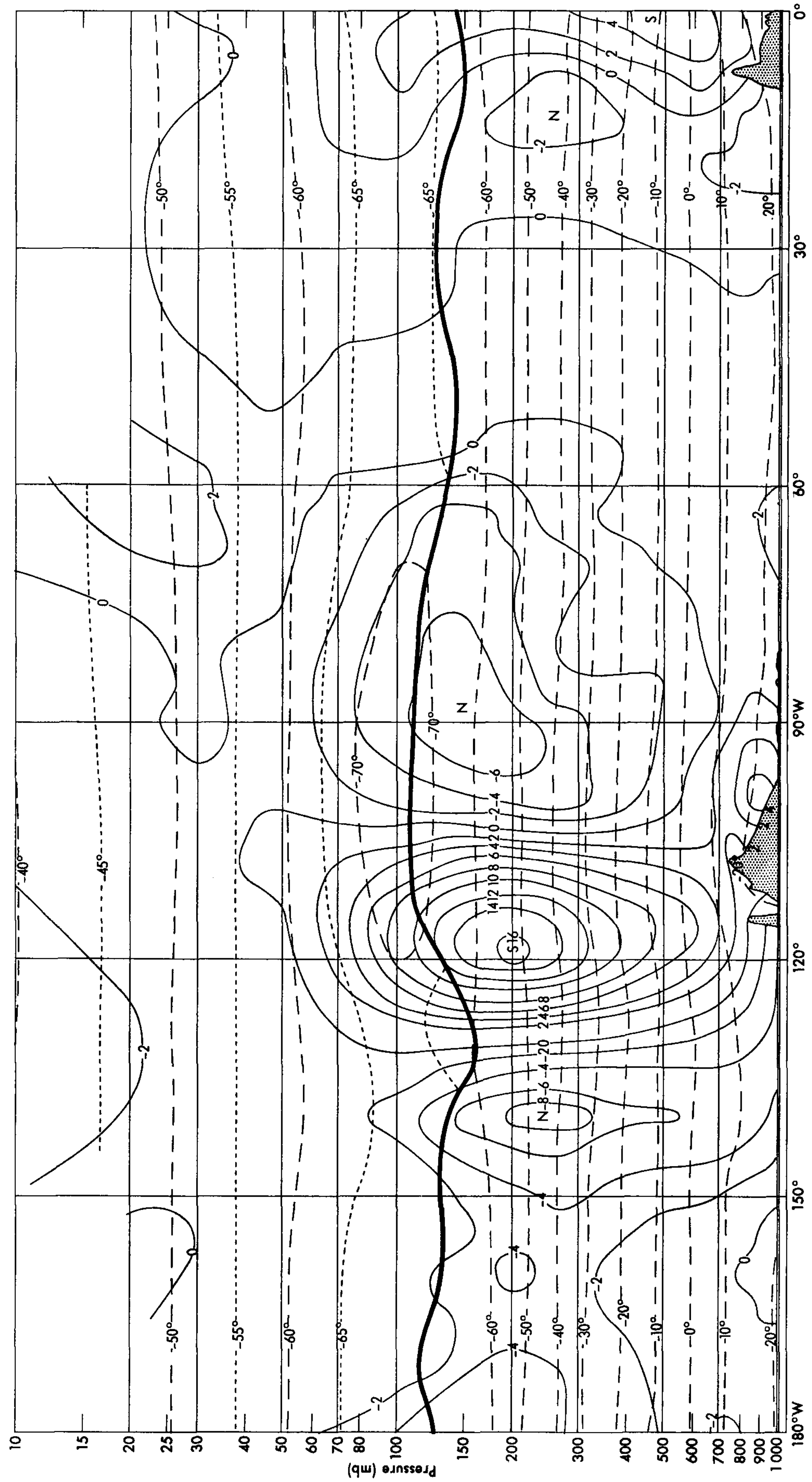


FIGURE 28 (a). MEAN FOR JUNE 1958

—— south to north wind component in m/s. ▬▬ tropopause. — — — temperature in °C

..... intermediate temperature values

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

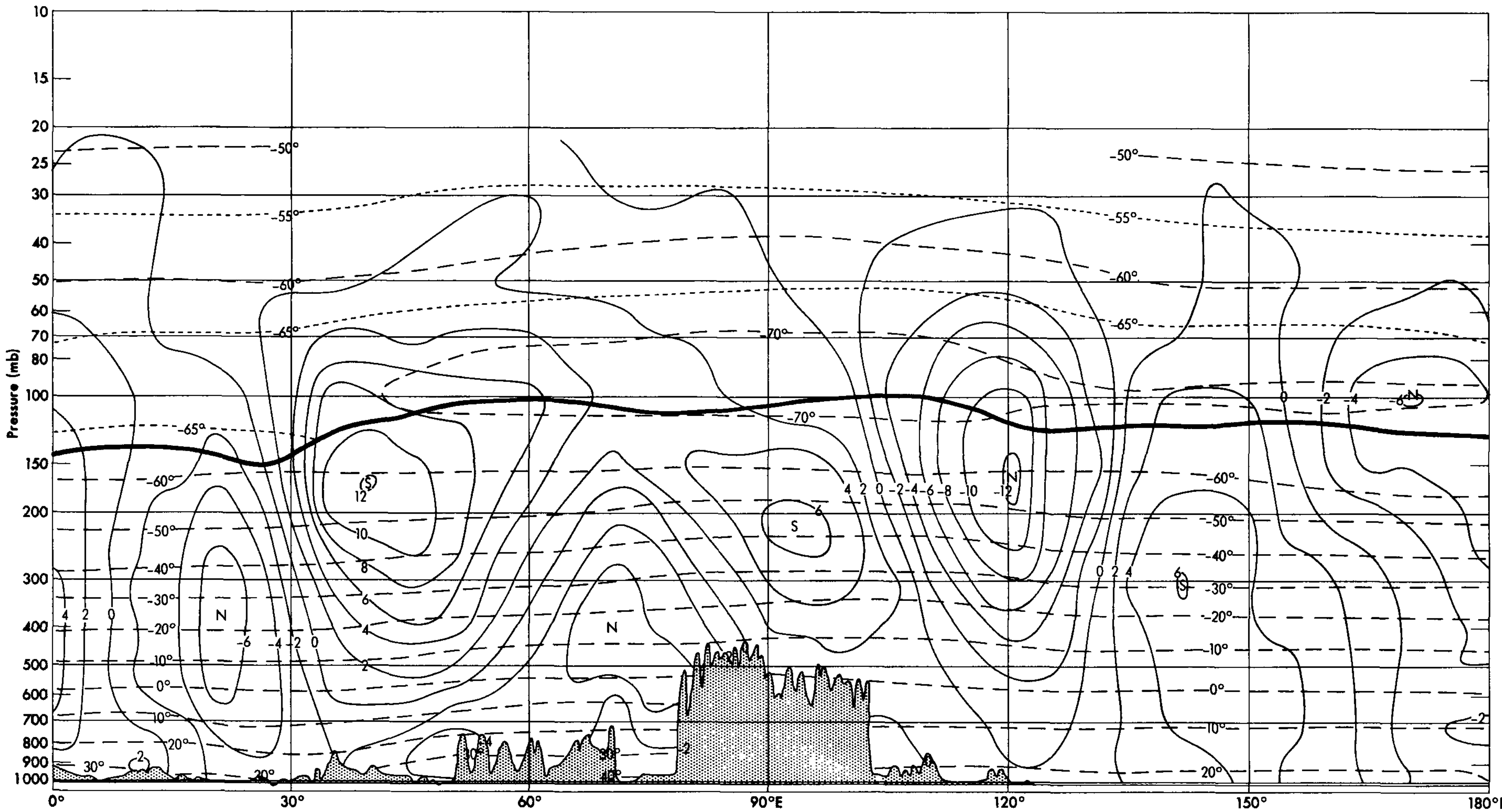


FIGURE 28 (b). MEAN FOR JUNE 1958

——— south to north wind component in m/s. ▬▬▬ tropopause. – – – – temperature in °C

..... intermediate temperature values

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

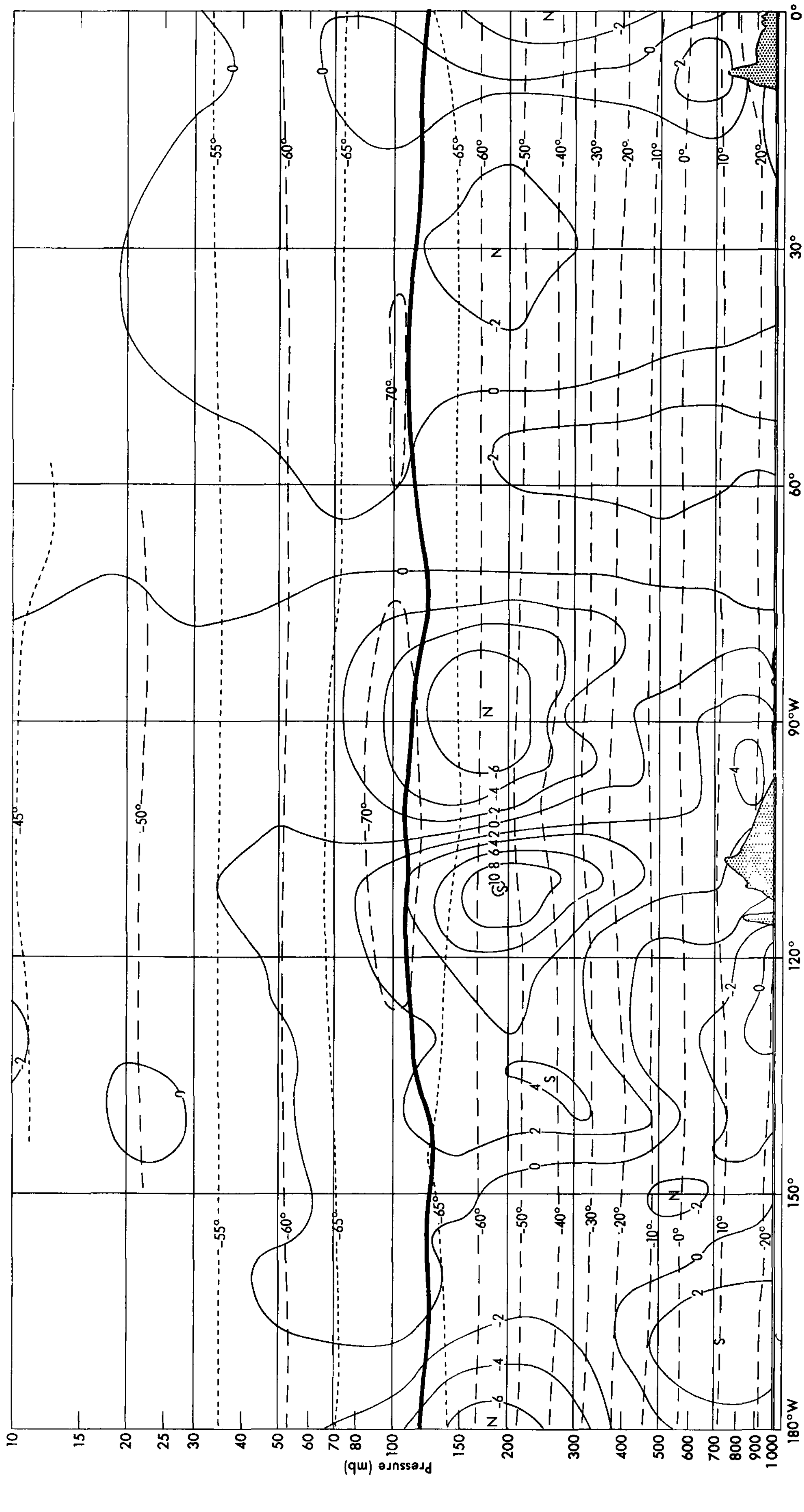


FIGURE 29 (a). MEAN FOR SEPTEMBER 1958

—— south to north wind component in m/s. ▬▬ tropopause. — — — temperature in °C

..... intermediate temperature values

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

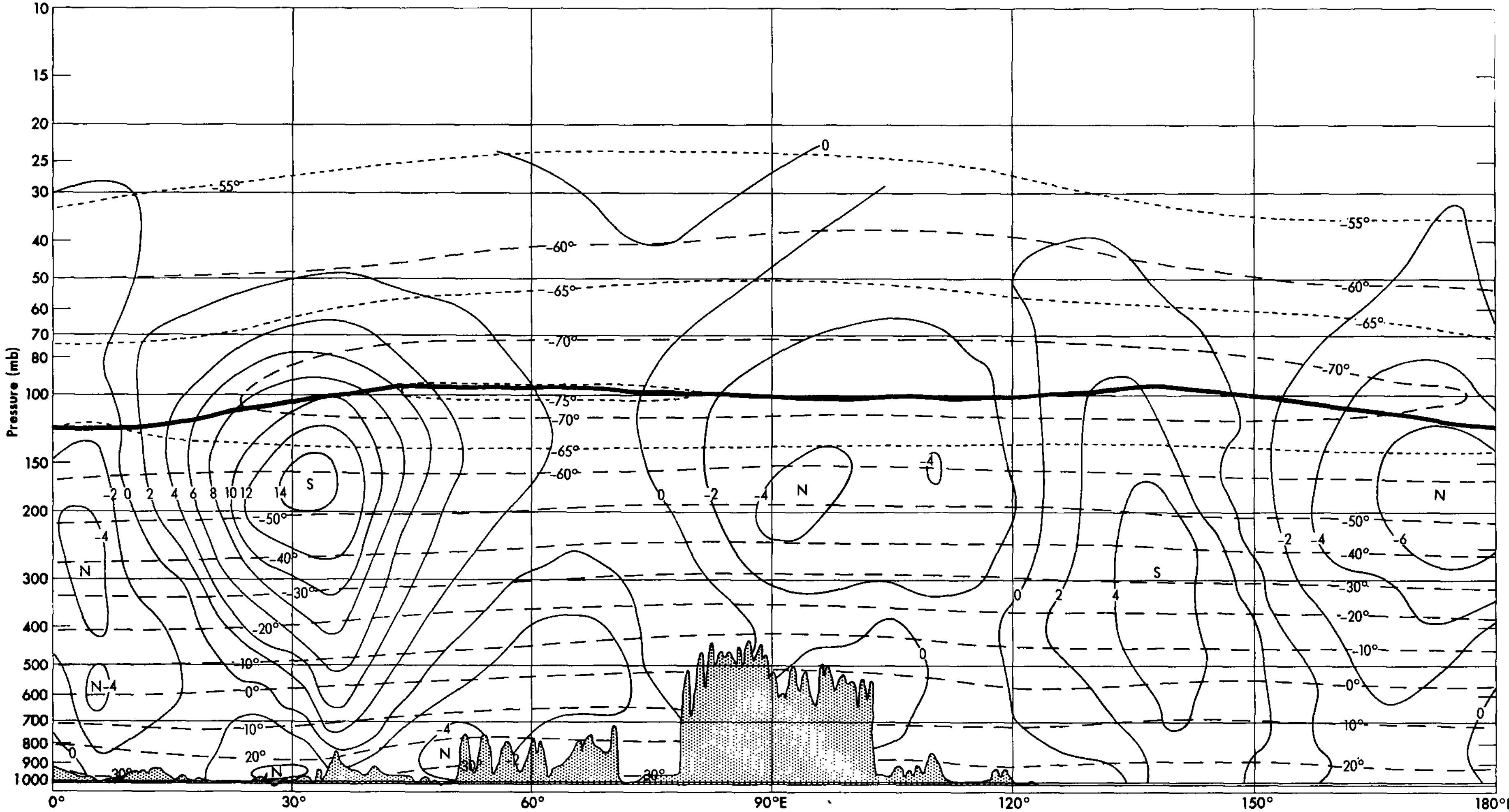


FIGURE 29 (b). MEAN FOR SEPTEMBER 1958

——— south to north wind component in m/s. ▬▬ tropopause. – – – – temperature in °C

..... intermediate temperature values

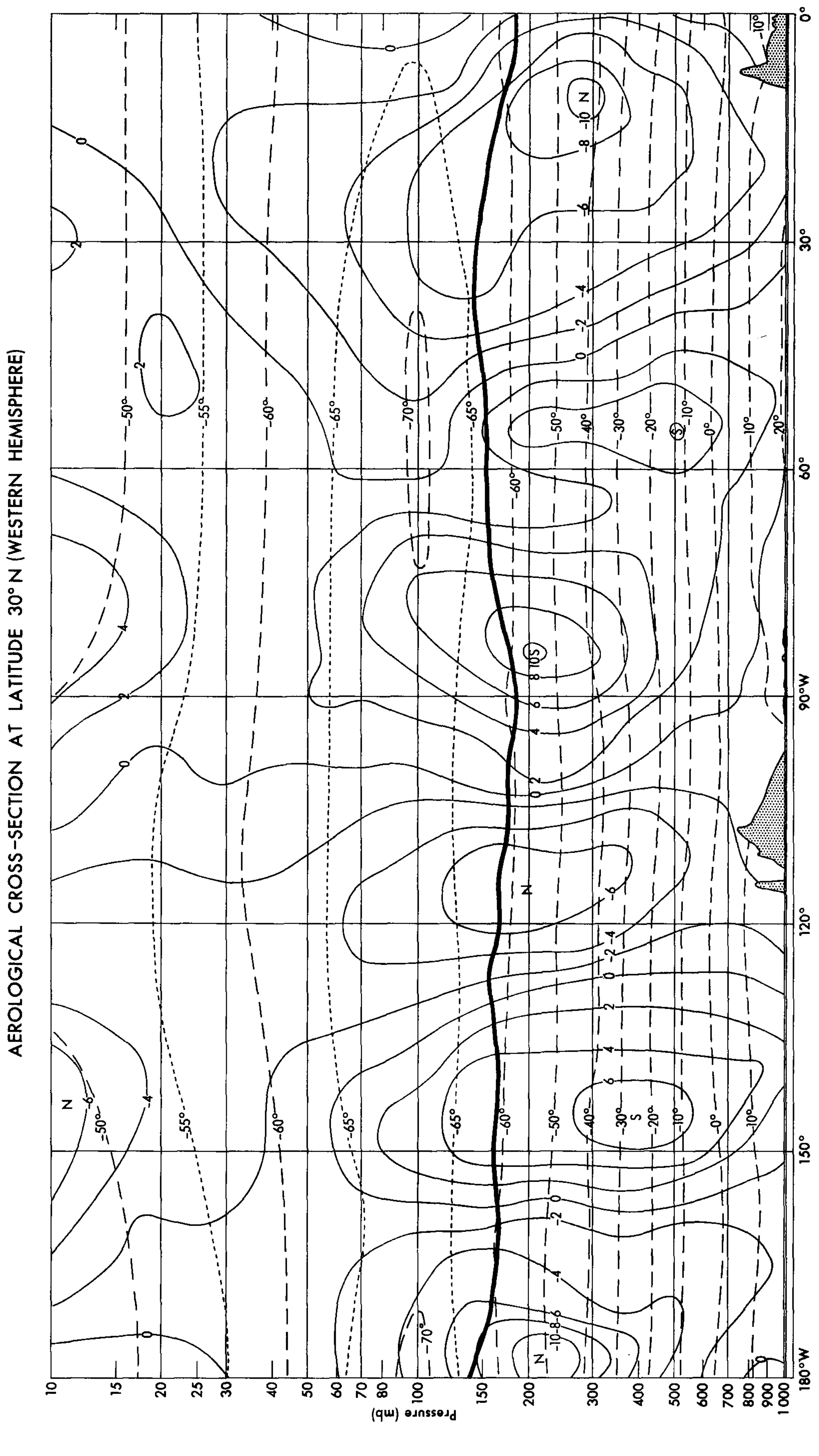


FIGURE 30 (a). MEAN FOR DECEMBER 1958

—— south to north wind component in m/s. ▬▬ tropopause. — — — temperature in °C

..... intermediate temperature values

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

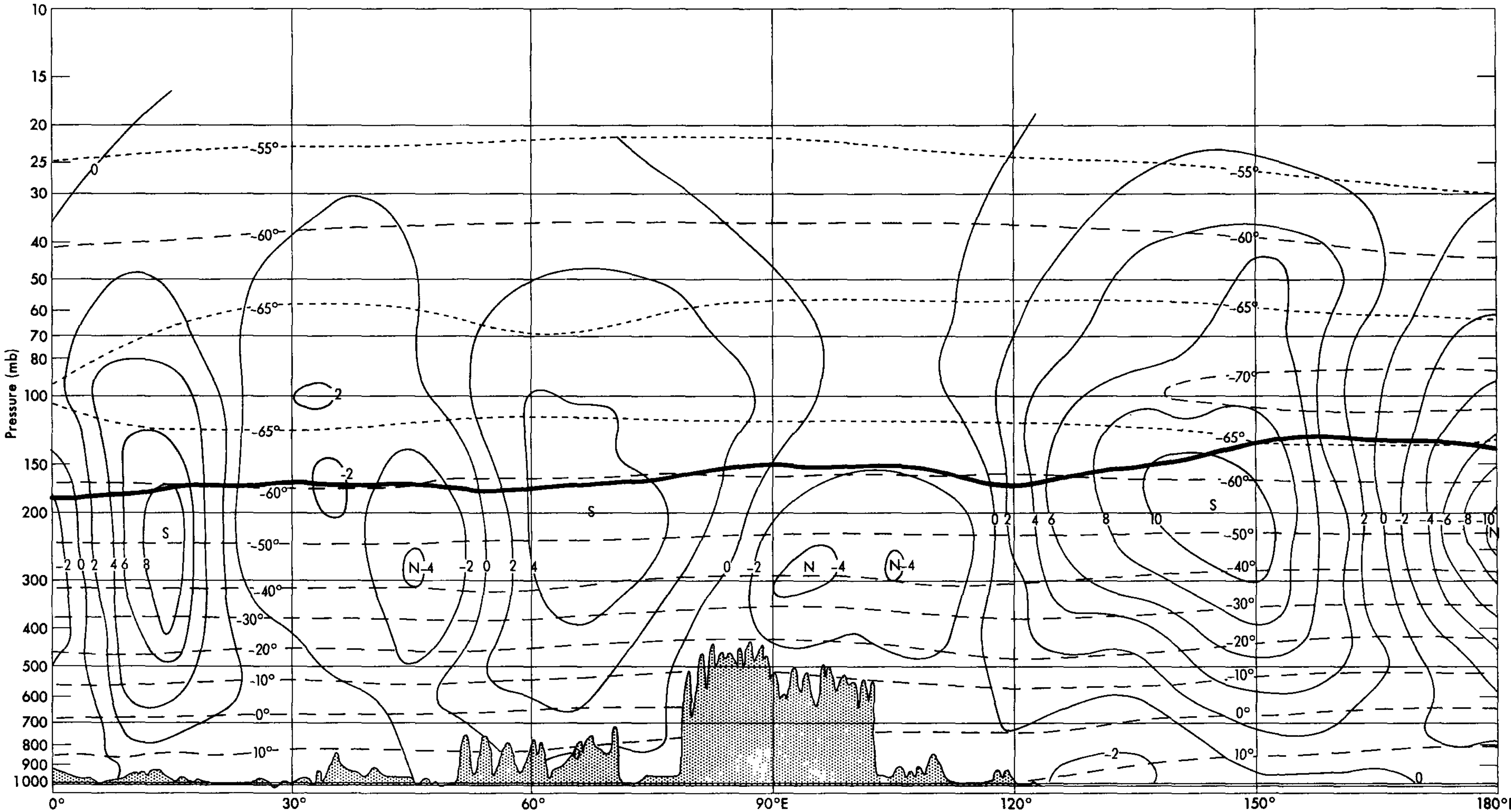


FIGURE 30 (b). MEAN FOR DECEMBER 1958

——— south to north wind component in m/s. ▬▬▬ tropopause. – – – – temperature in °C

..... intermediate temperature values

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

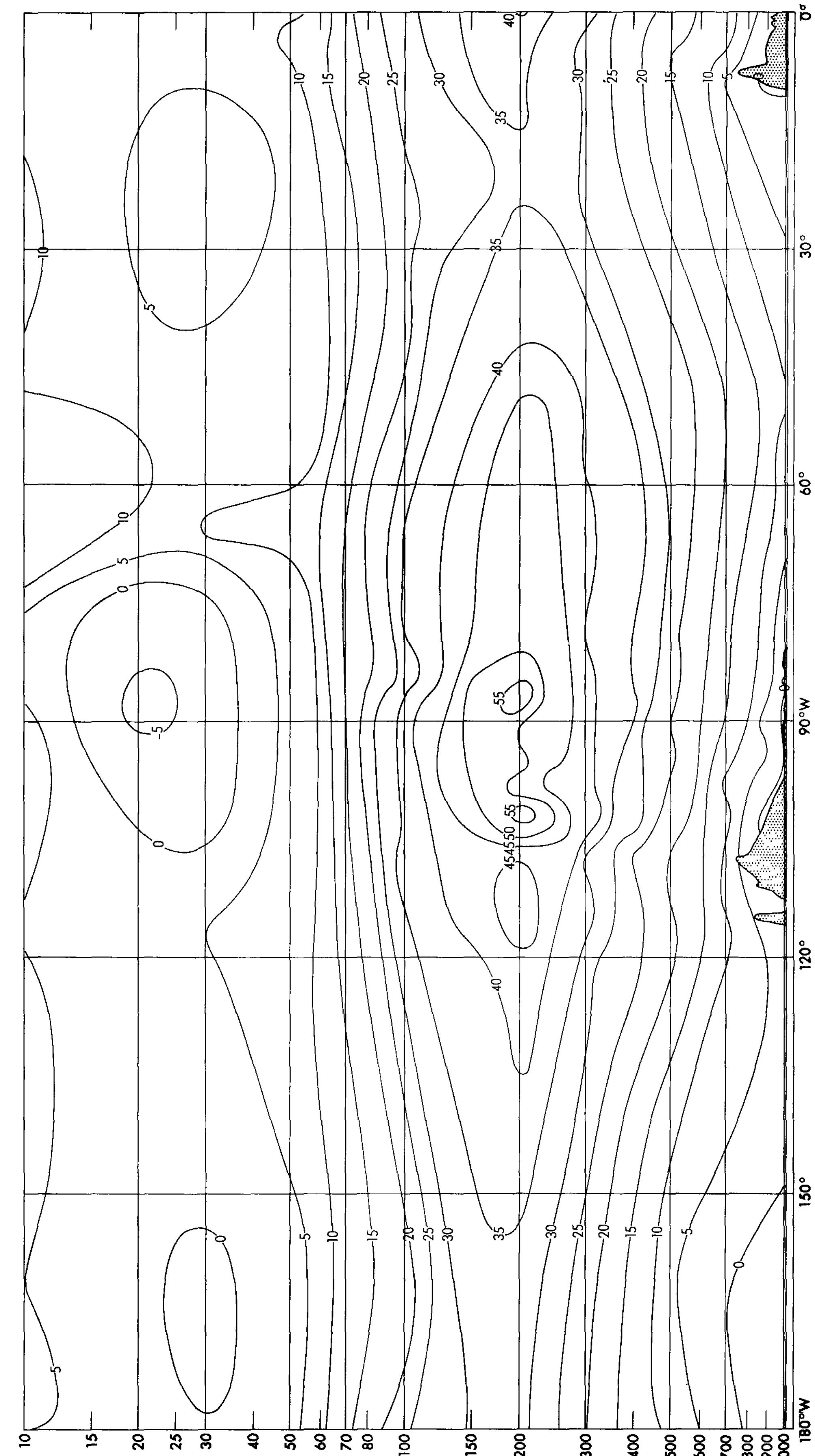


FIGURE 31 (a). MEAN FOR MARCH 1958

—— west to east wind component in m/s.

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

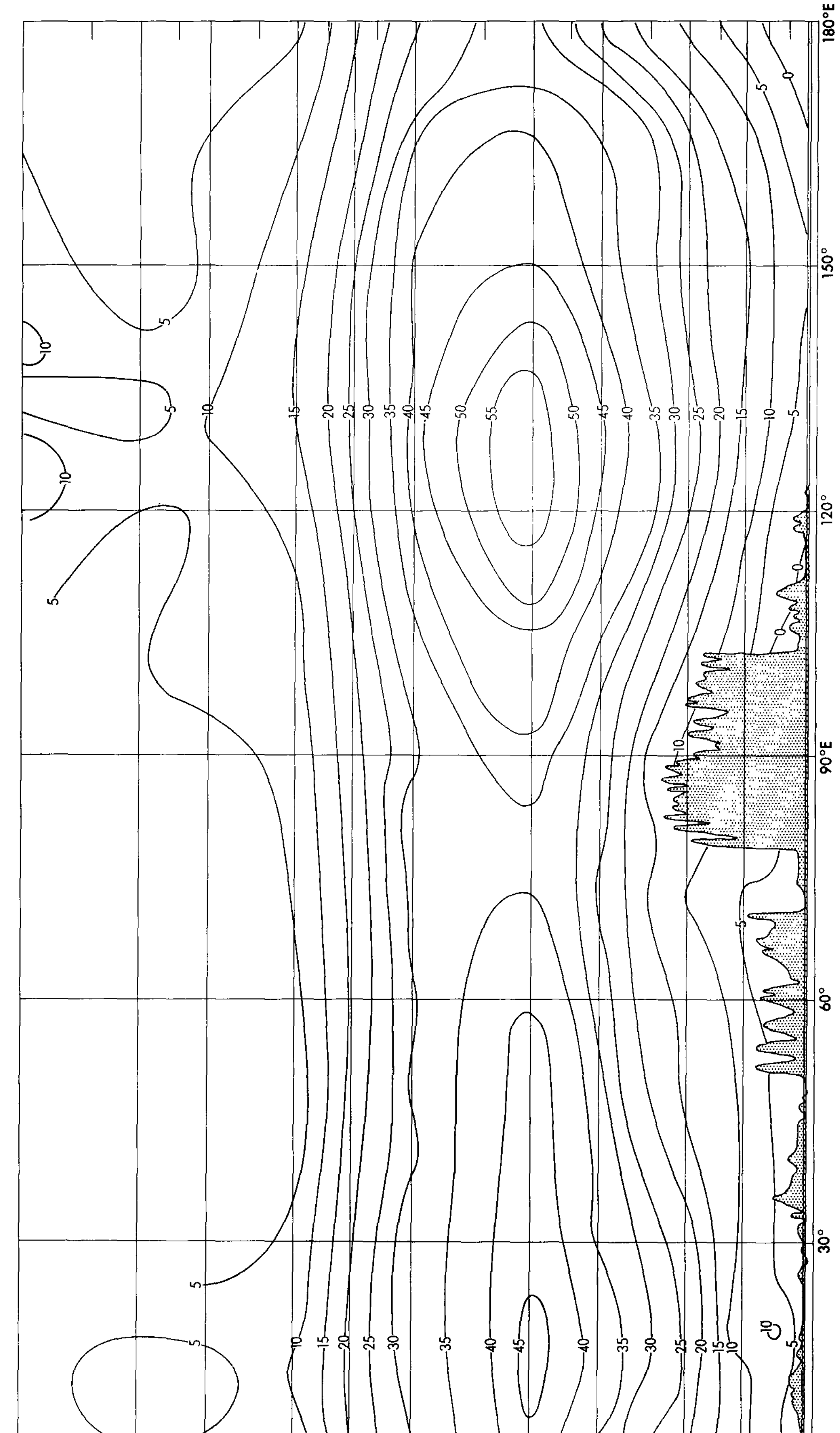


FIGURE 31 (b). MEAN FOR MARCH 1958

—— west to east wind component in m/s.

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

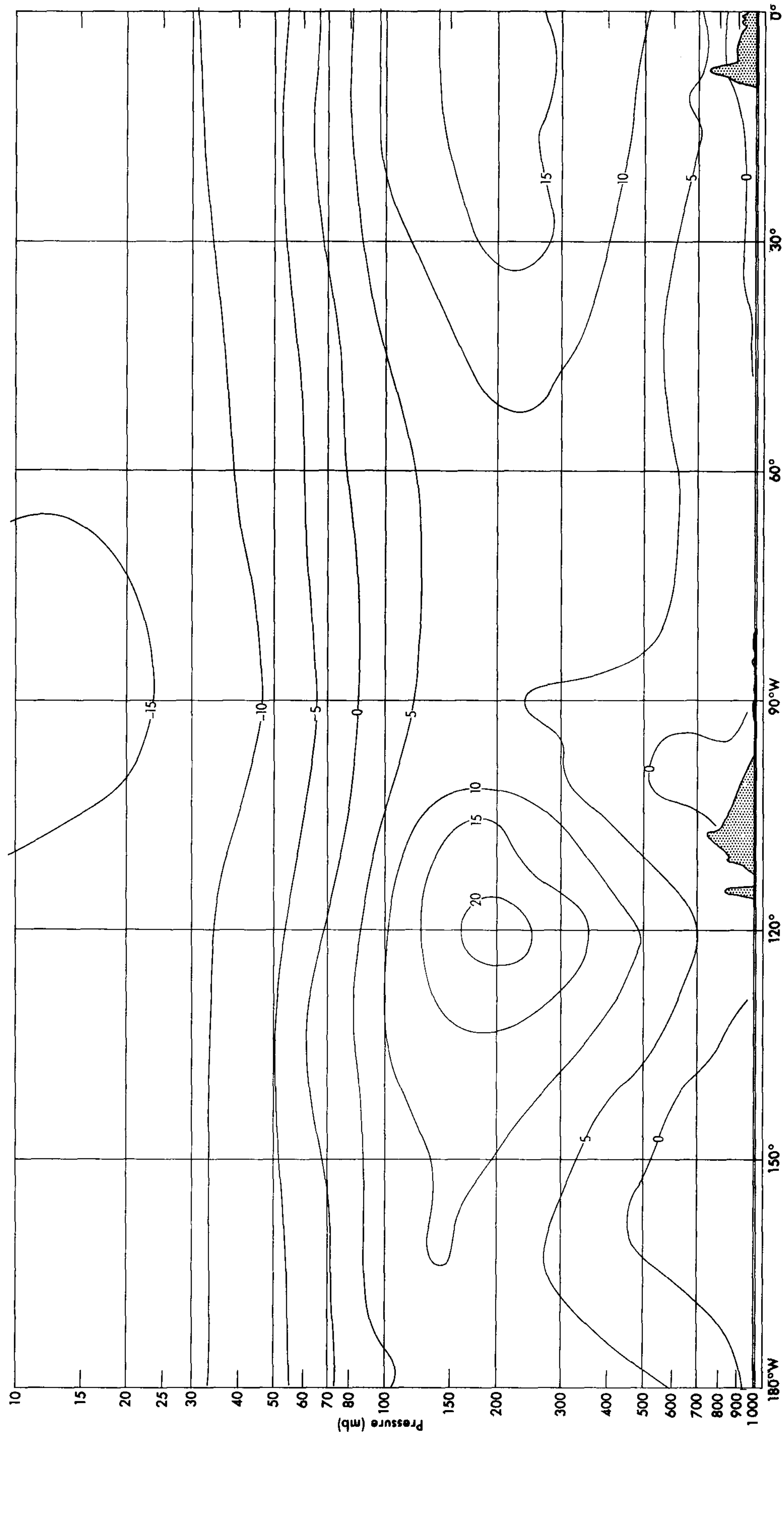


FIGURE 32 (a). MEAN FOR JUNE 1958

——— west to east wind component in m/s.

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

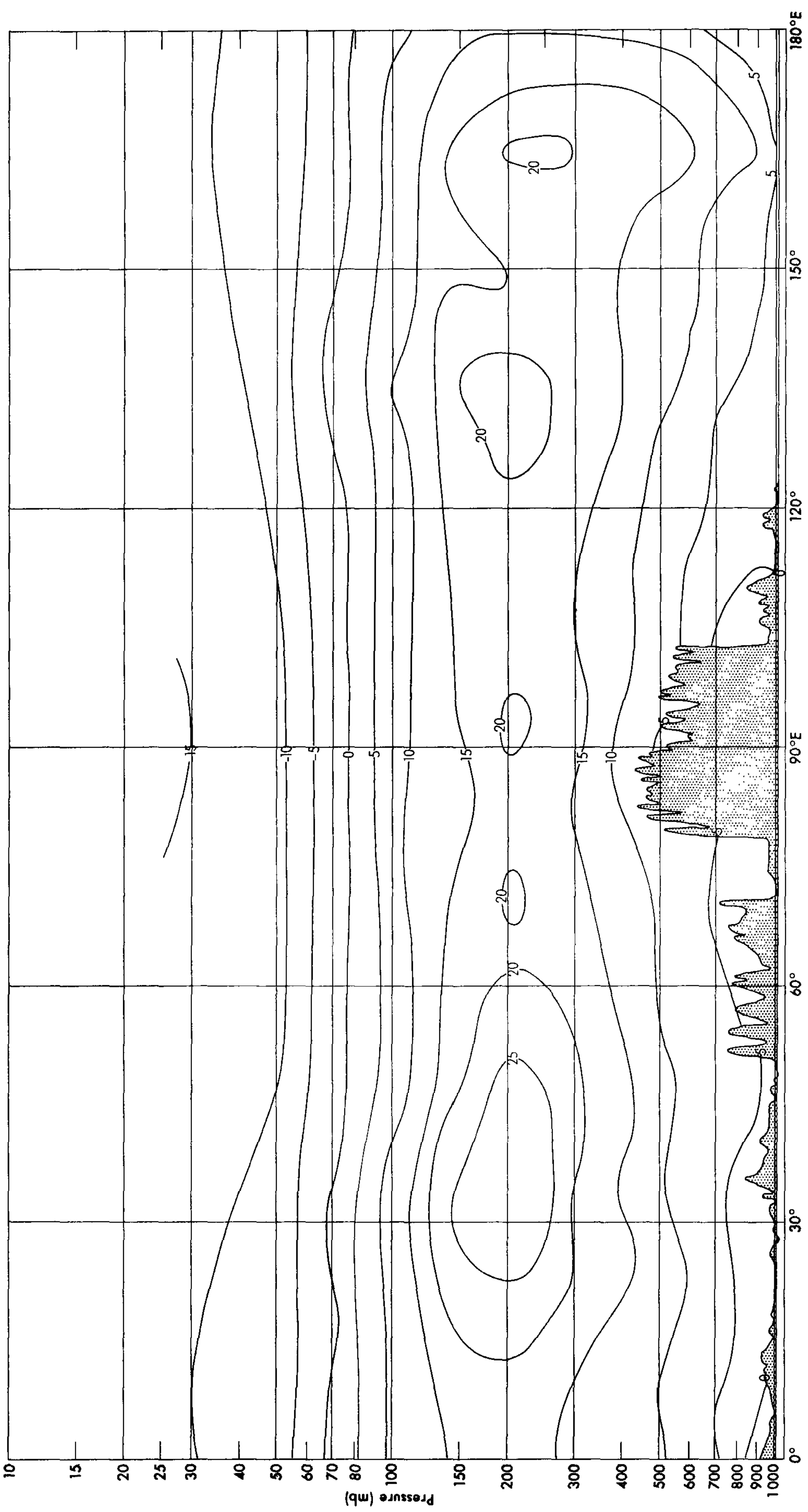


FIGURE 32 (b). MEAN FOR JUNE 1958

—— west to east wind component in m/s.

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

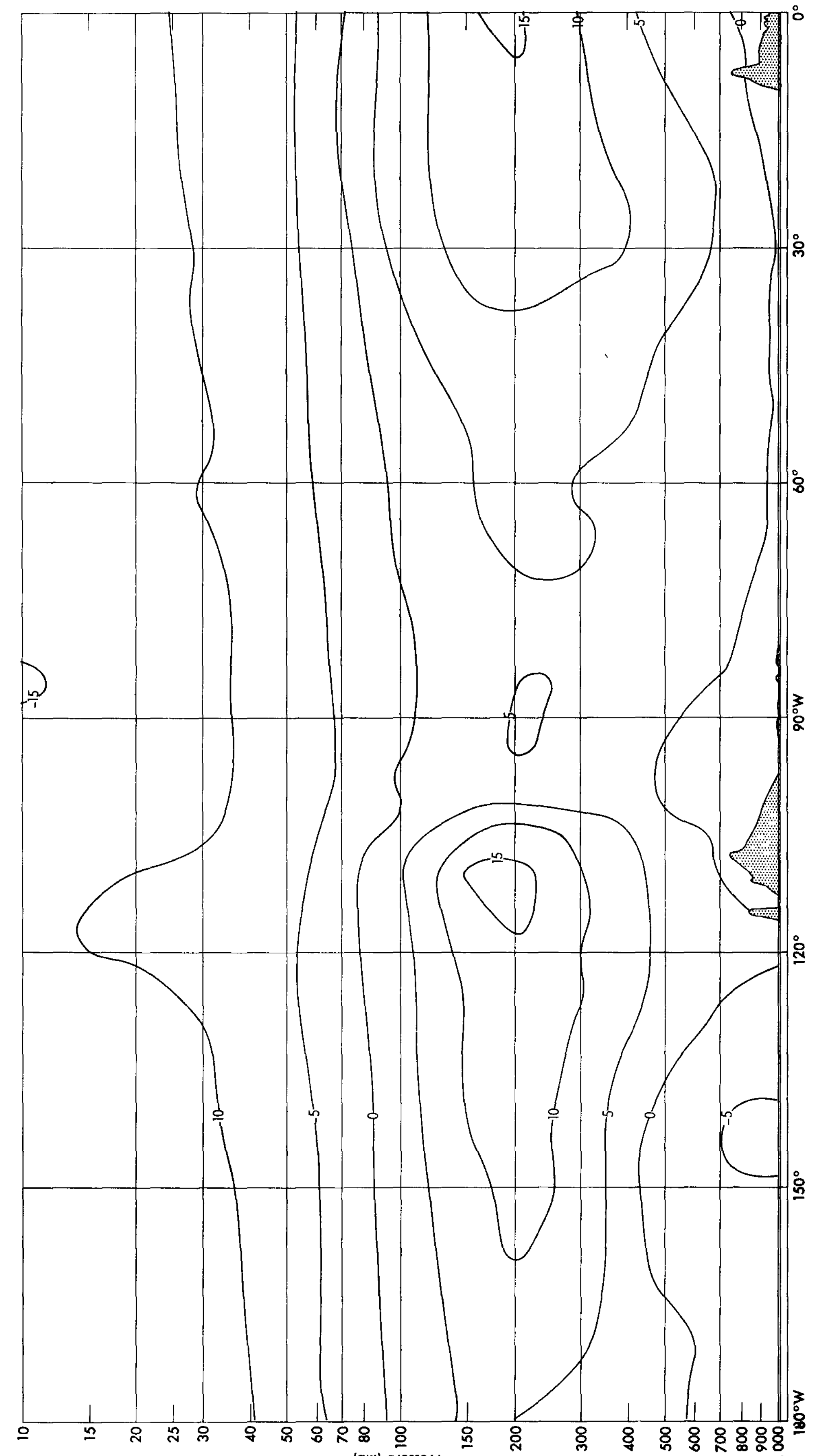


FIGURE 33 (a). MEAN FOR SEPTEMBER 1958

—— west to east wind component in m/s.

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

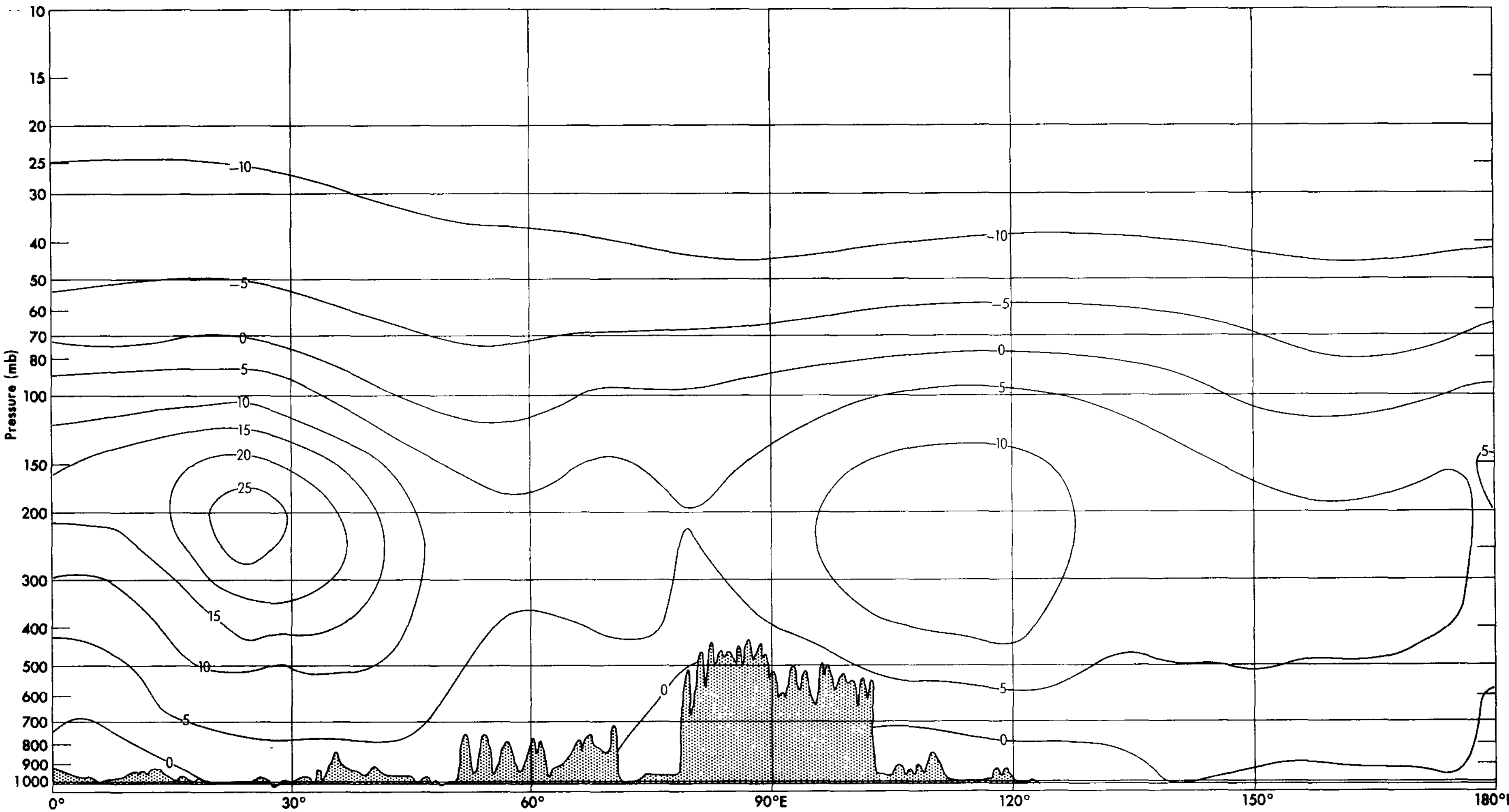


FIGURE 33 (b). MEAN FOR SEPTEMBER 1958

—— west to east wind component in m/s.

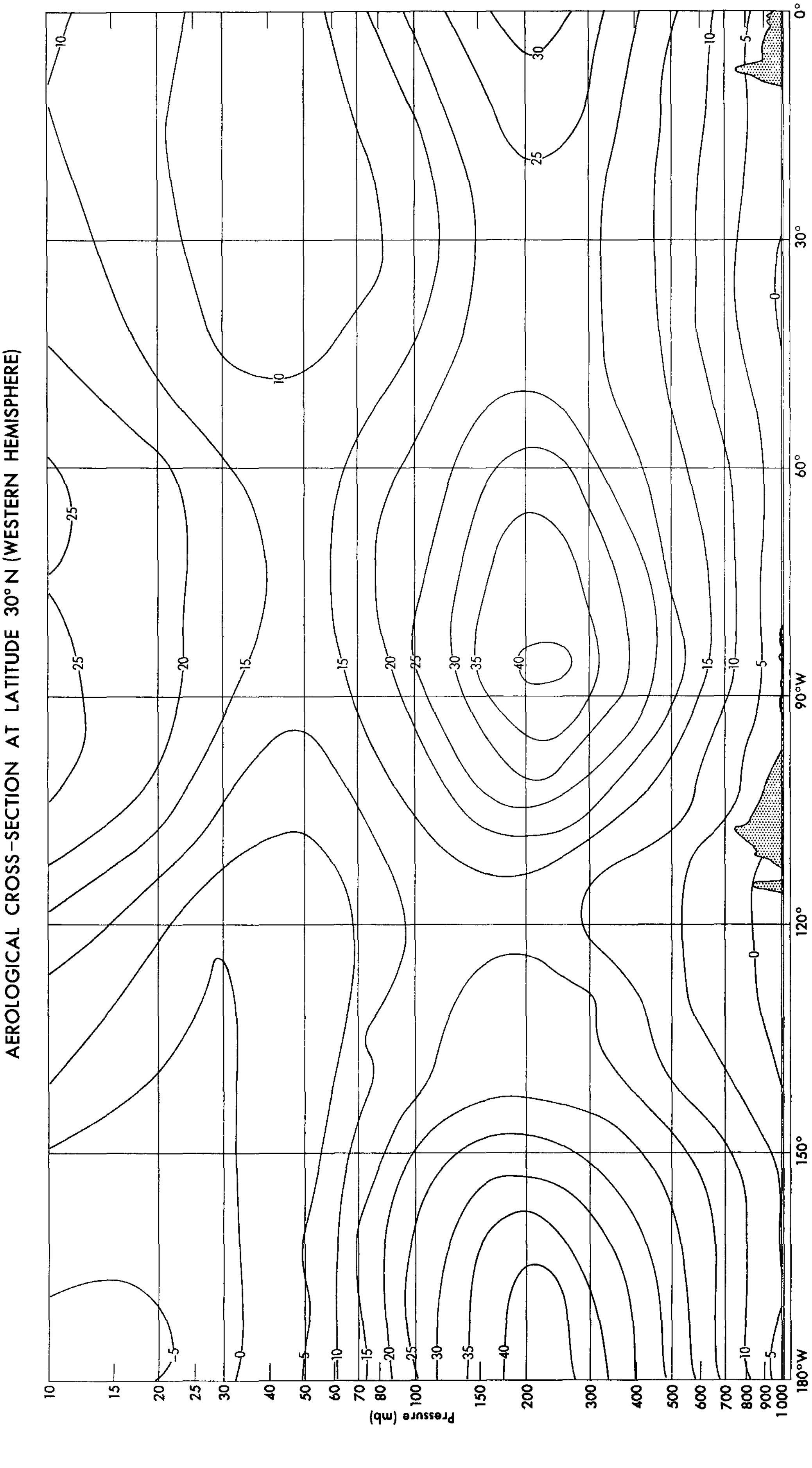


FIGURE 34 (a). MEAN FOR DECEMBER 1958

—— west to east wind component in m/s.

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

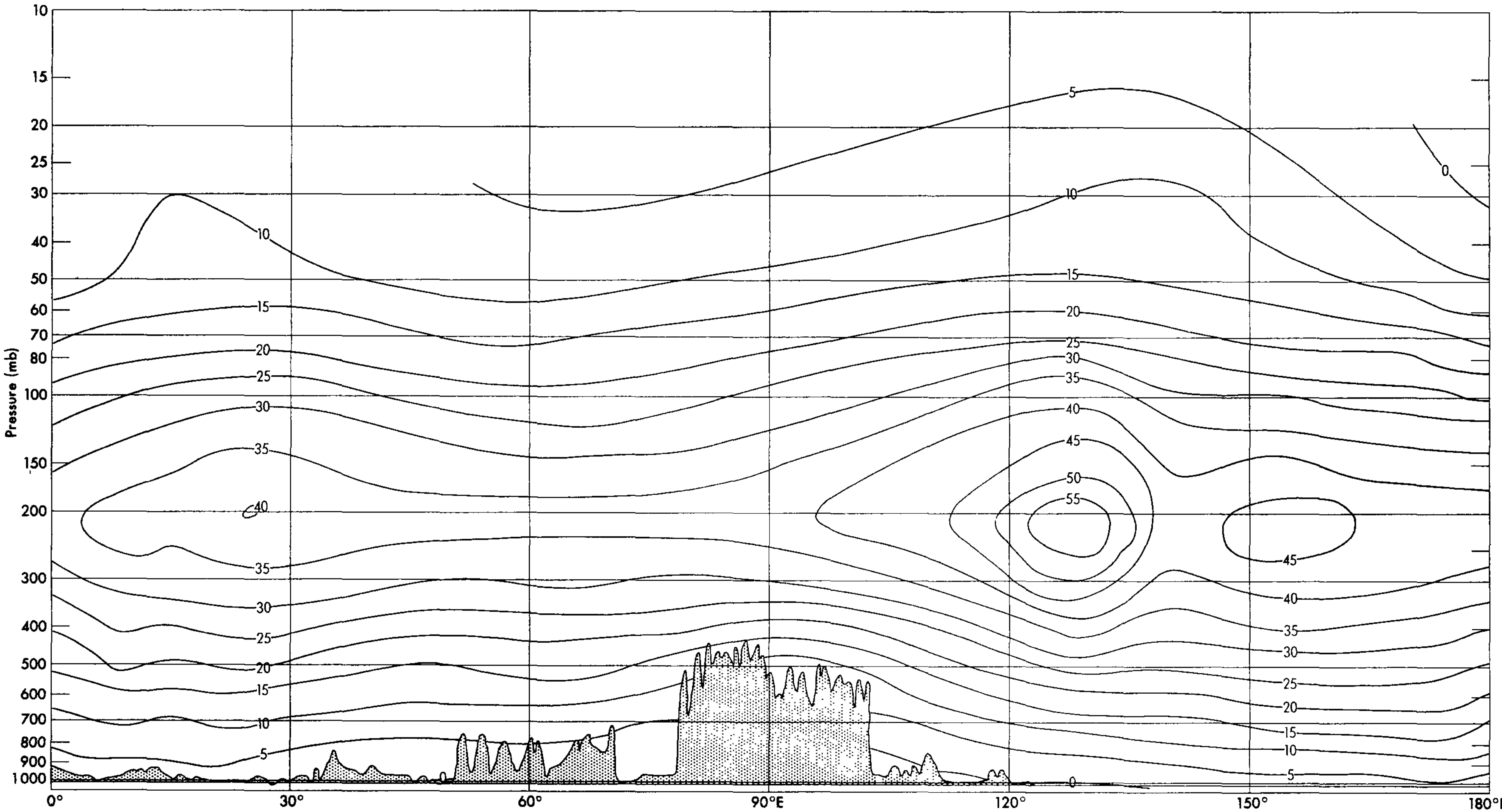


FIGURE 34 (b). MEAN FOR DECEMBER 1958

——— west to east wind component in m/s.

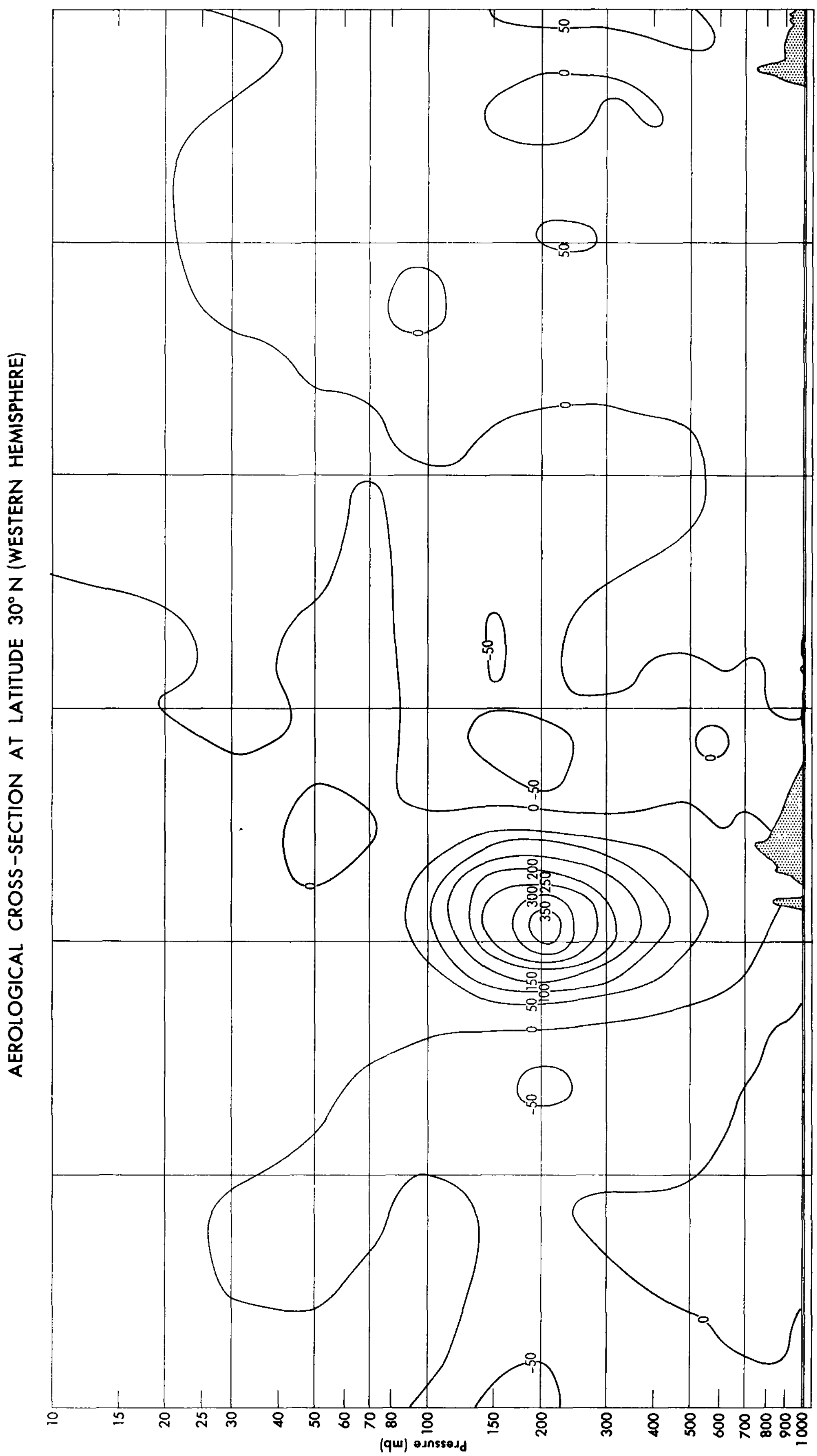


FIGURE 35 (a). TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

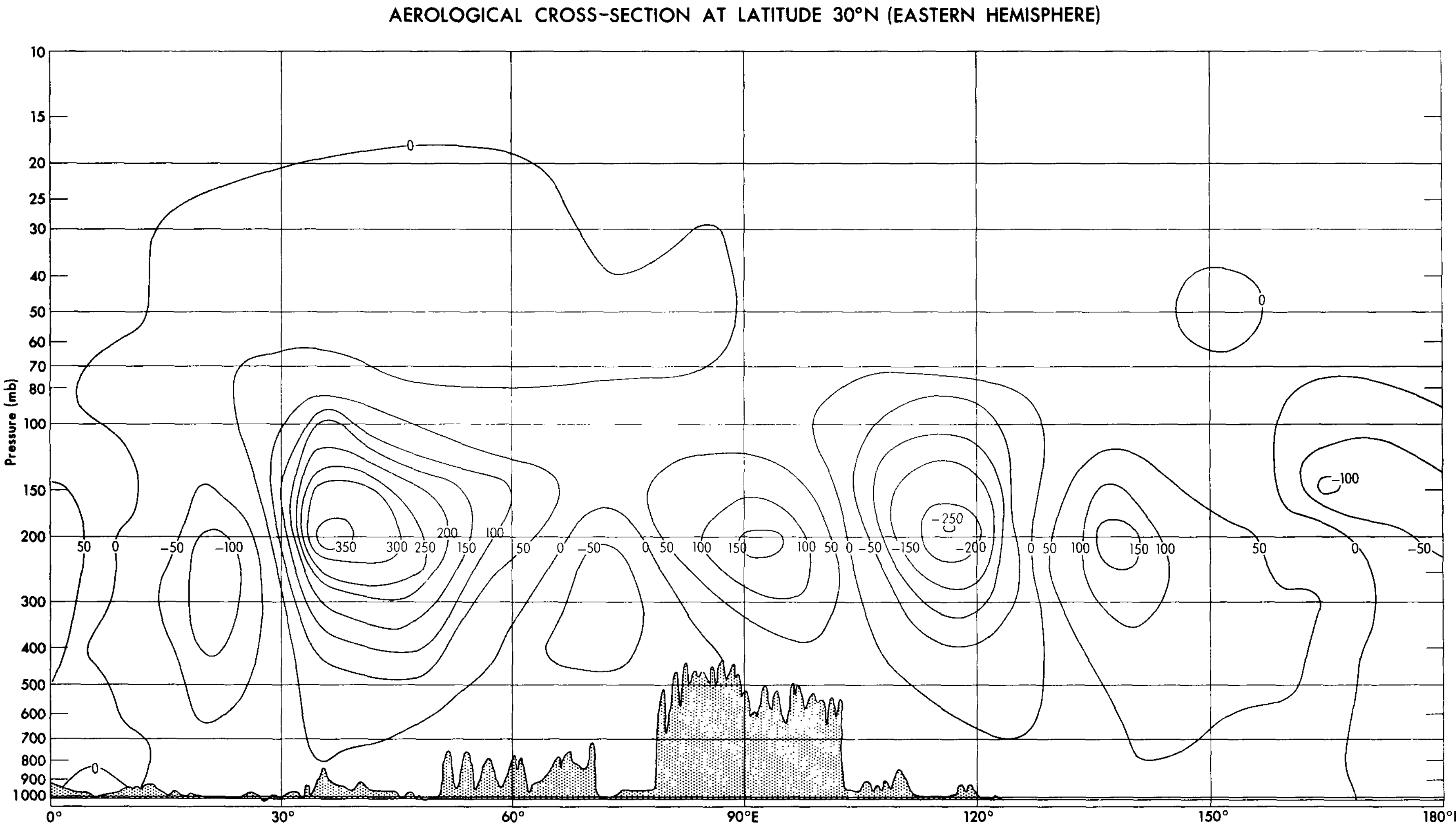


FIGURE 35 (b). TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

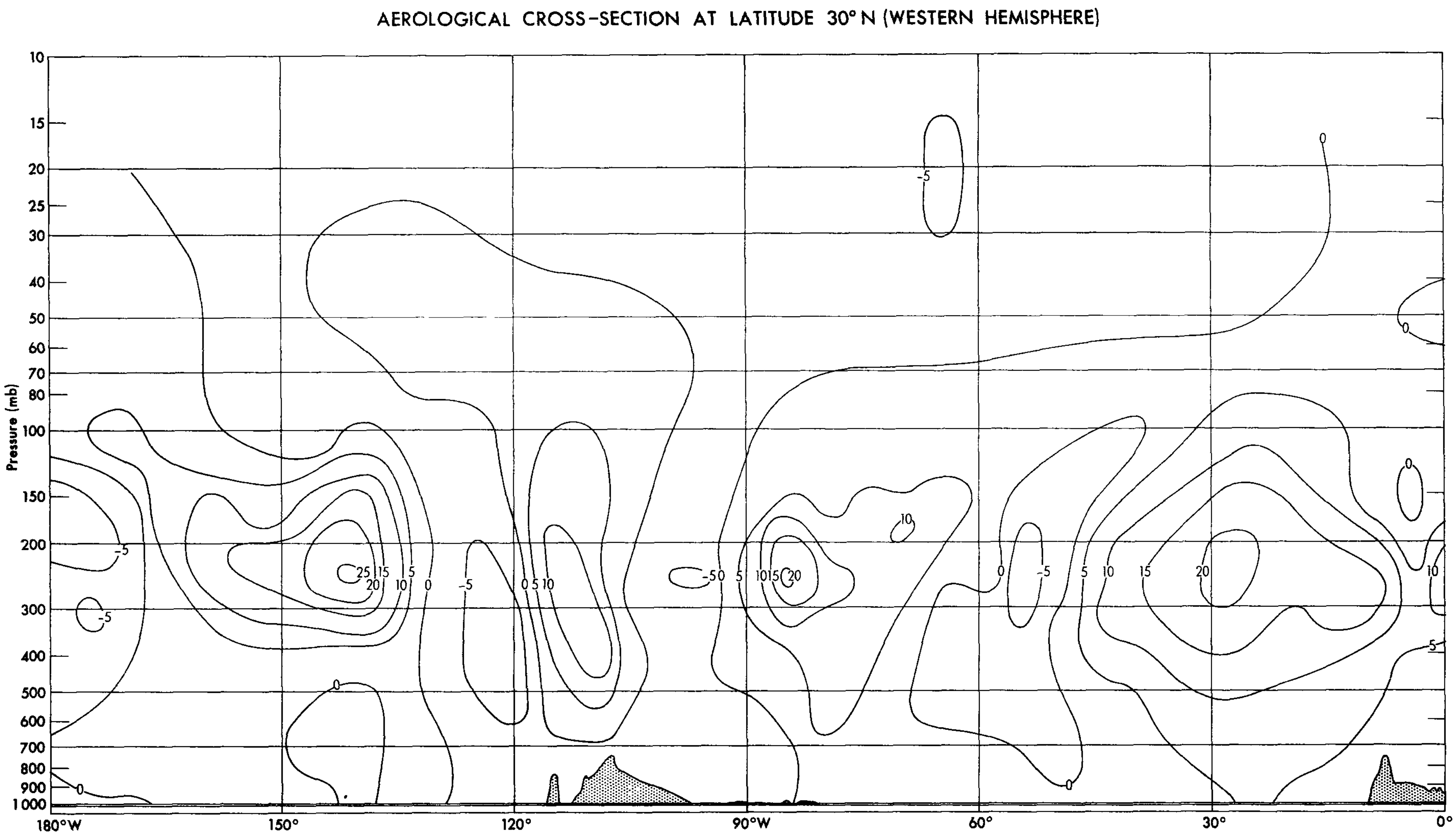


FIGURE 36 (a). LOCAL EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

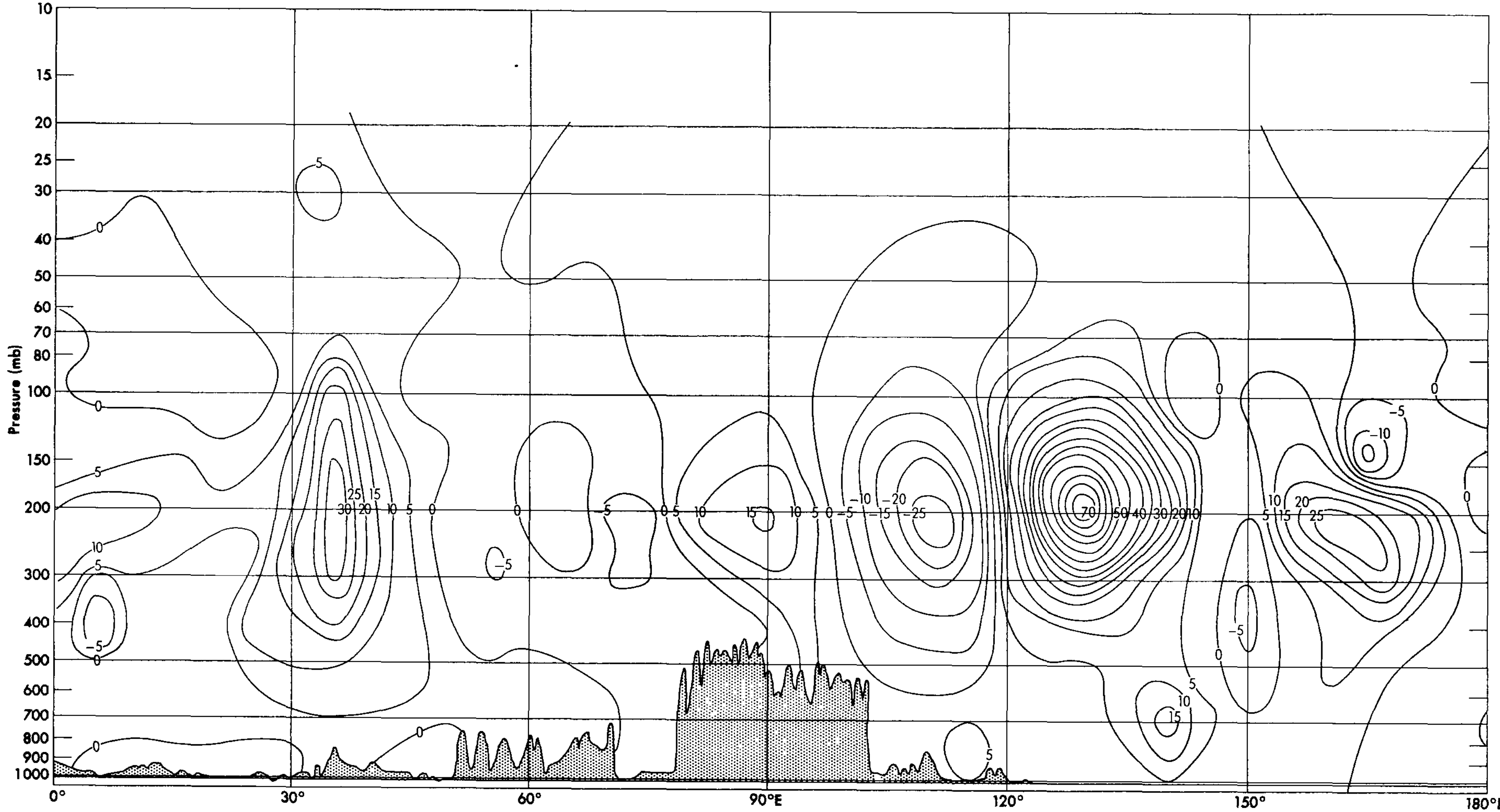


FIGURE 36 (b). LOCAL EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

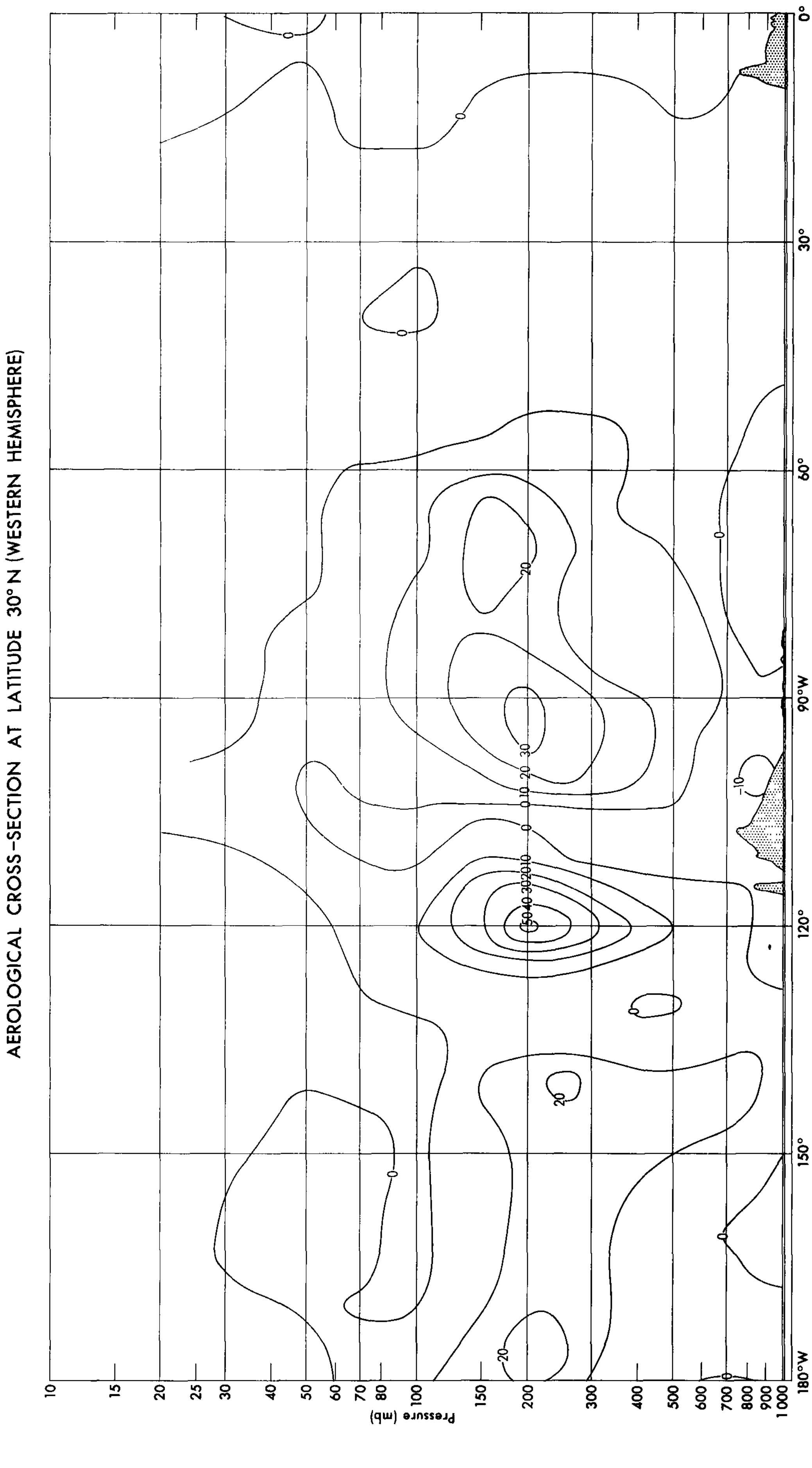


FIGURE 37 (a). STANDING EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

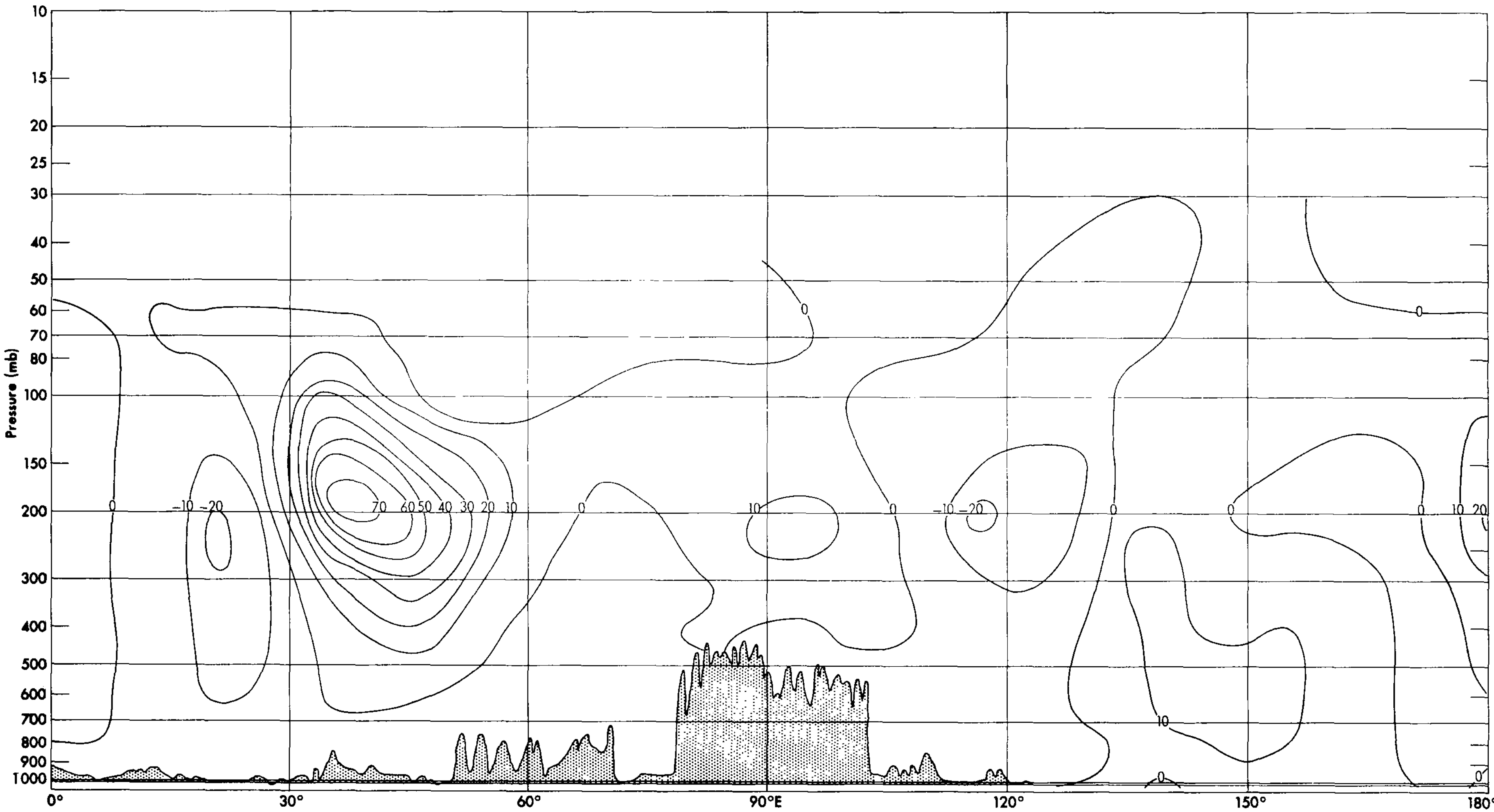


FIGURE 37 (b). STANDING EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

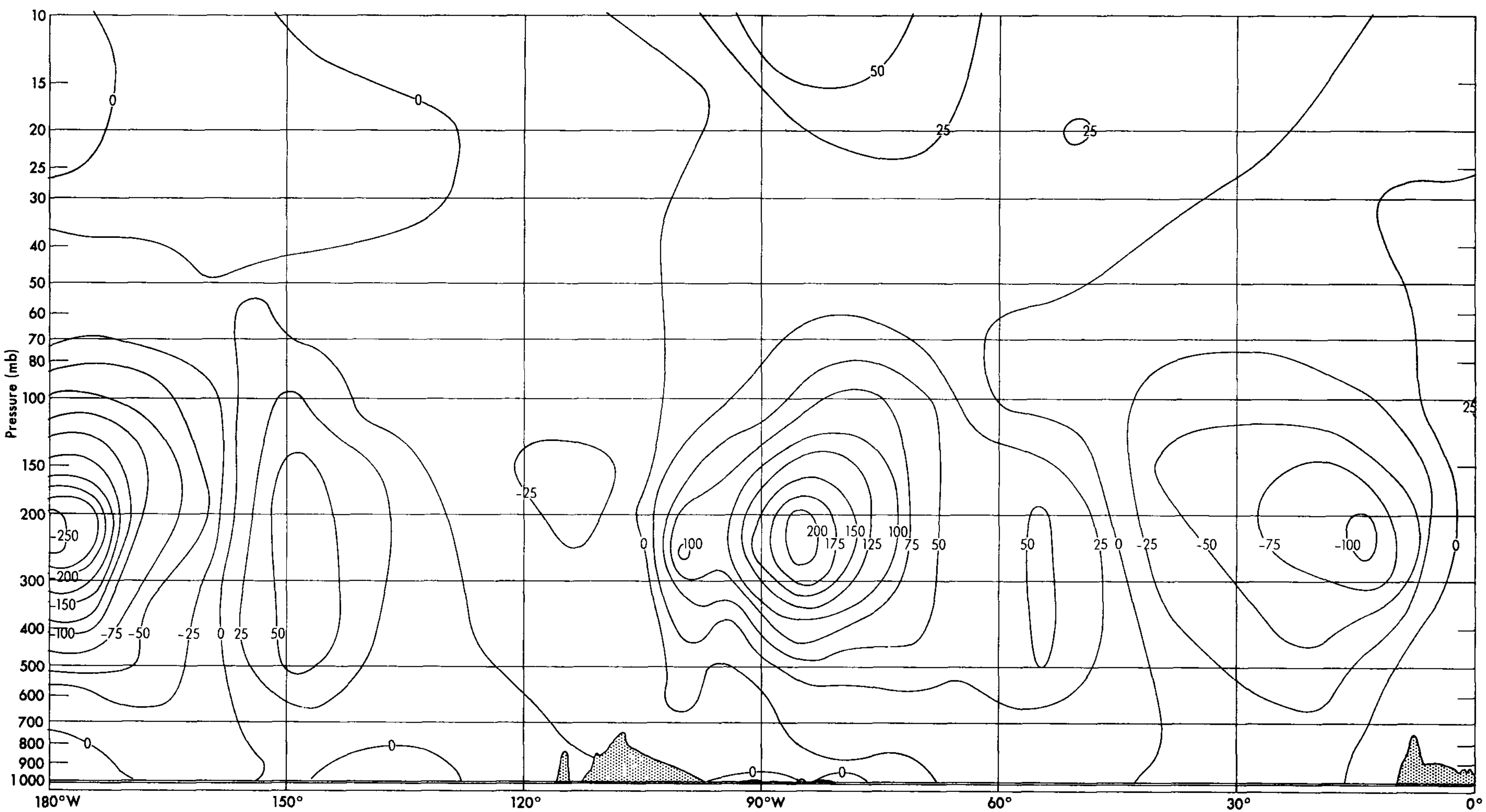


FIGURE 38 (a). TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

FIGURE 38 (b). TOTAL FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

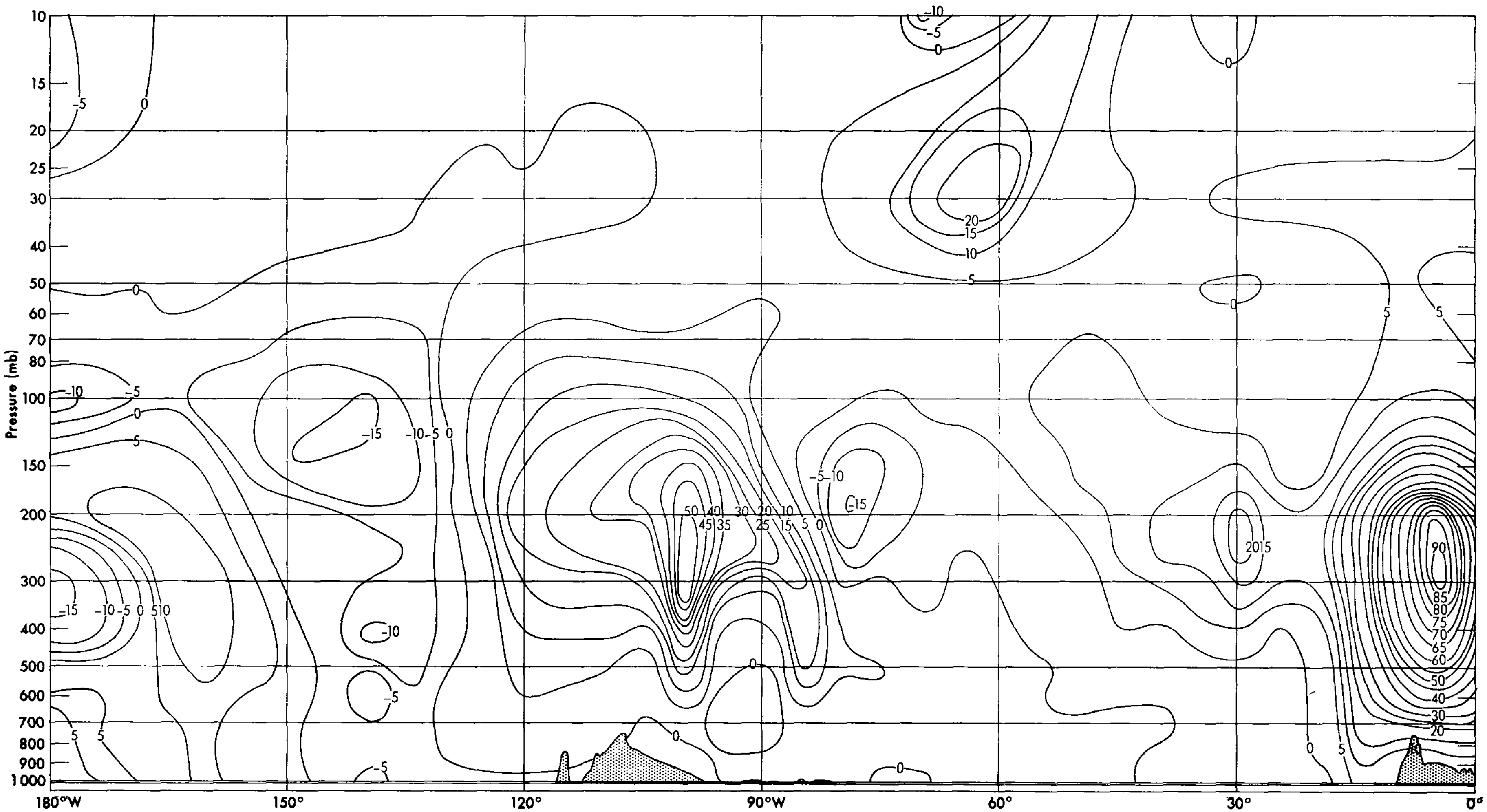


FIGURE 39 (a). LOCAL EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

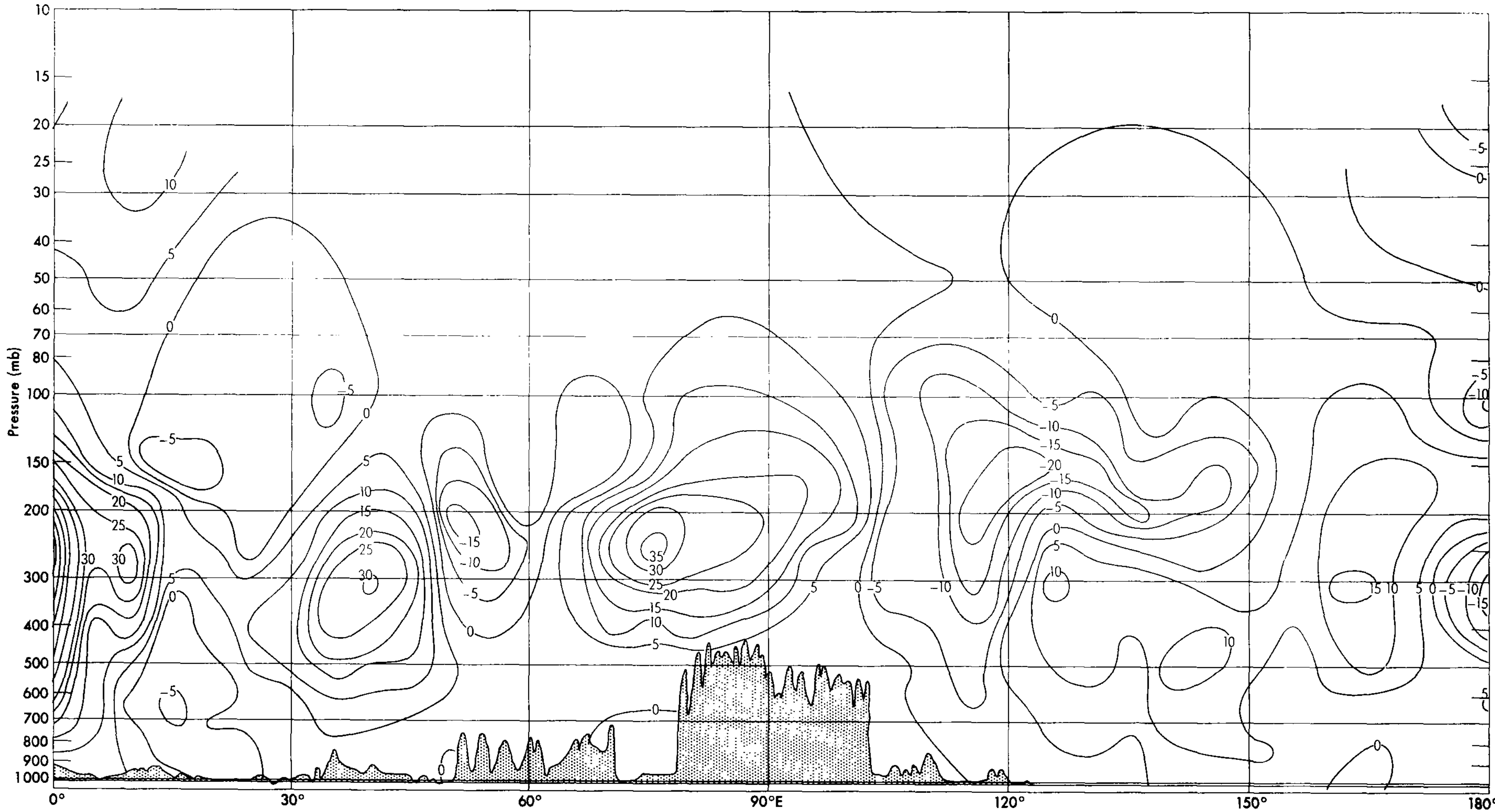


FIGURE 39 (b). LOCAL EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

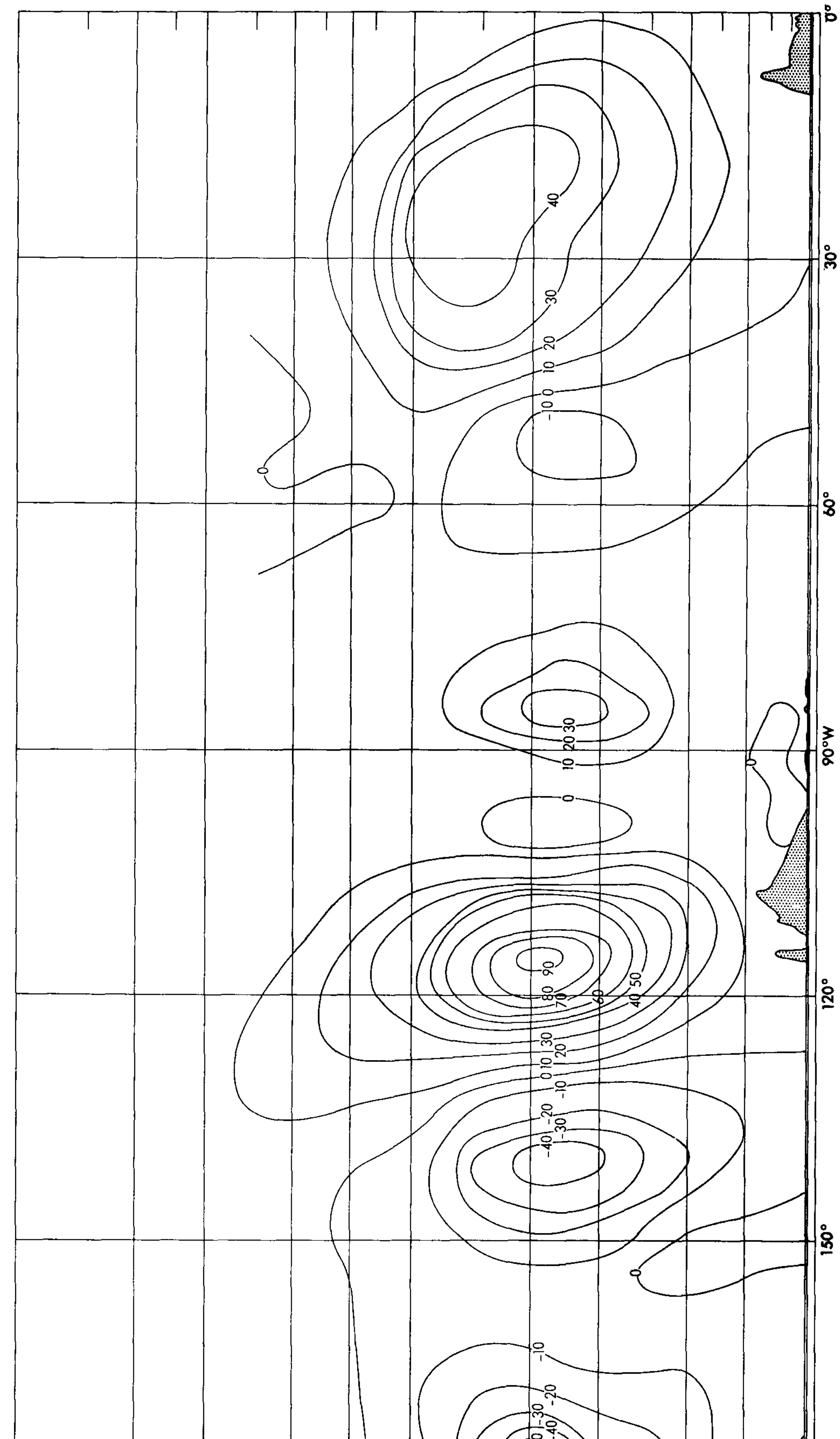


FIGURE 40 (a). STANDING EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

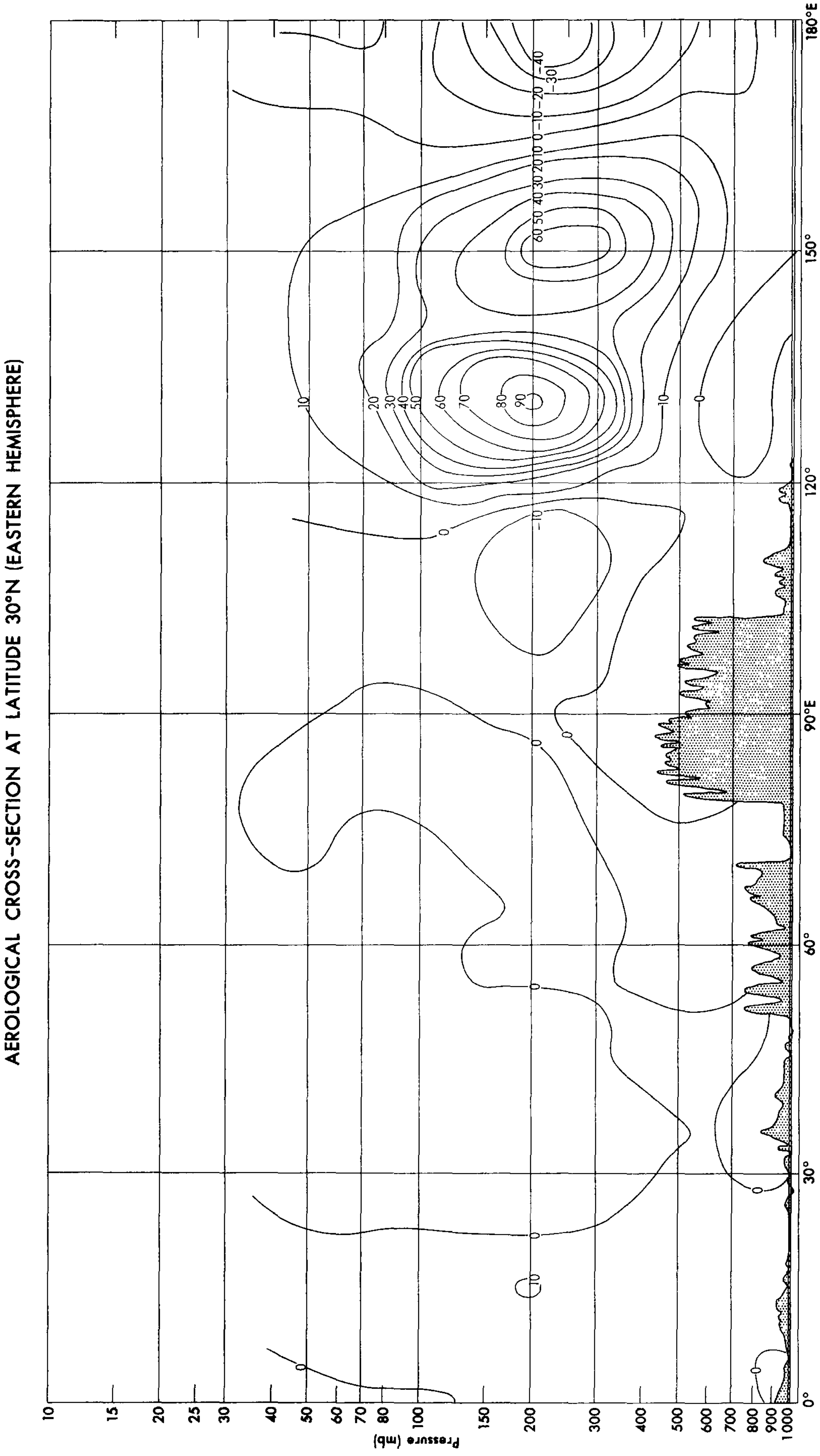


FIGURE 40 (b). STANDING EDDY FLUX OF RELATIVE ANGULAR MOMENTUM ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^{20} g cm^2/s^2 per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

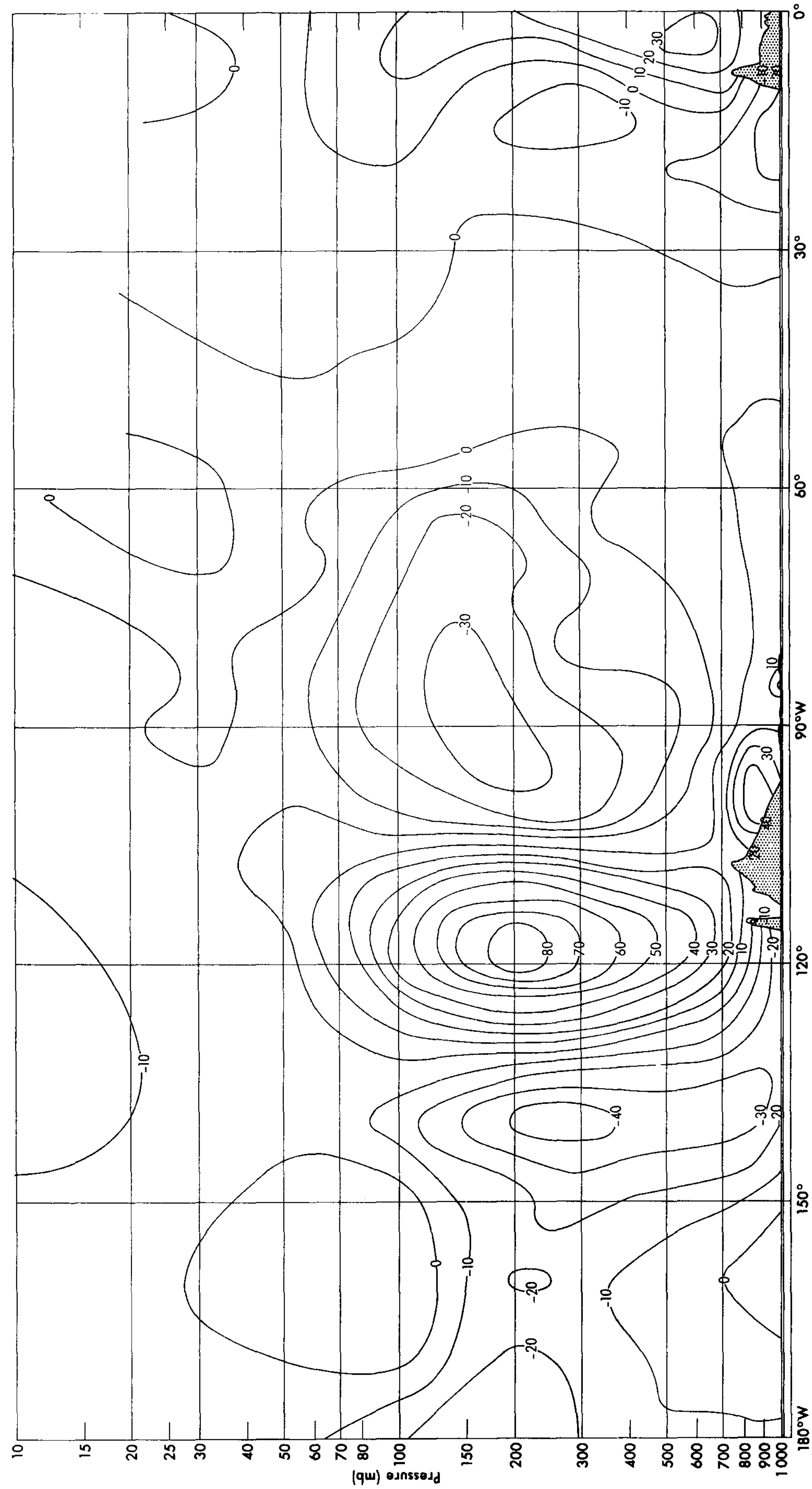


FIGURE 41 (a). TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^7 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

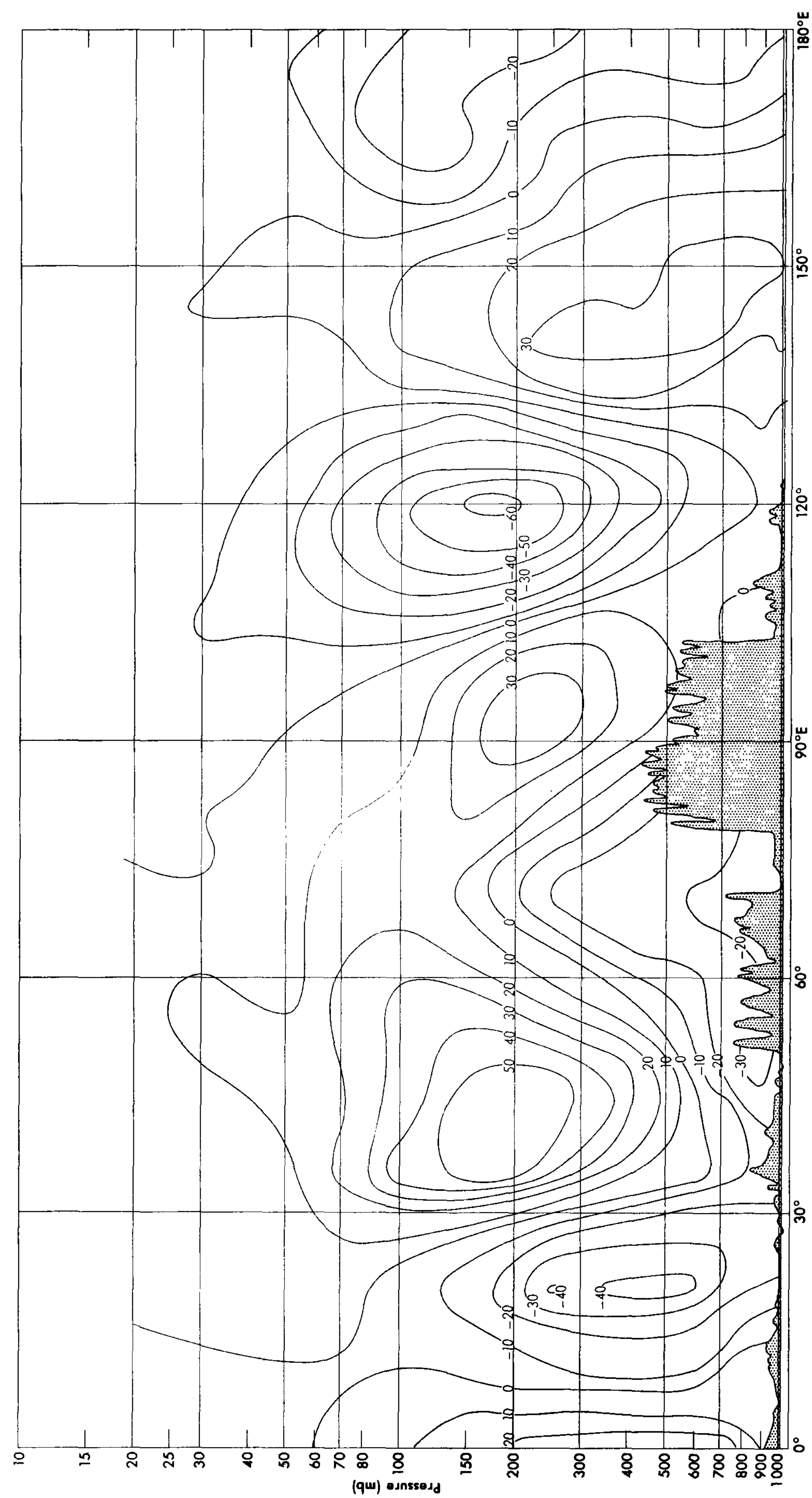


FIGURE 41 (b). TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^7 cal/s per mb per degree longitude

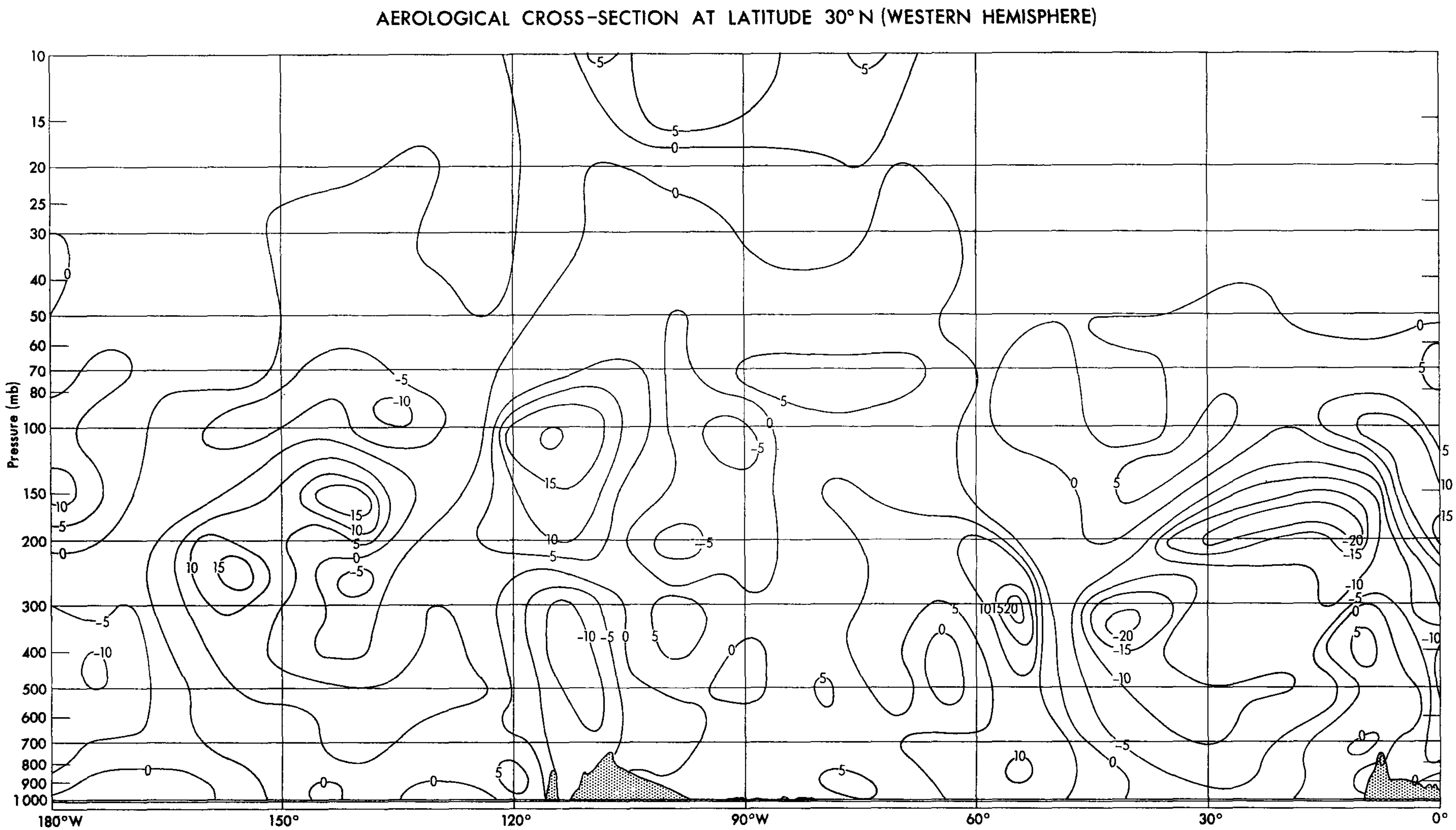


FIGURE 42 (a). LOCAL EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^5 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

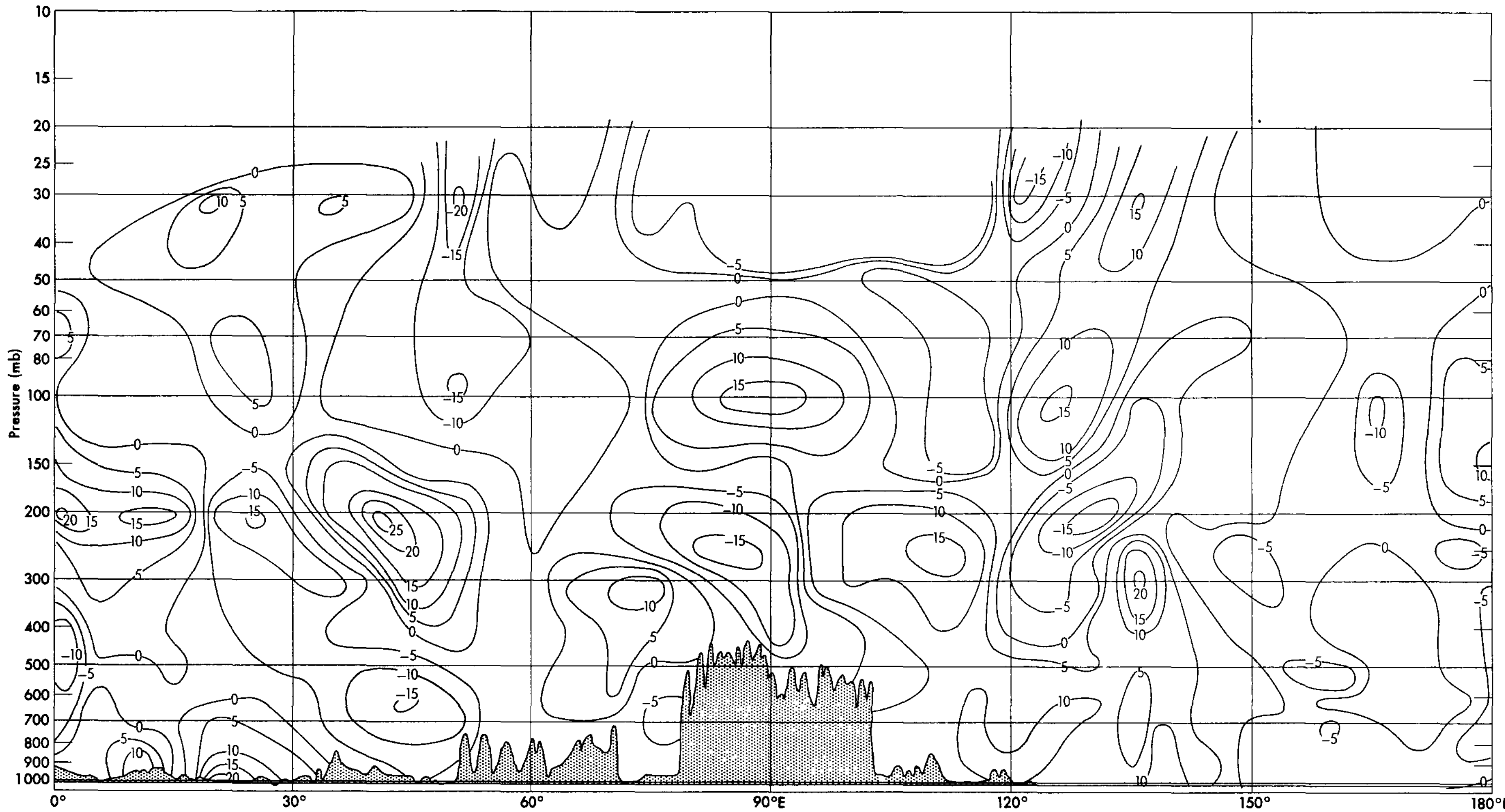


FIGURE 42 (b). LOCAL EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^5 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

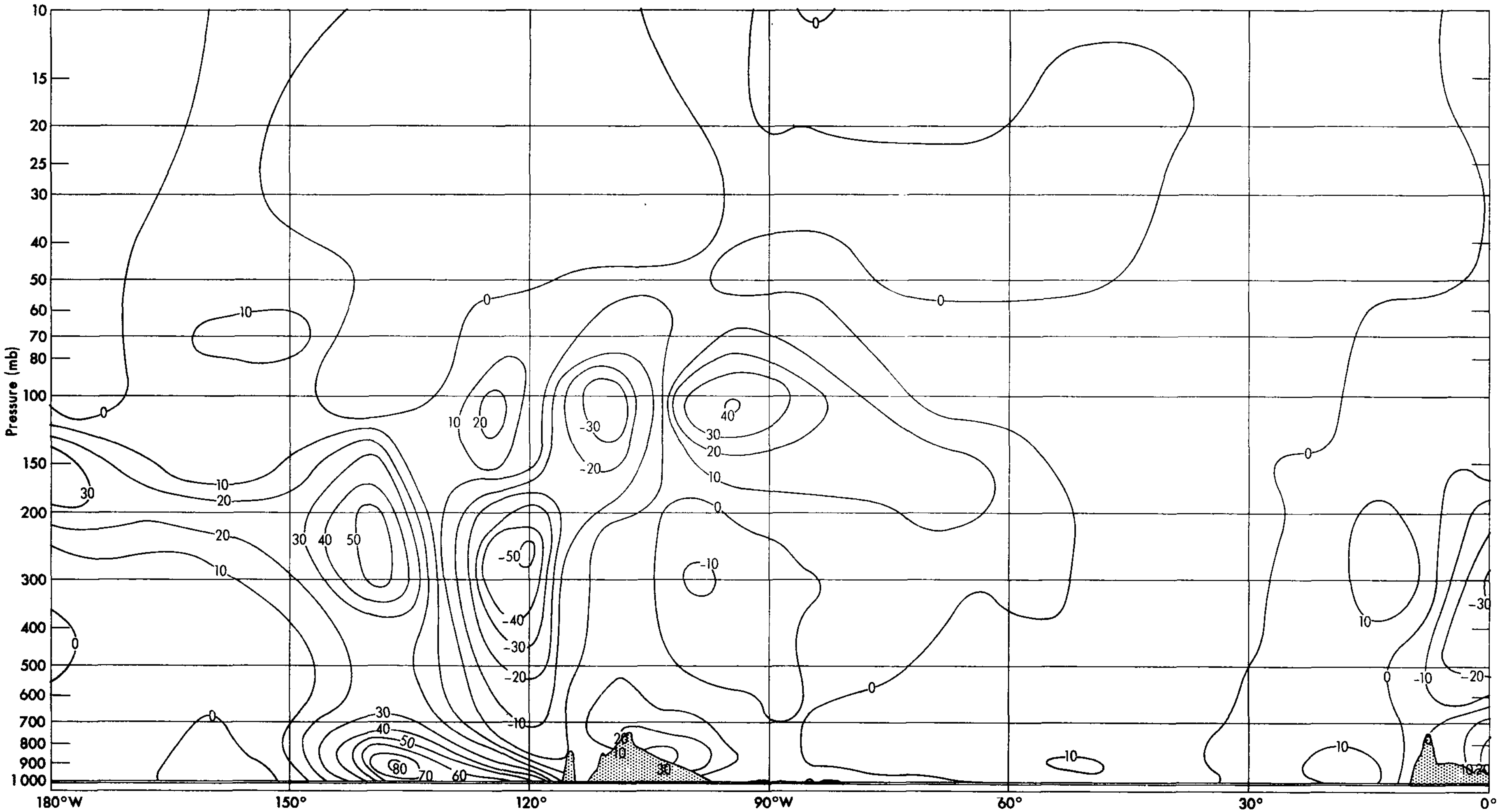


FIGURE 43 (a). STANDING EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^4 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

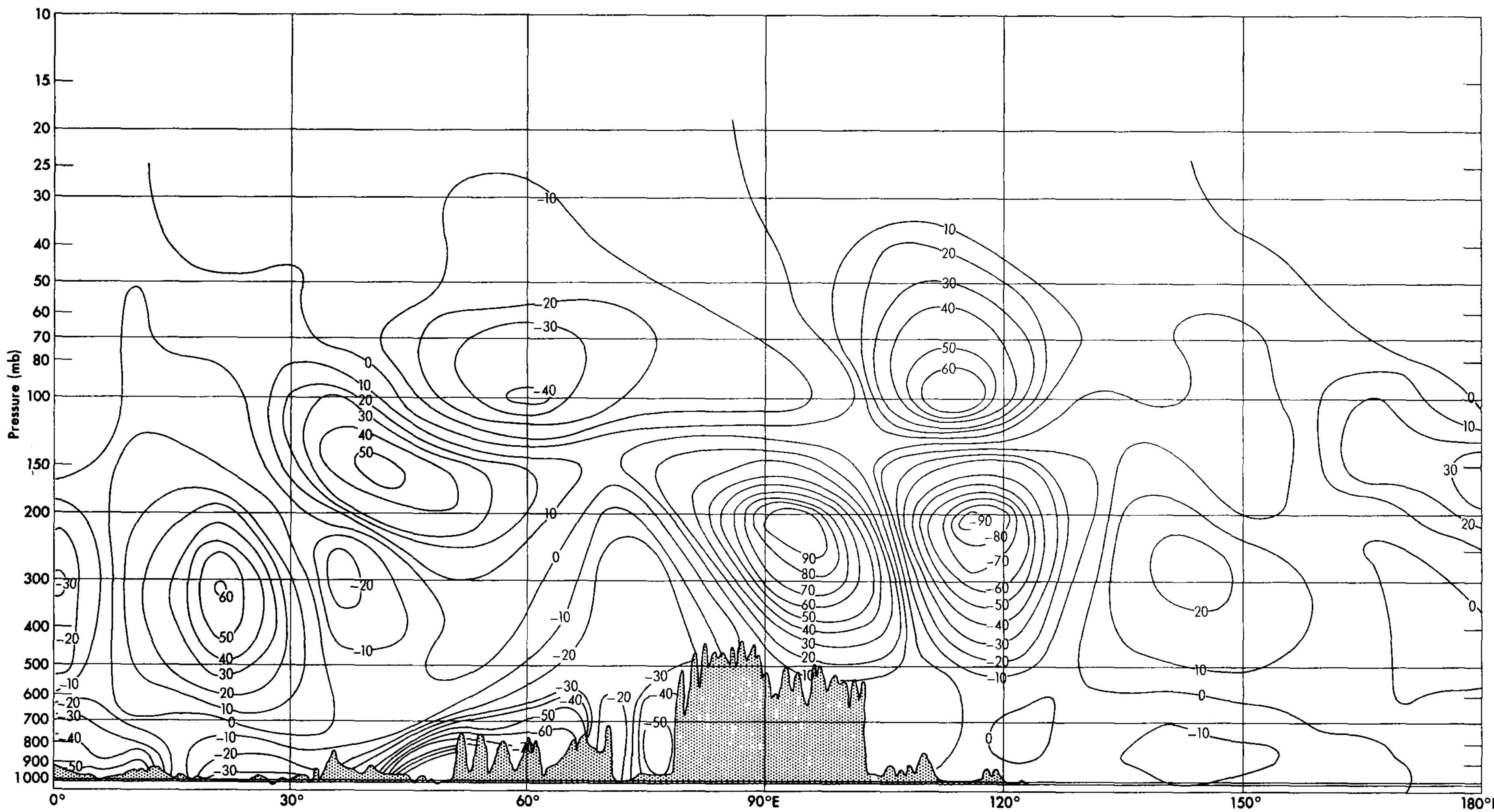


FIGURE 43 (b).. STANDING EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^4 cal/s per mb per degree longitude

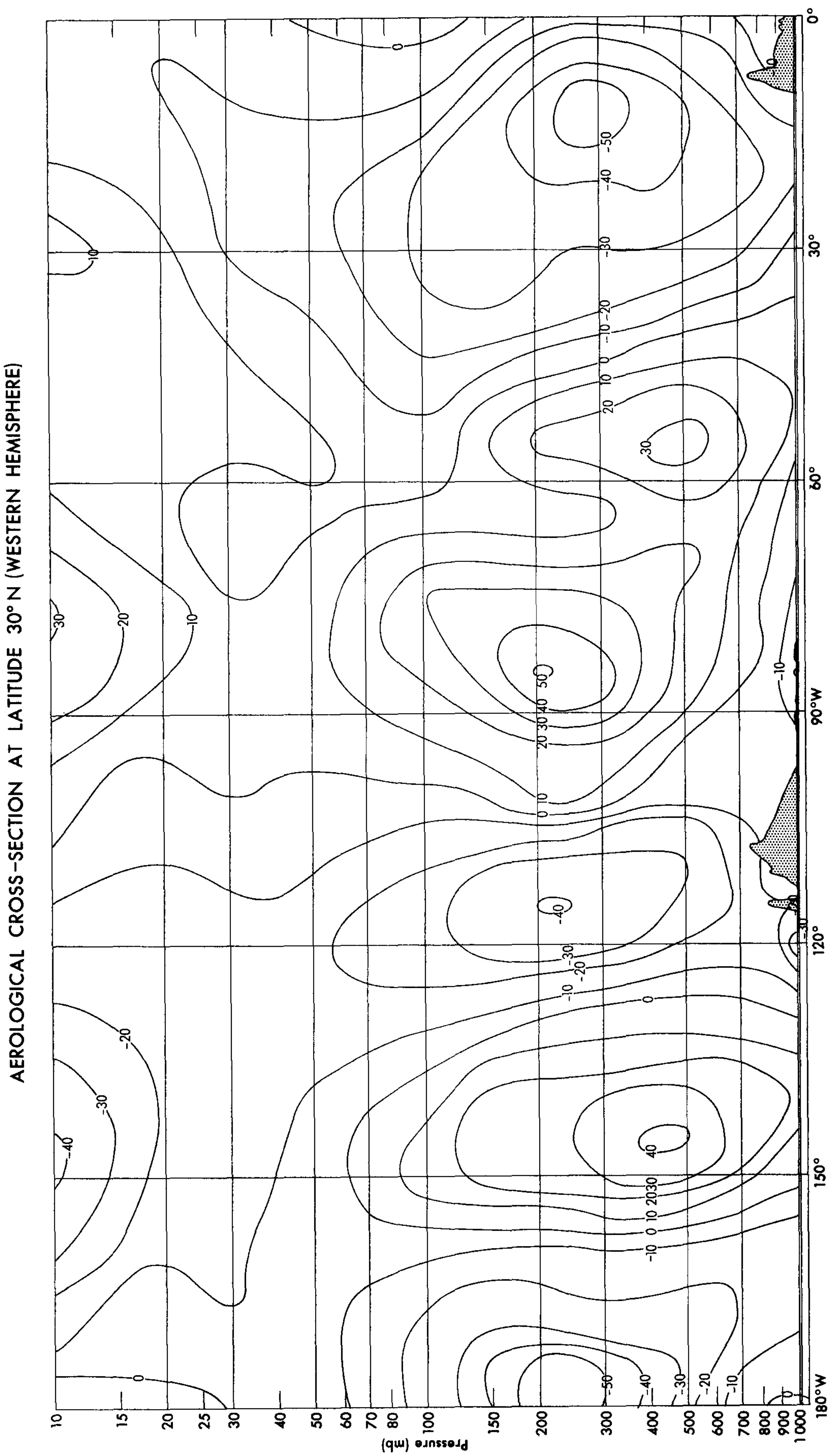


FIGURE 44 (a). TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°FOR DECEMBER 1958 IN UNITS OF 10^7 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

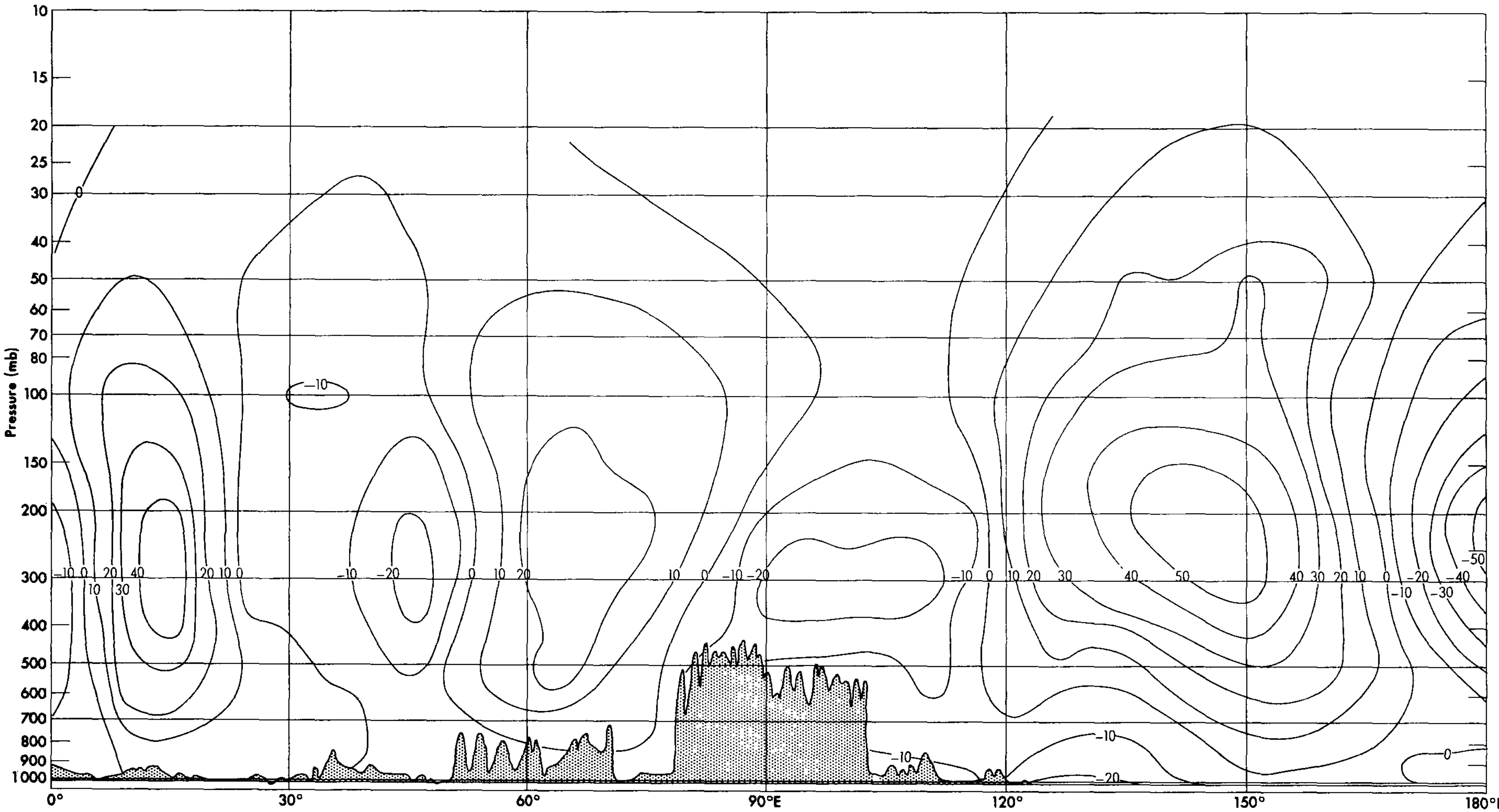


FIGURE 44 (b). TOTAL FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^7 cal/s per mb per degree longitude

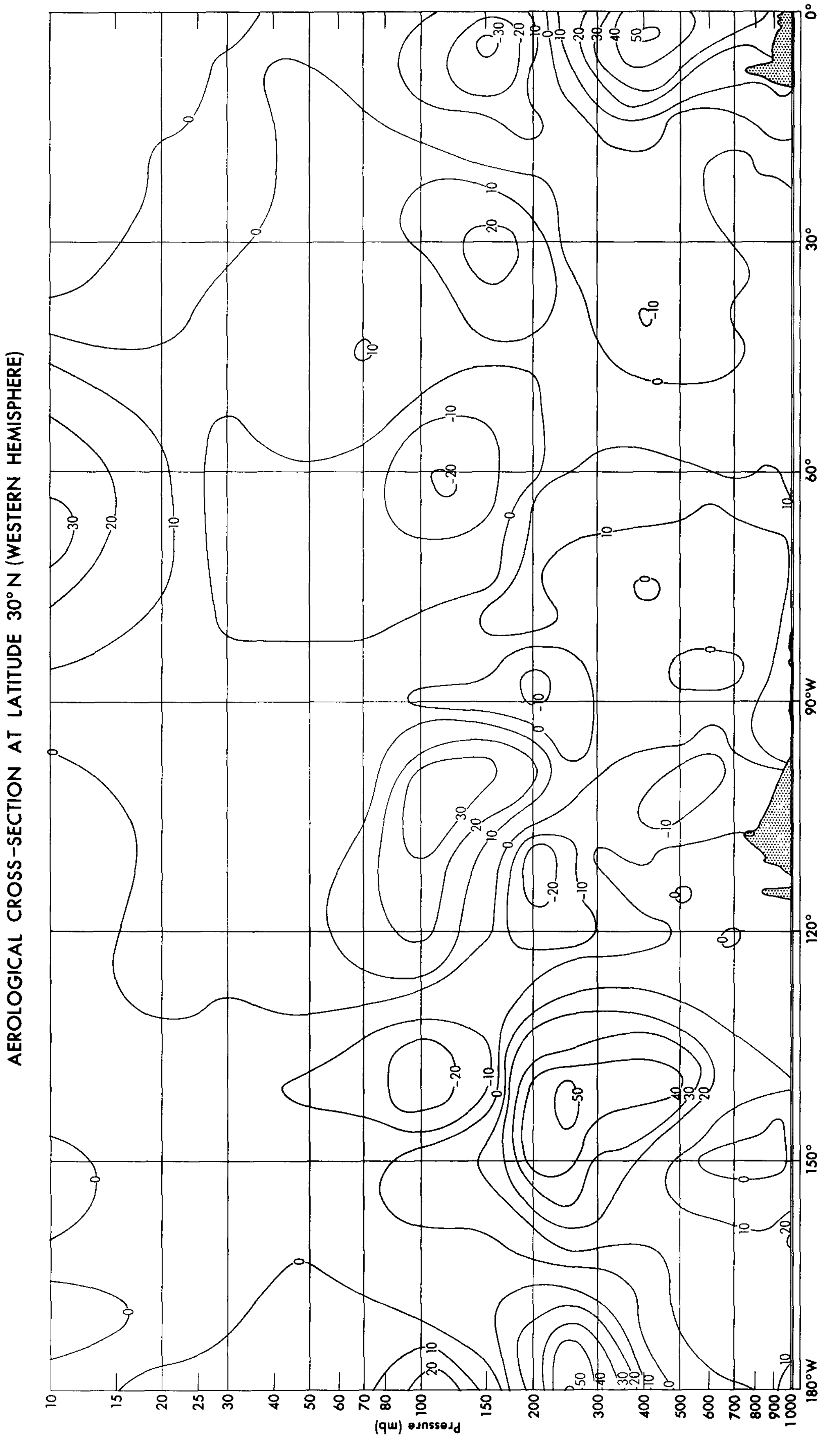


FIGURE 45 (a). LOCAL EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^5 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

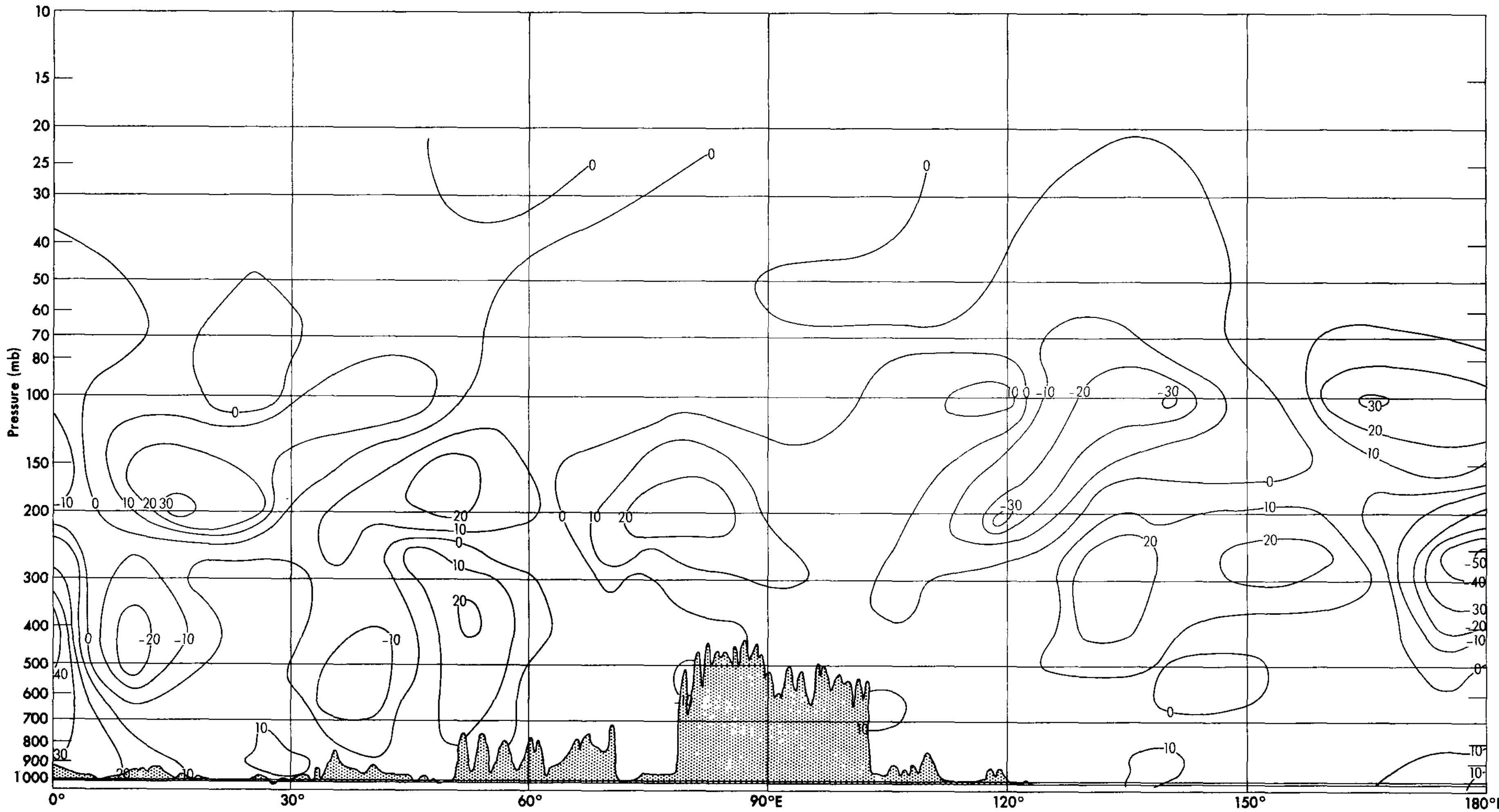


FIGURE 45 (b). LOCAL EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^5 cal/s per mb per degree longitude

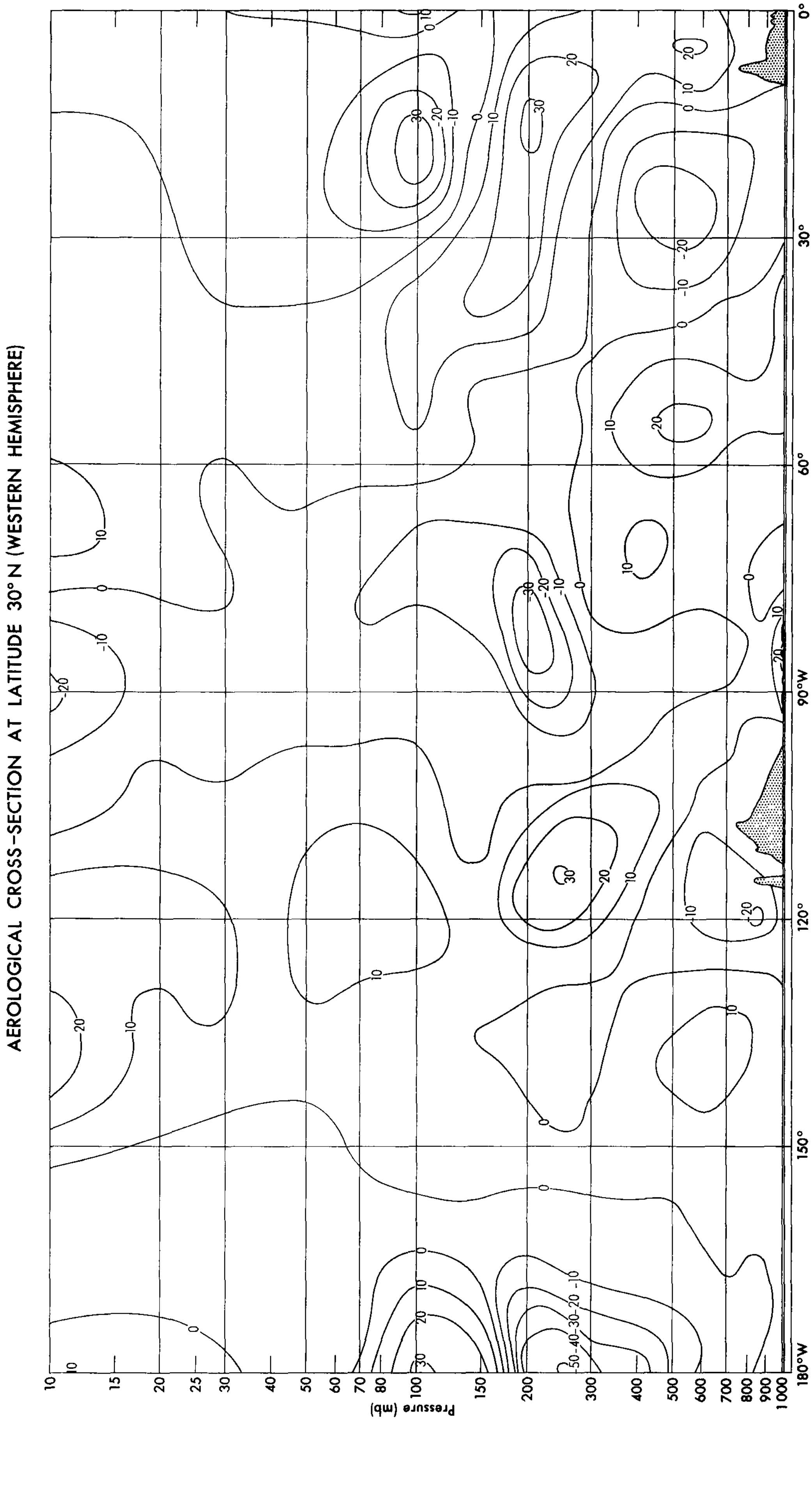


FIGURE 46 (a). STANDING EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^4 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

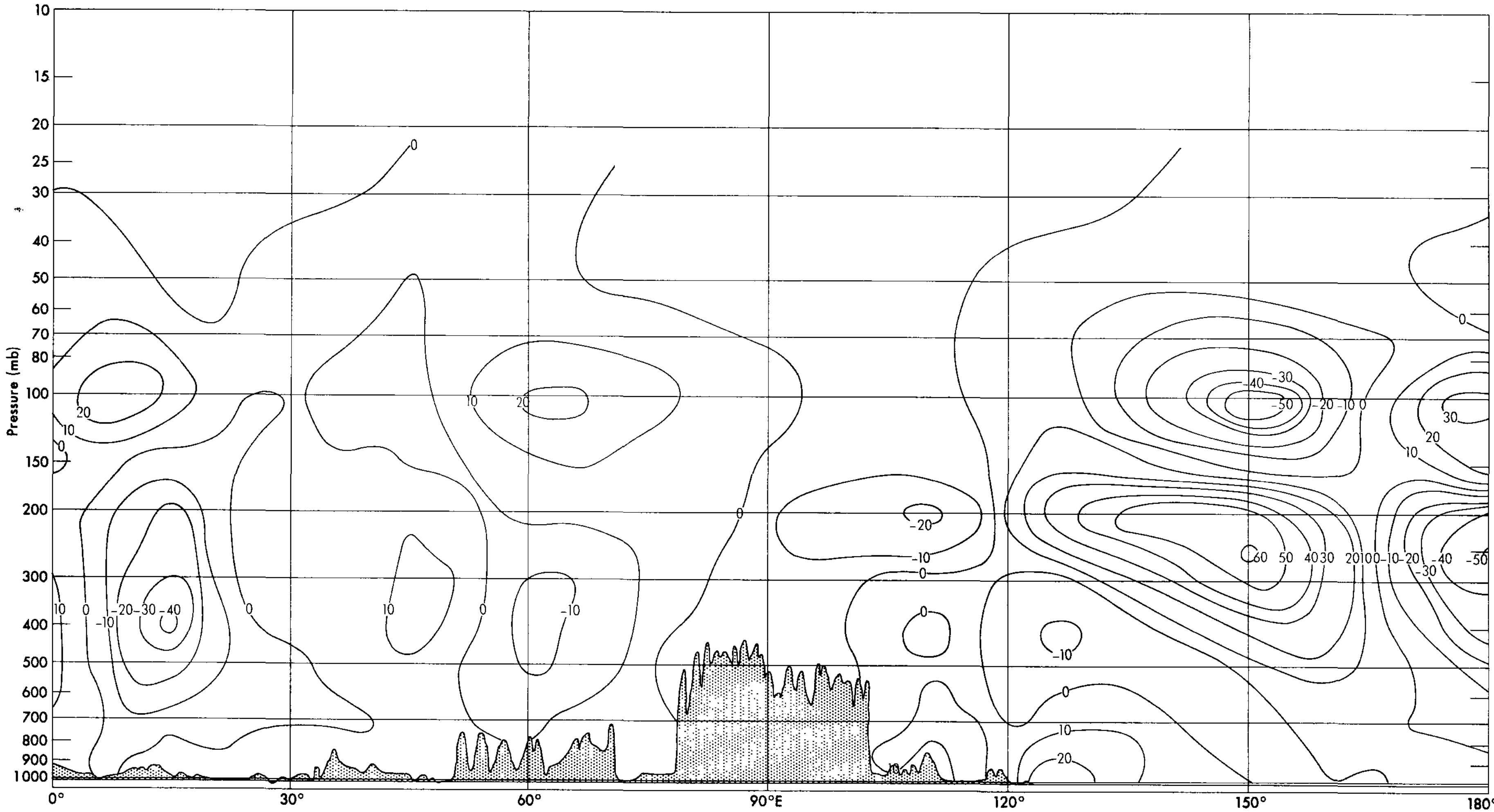


FIGURE 46 (b). STANDING EDDY FLUX OF SENSIBLE HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^4 cal/s per mb per degree longitude

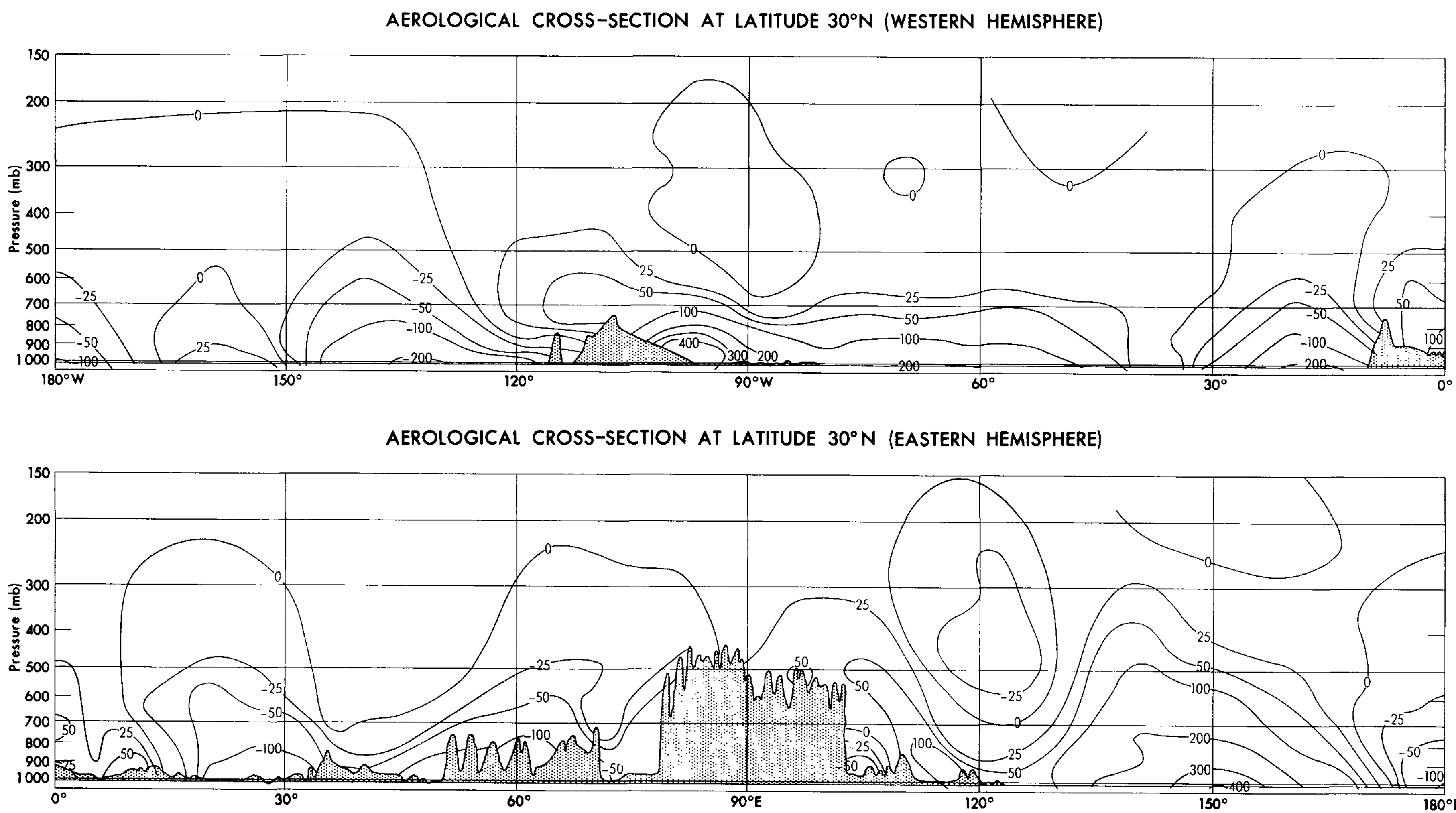
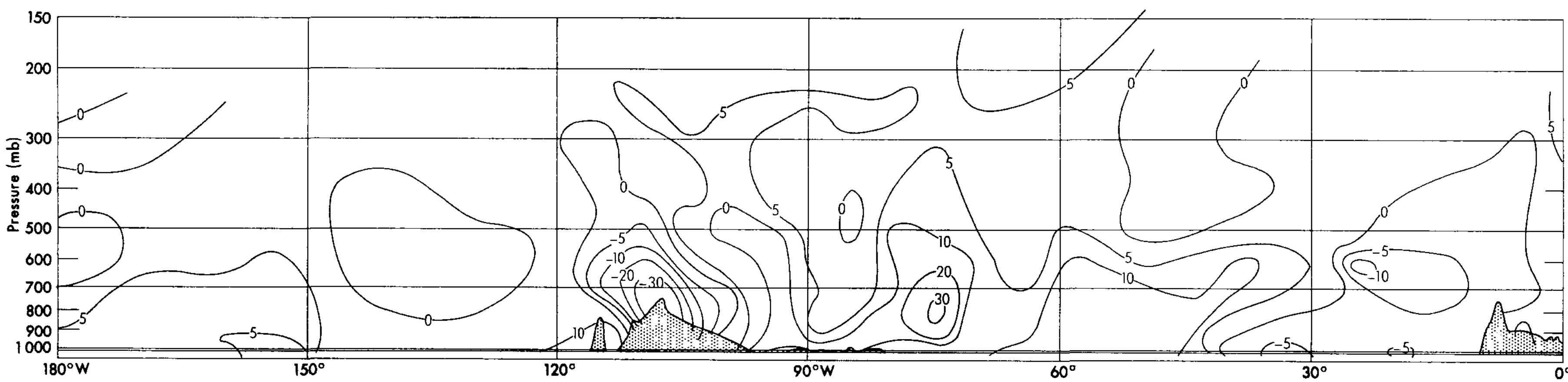


FIGURE 47 (a) and (b). TOTAL FLUX OF LATENT HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^8 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (WESTERN HEMISPHERE)



AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

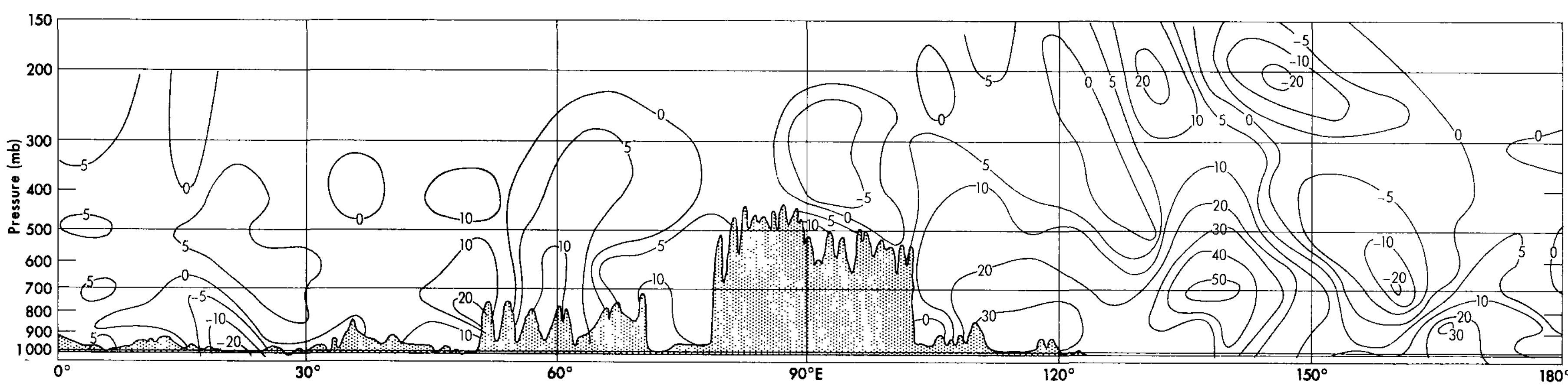


FIGURE 48 (a) and (b). LOCAL EDDY FLUX OF LATENT HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^8 cal/s per mb per degree longitude

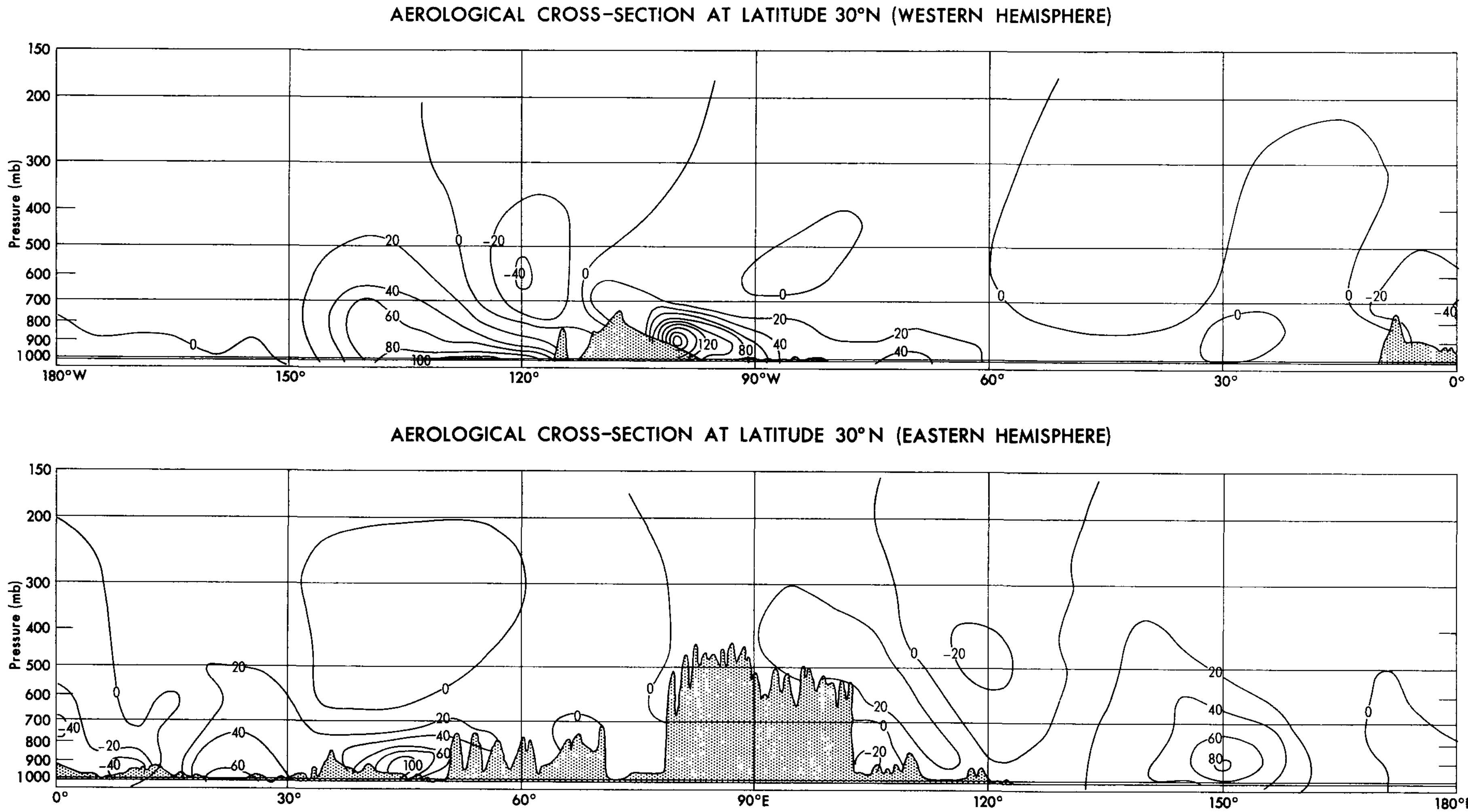


FIGURE 49 (a) and (b). STANDING EDDY FLUX OF LATENT HEAT ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^8 cal/s per mb per degree longitude

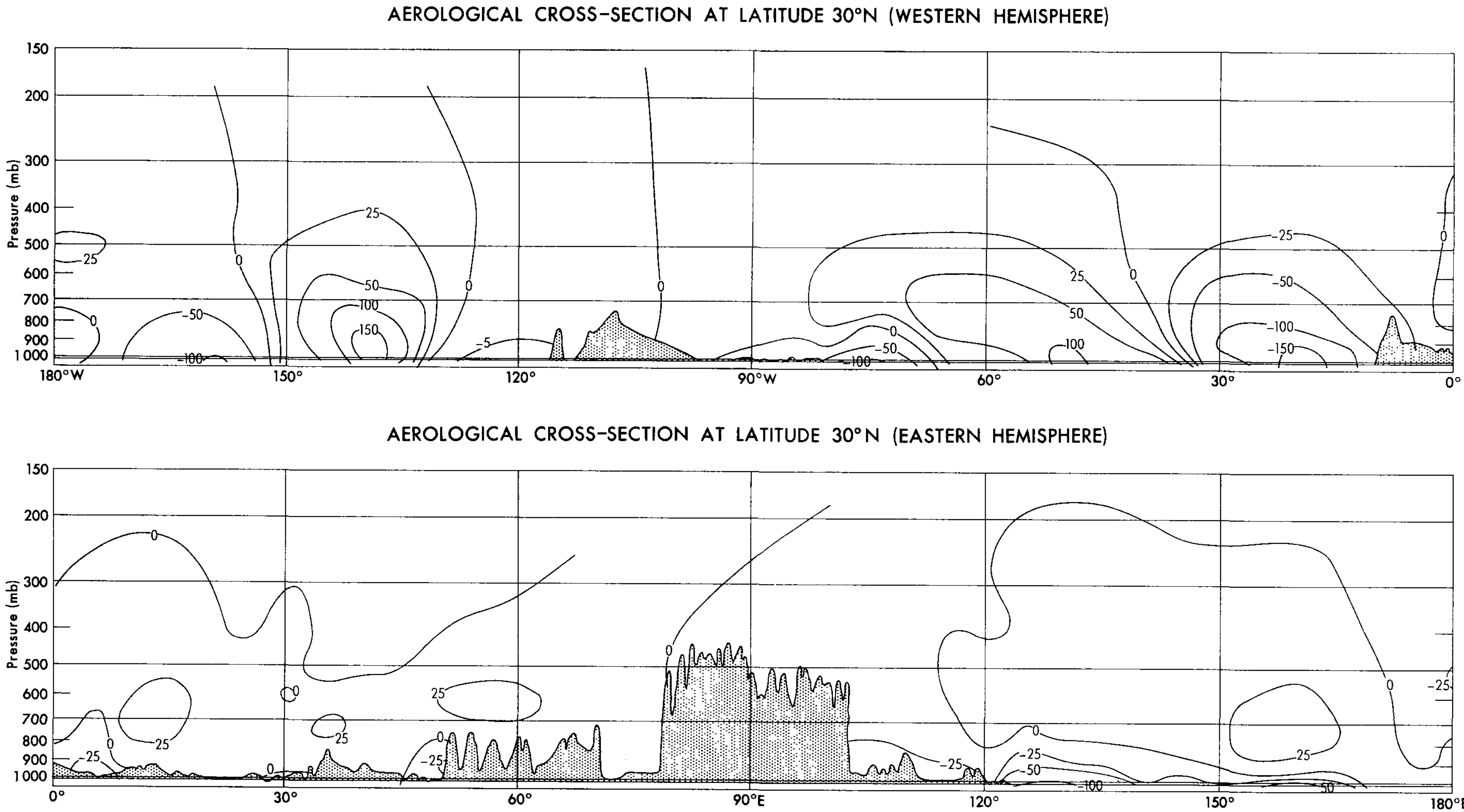


FIGURE 50 (a) and (b). TOTAL FLUX OF LATENT HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^8 cal/s per mb per degree longitude

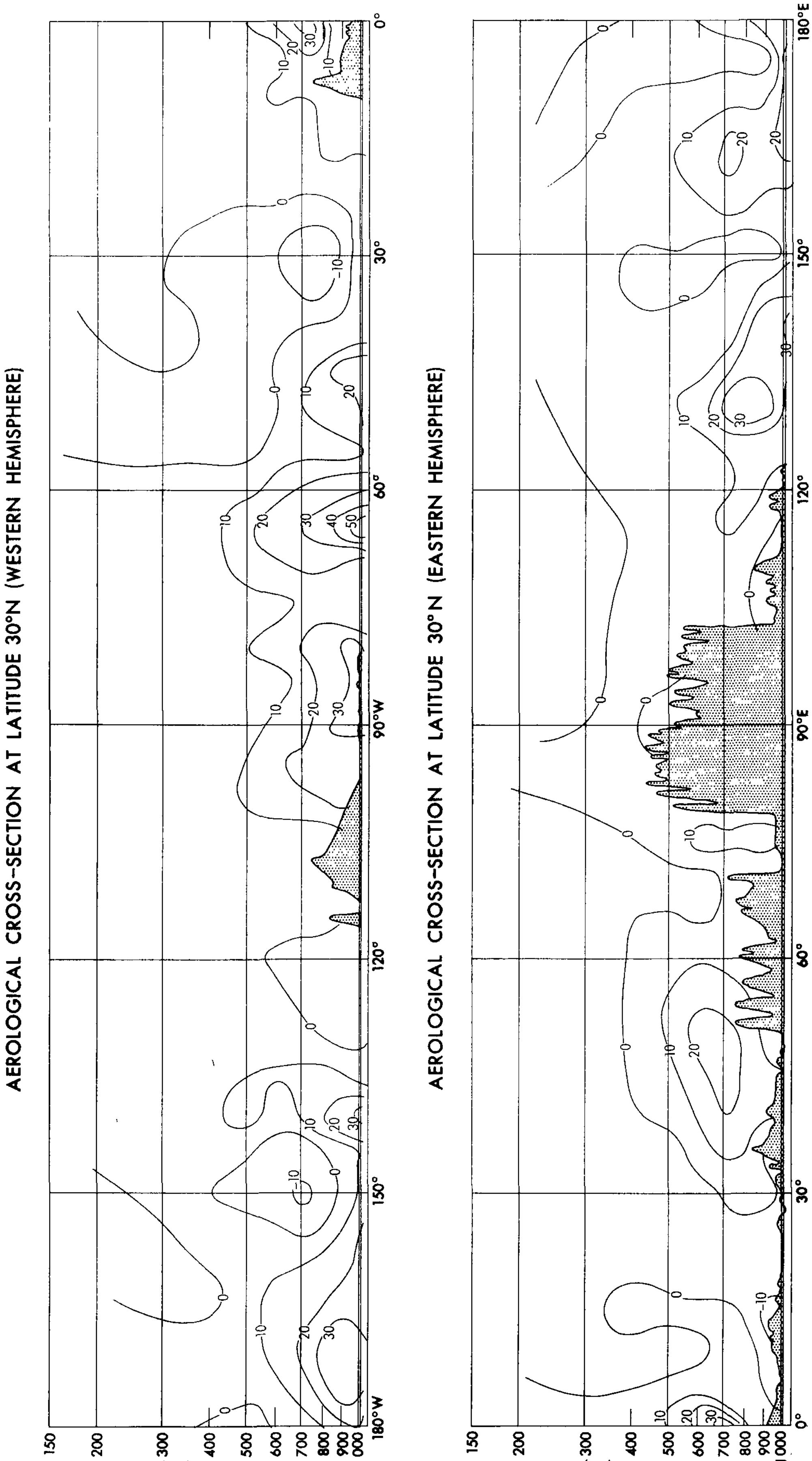


FIGURE 51 (a) and (b). LOCAL EDDY FLUX OF LATENT HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^8 cal/s per mb per degree longitude

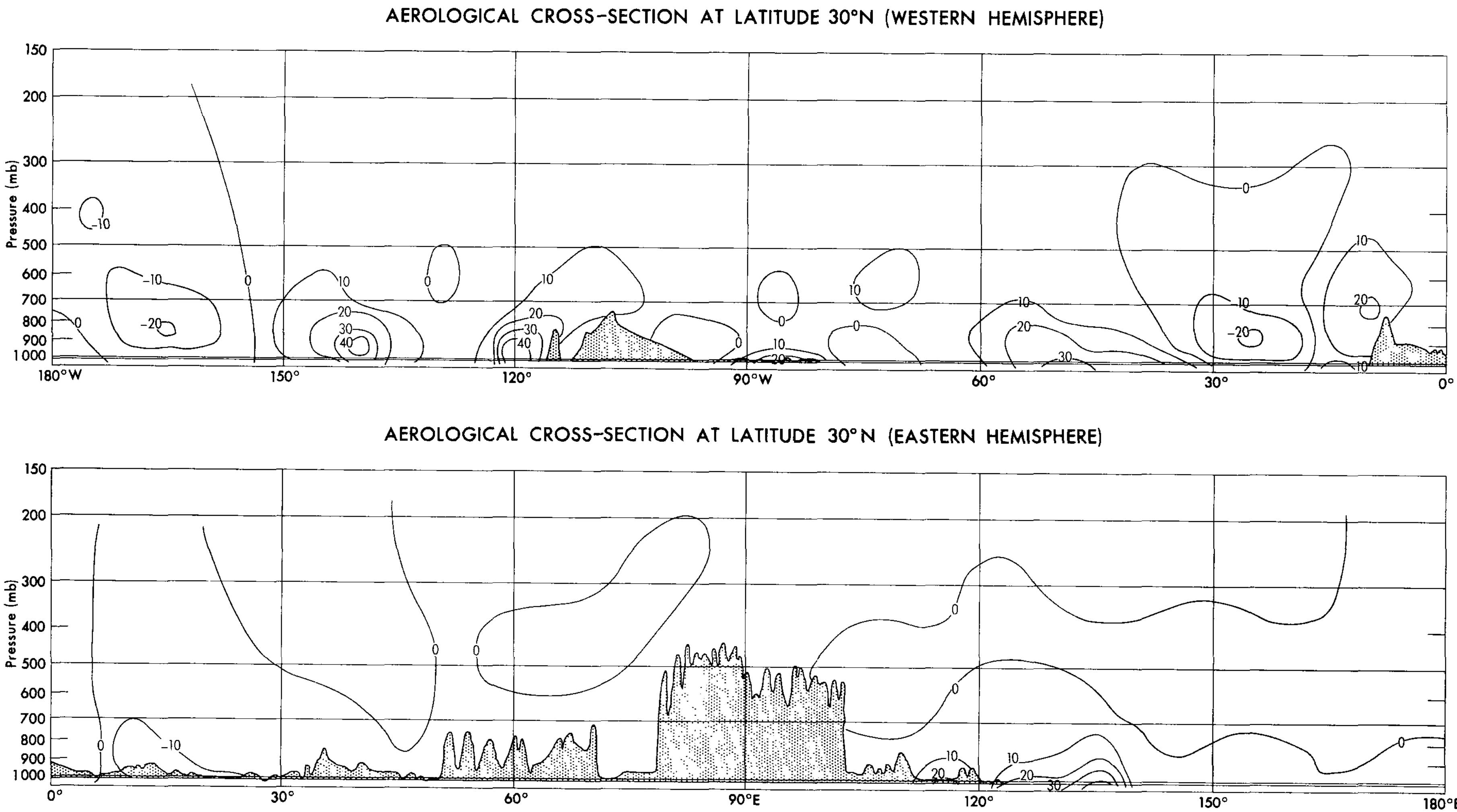


FIGURE 52 (a) and (b). STANDING EDDY FLUX OF LATENT HEAT ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^8 cal/s per mb per degree longitude

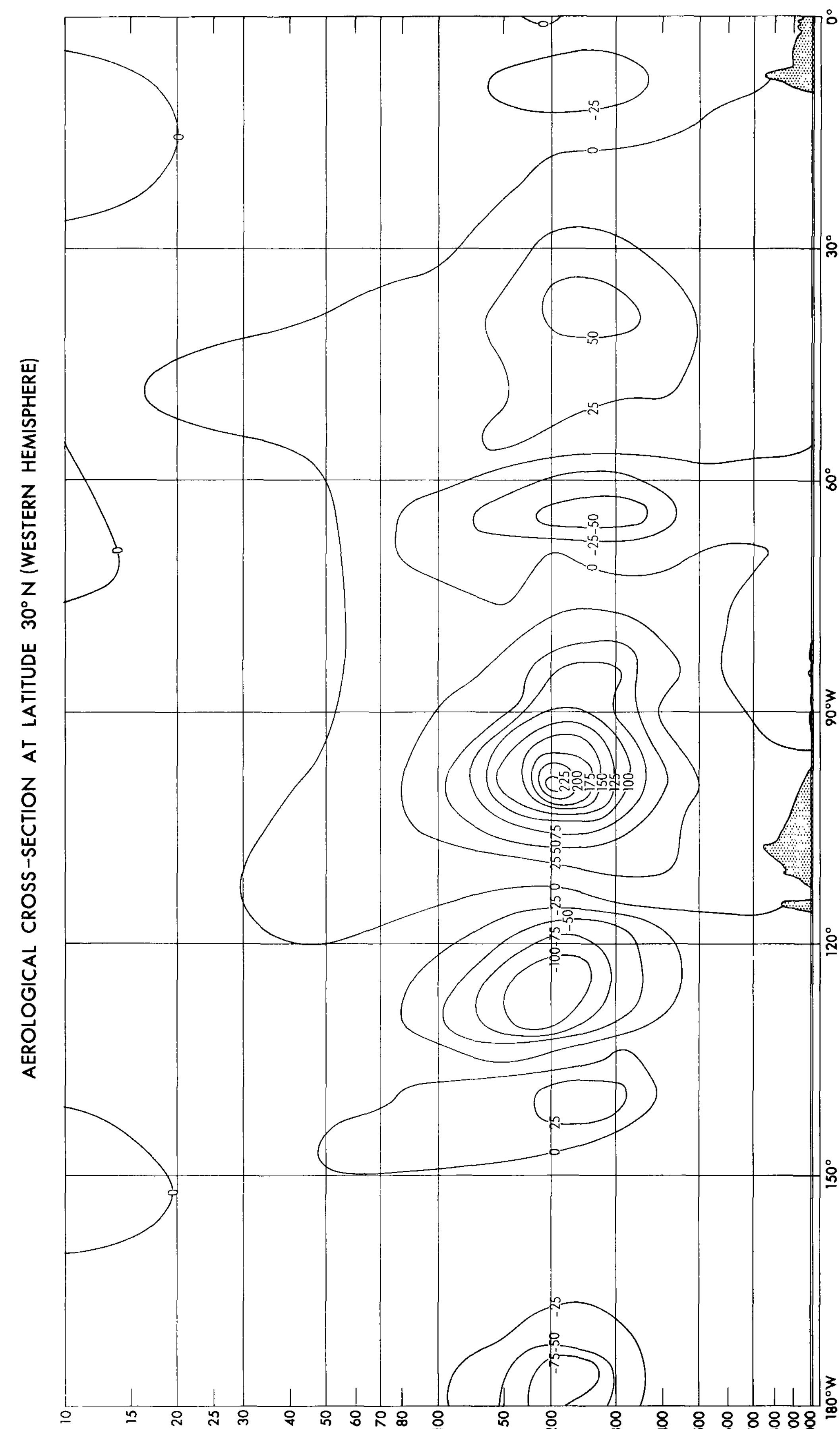


FIGURE 53 (a). TOTAL FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N FOR MARCH 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

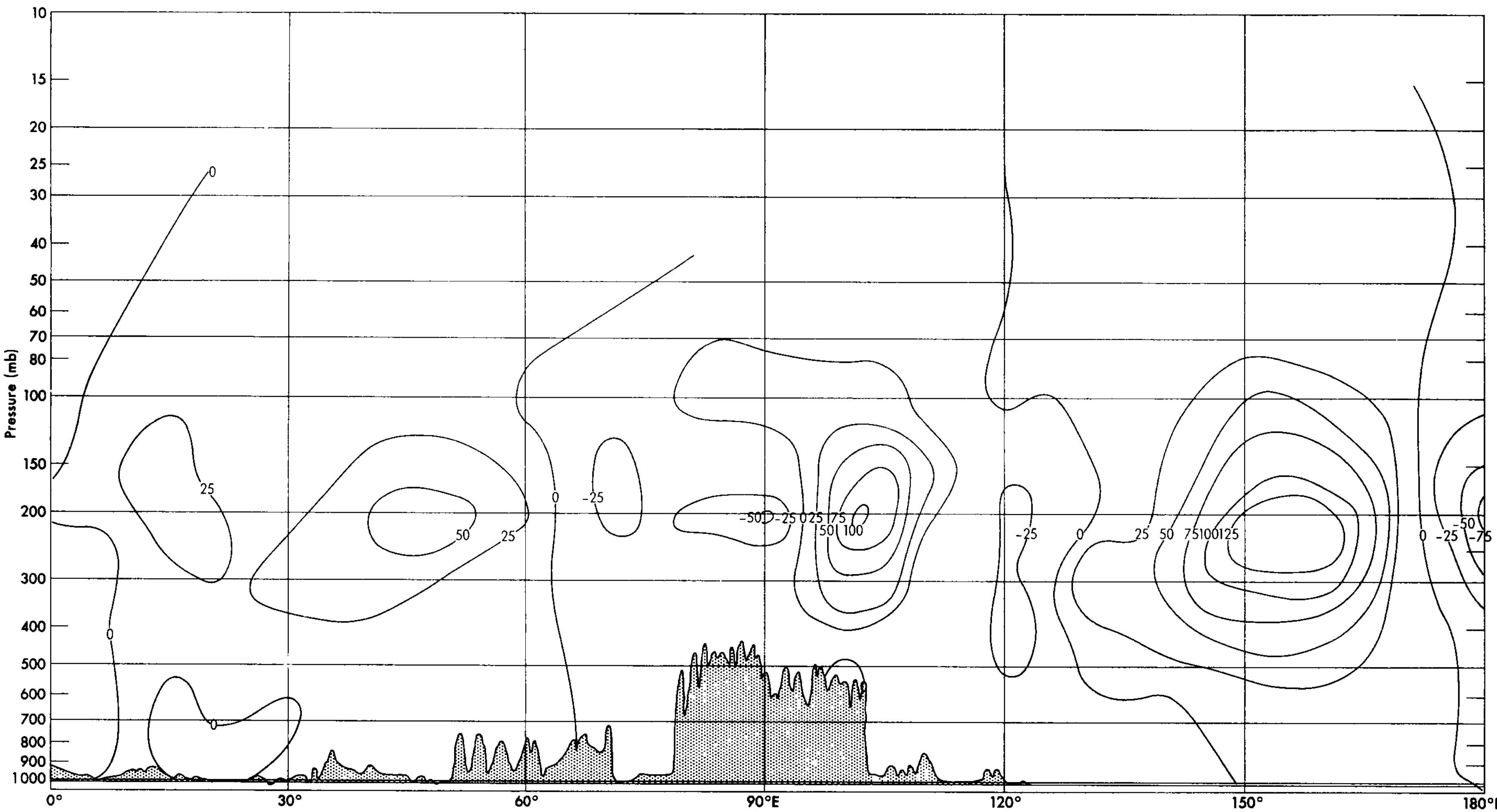


FIGURE 53 (b). TOTAL FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N FOR MARCH 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

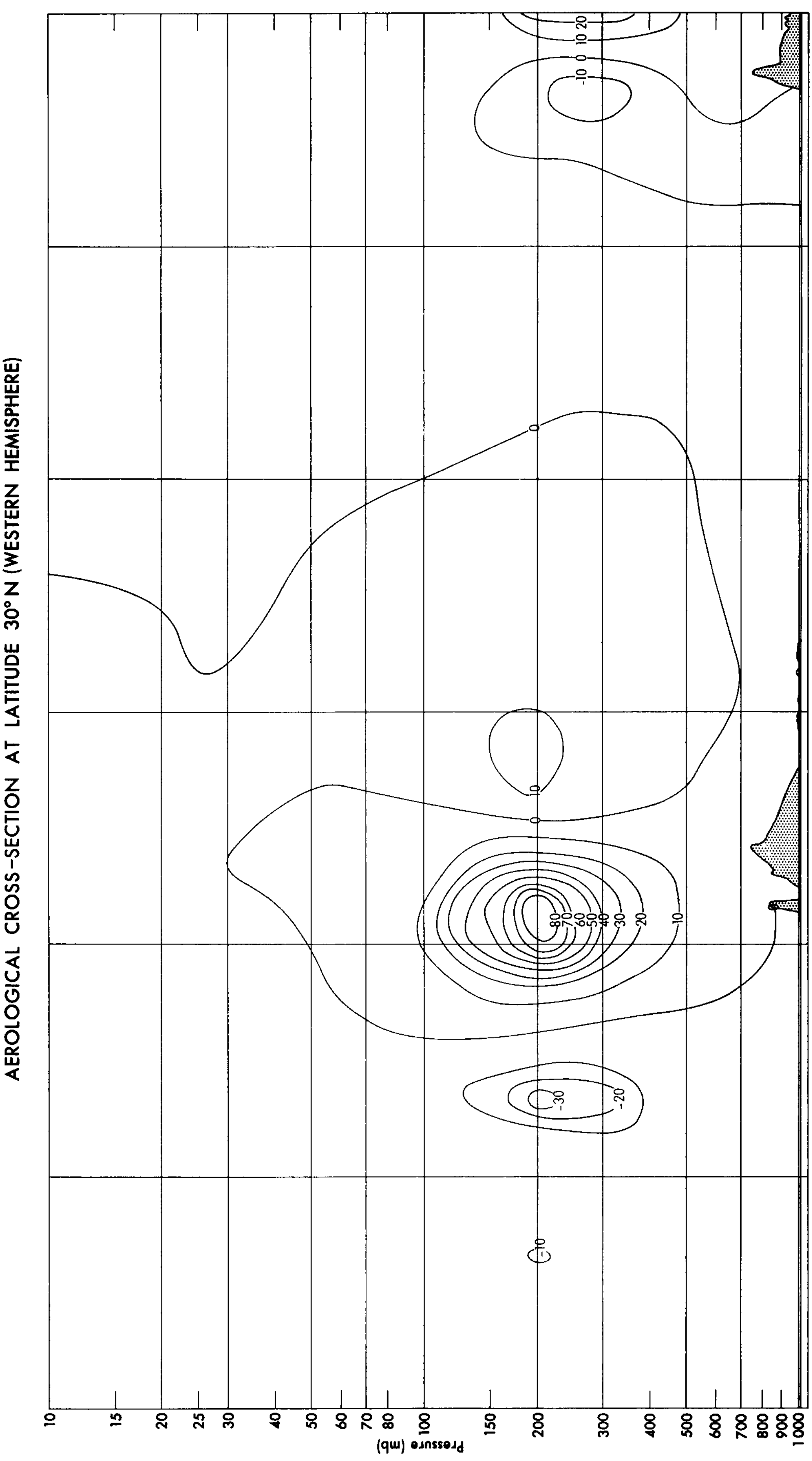


FIGURE 54 (a). TOTAL FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

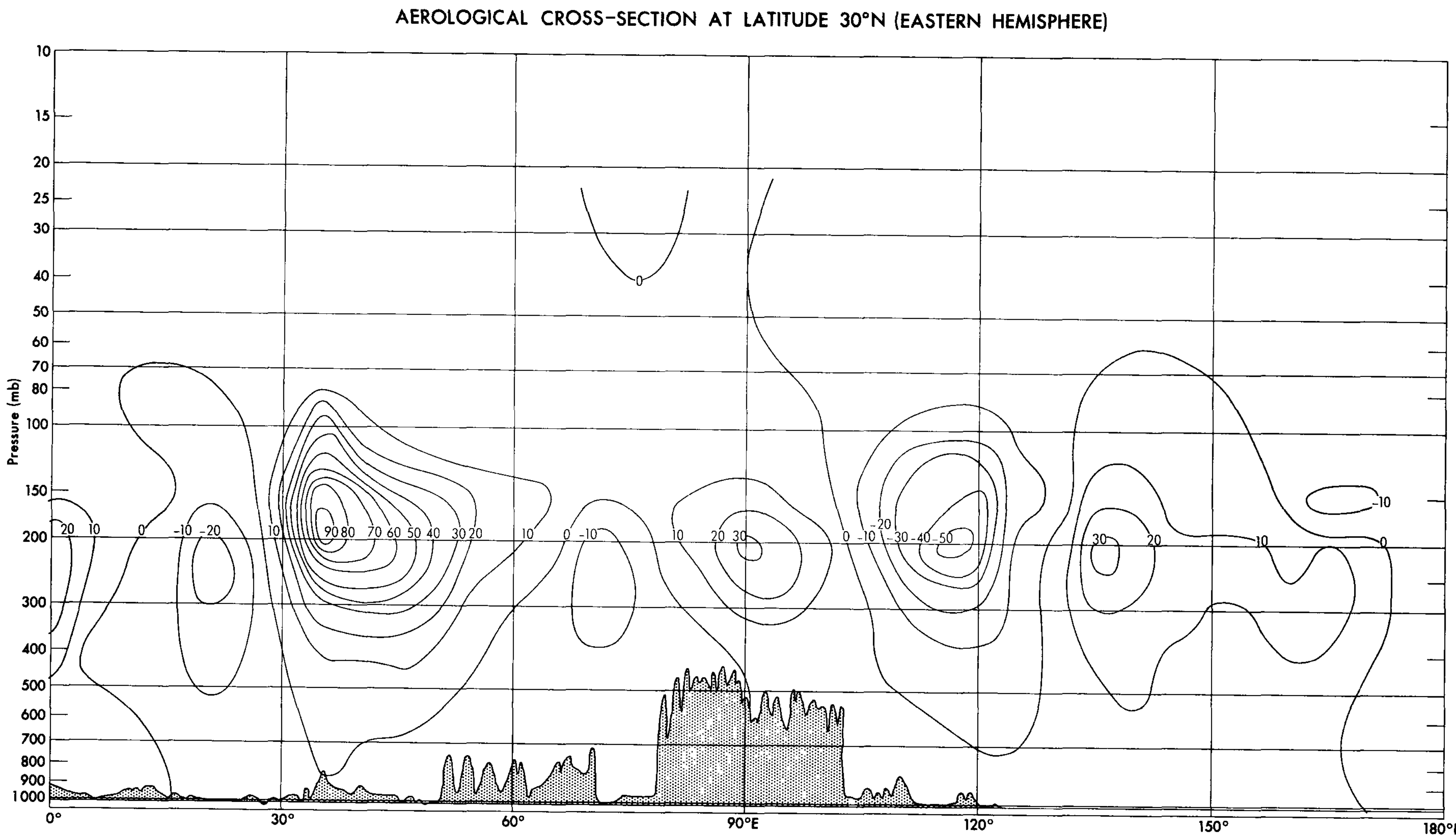


FIGURE 54 (b). TOTAL FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

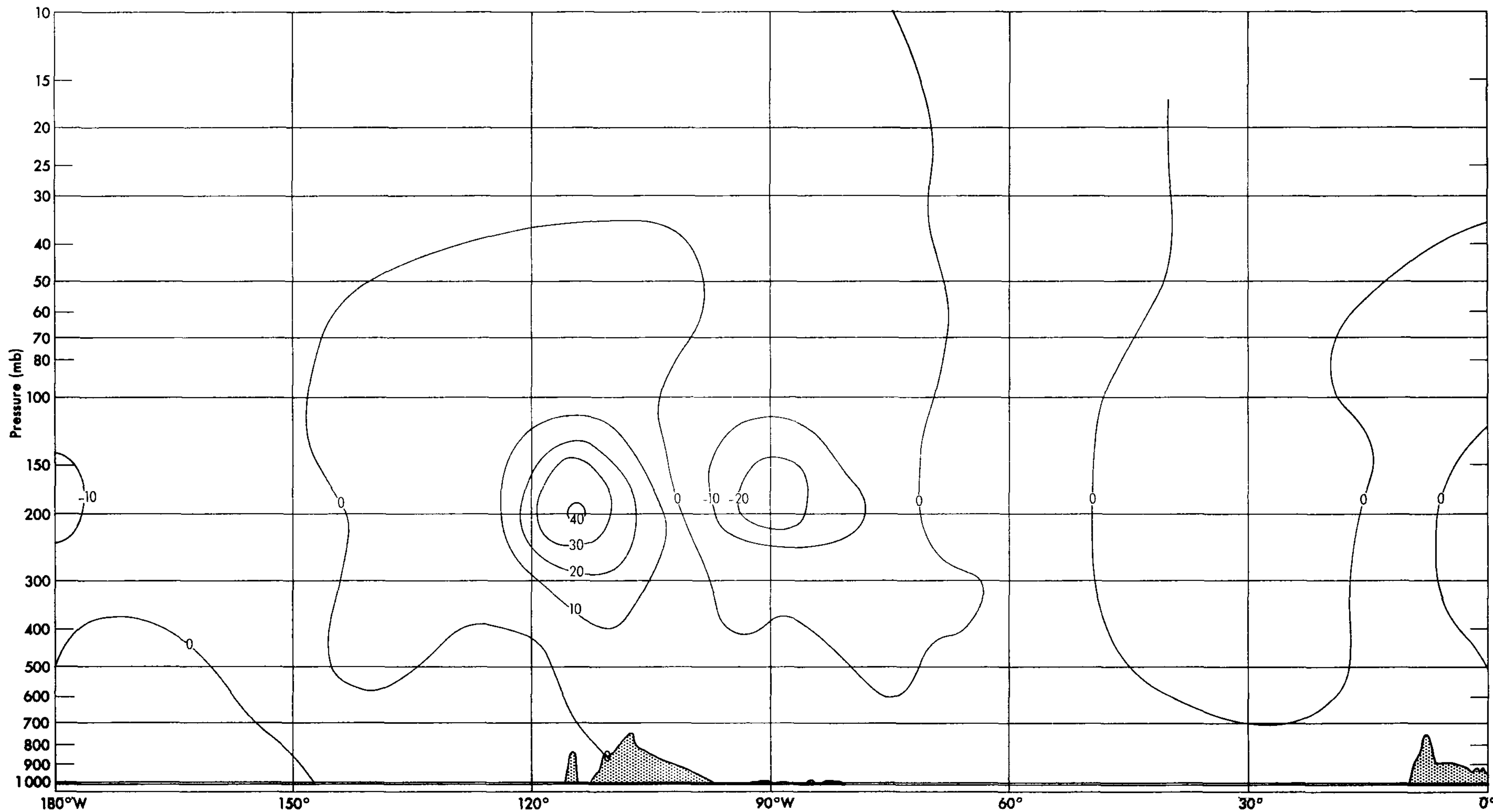


FIGURE 55 (a). TOTAL FLUX OF KINETIC ENERGY ACR CSS LATITUDE 30°N FOR SEPTEMBER 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

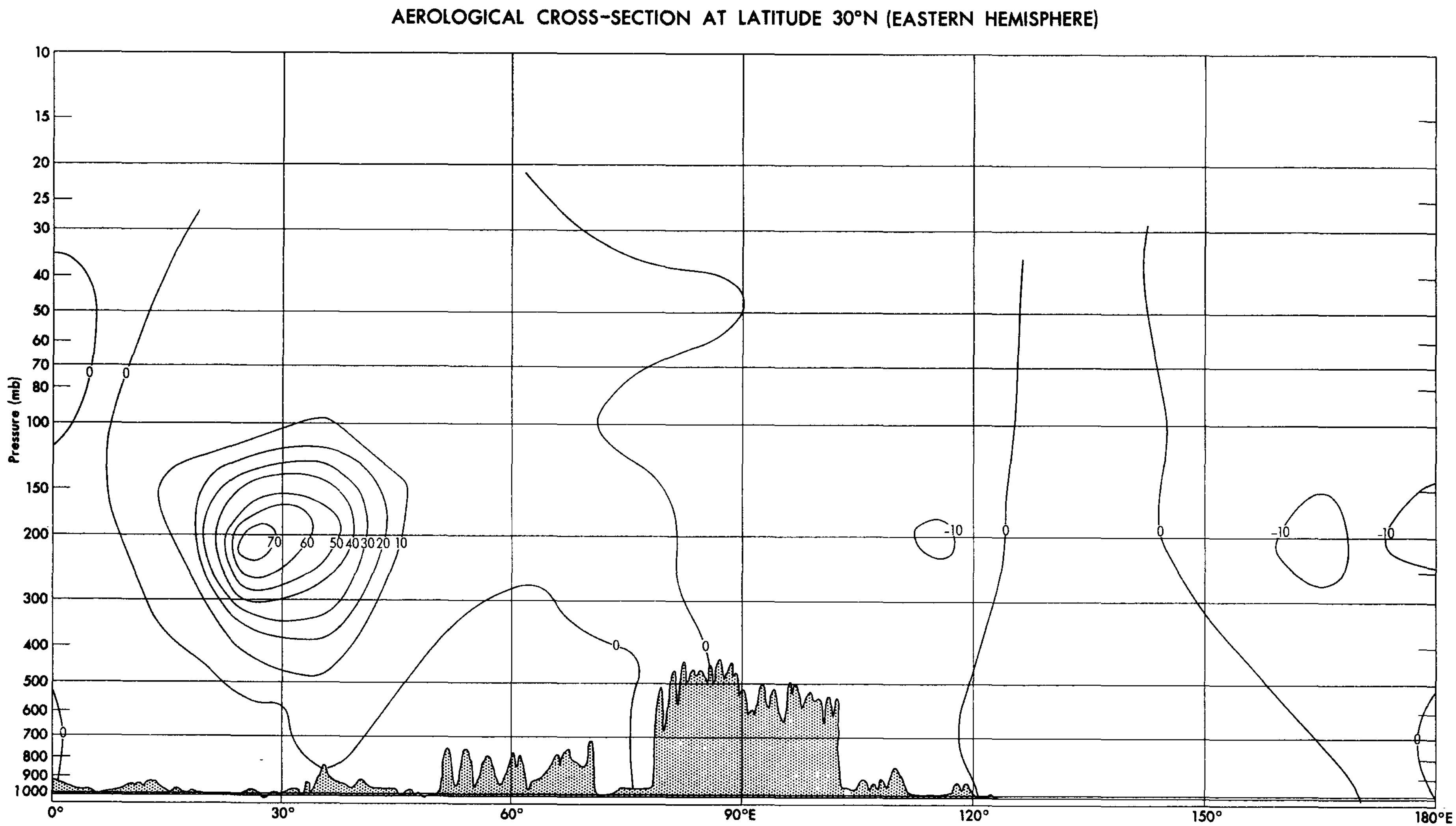


FIGURE 55 (b). TOTAL FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N FOR SEPTEMBER 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

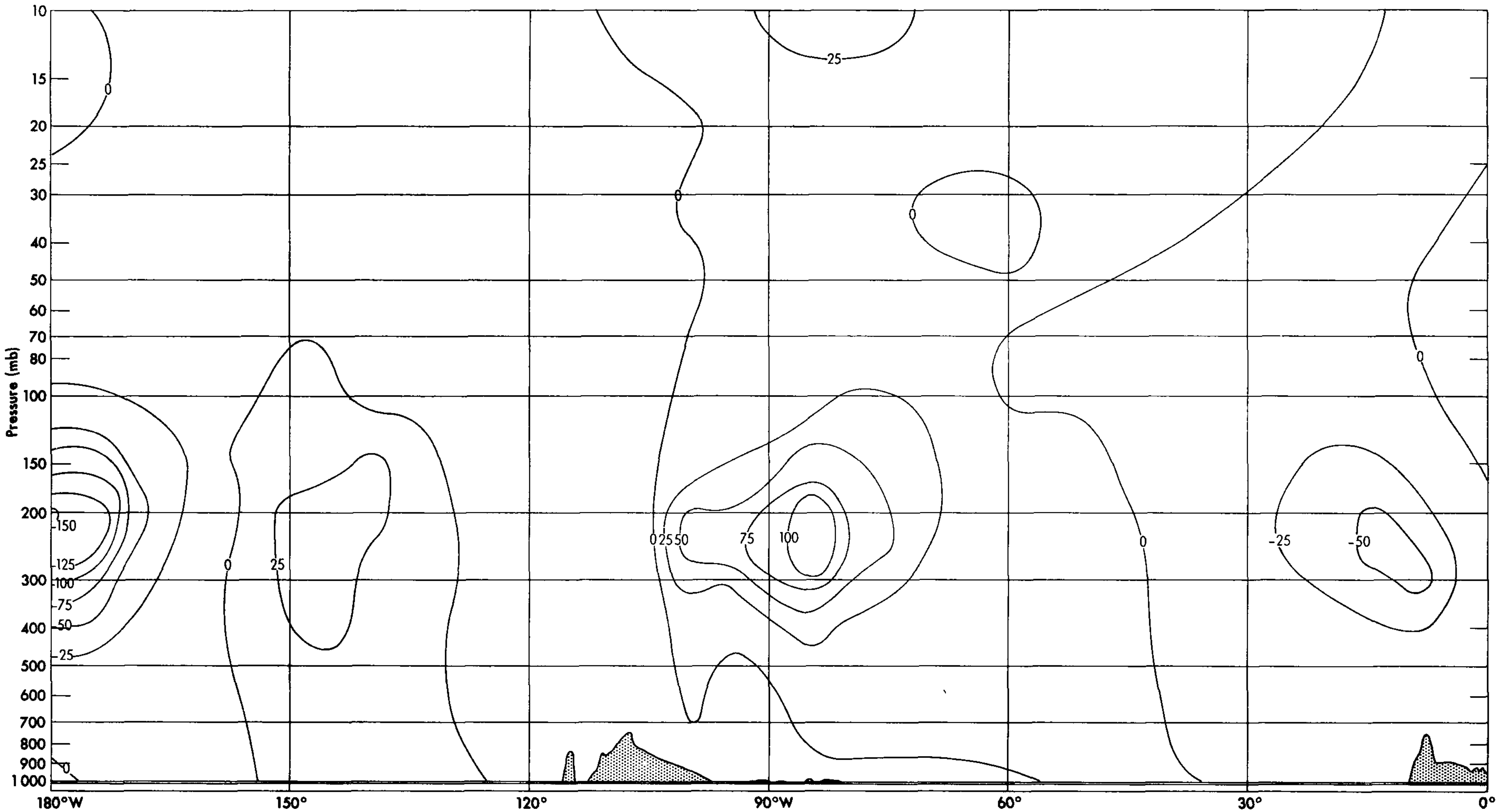


FIGURE 56 (a). TOTAL FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

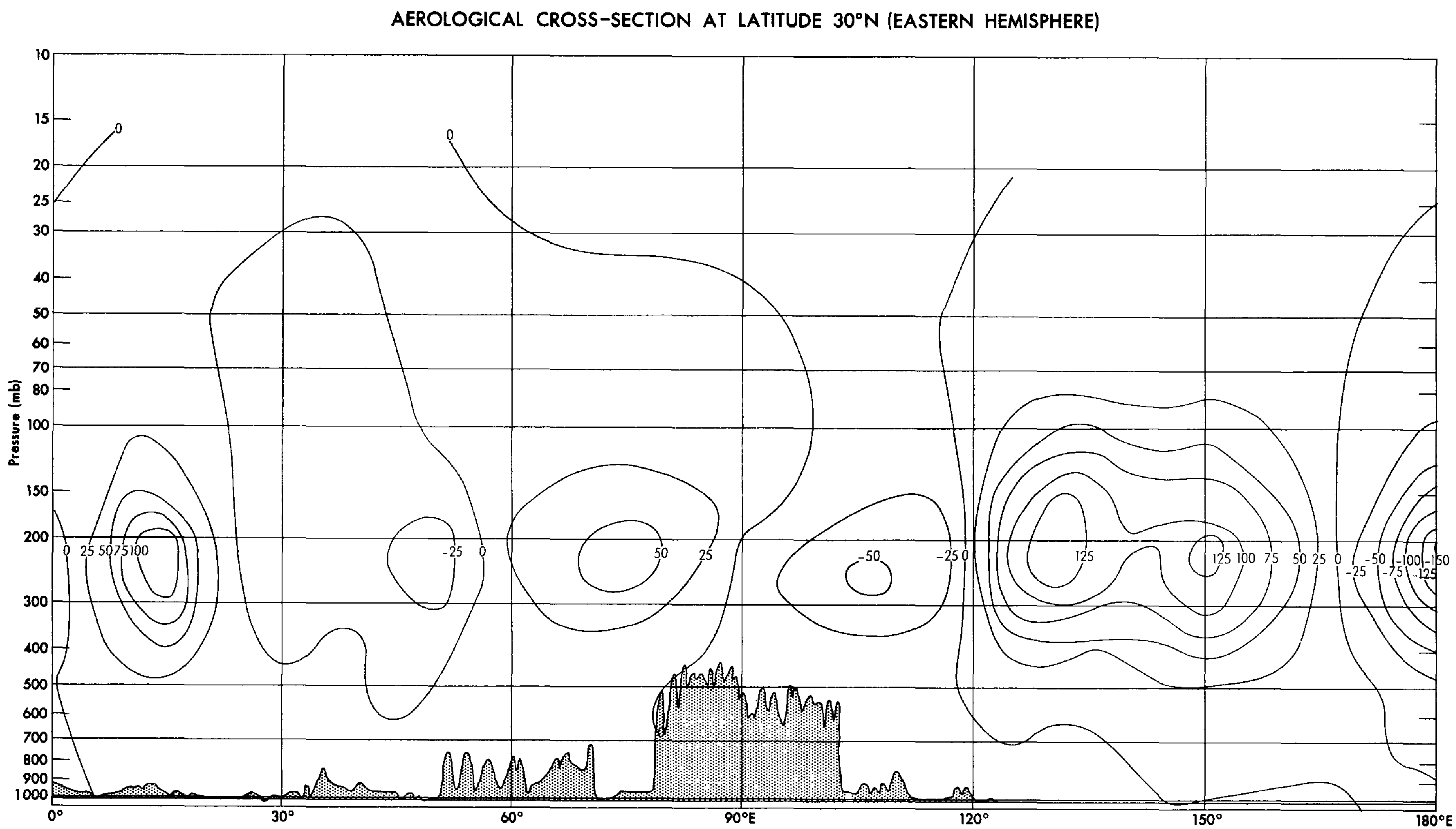


FIGURE 56 (b). TOTAL FLUX OF KINETIC ENERGY ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^6 cal/s per mb per degree longitude

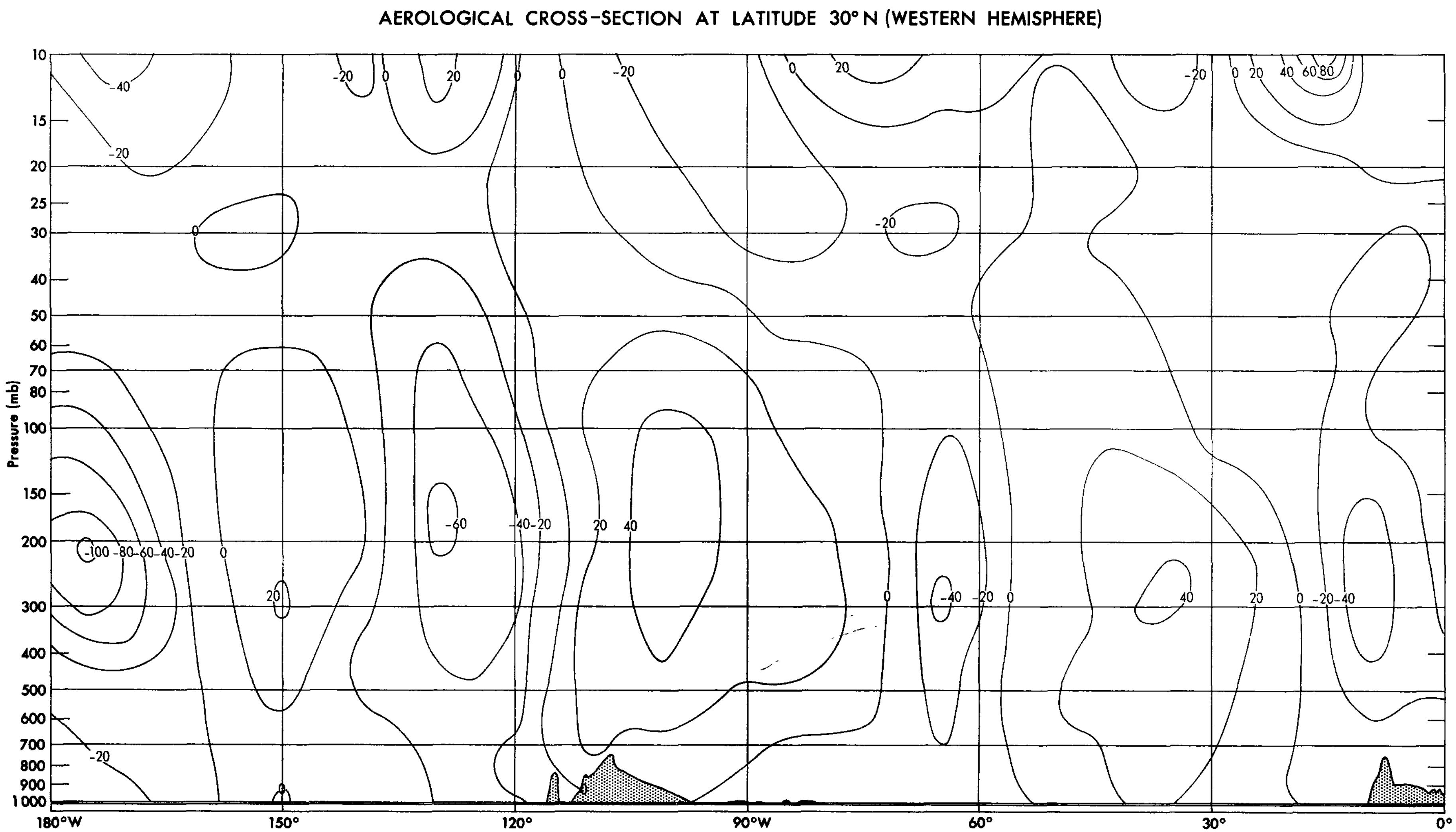


FIGURE 57 (a). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°N FOR MARCH 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

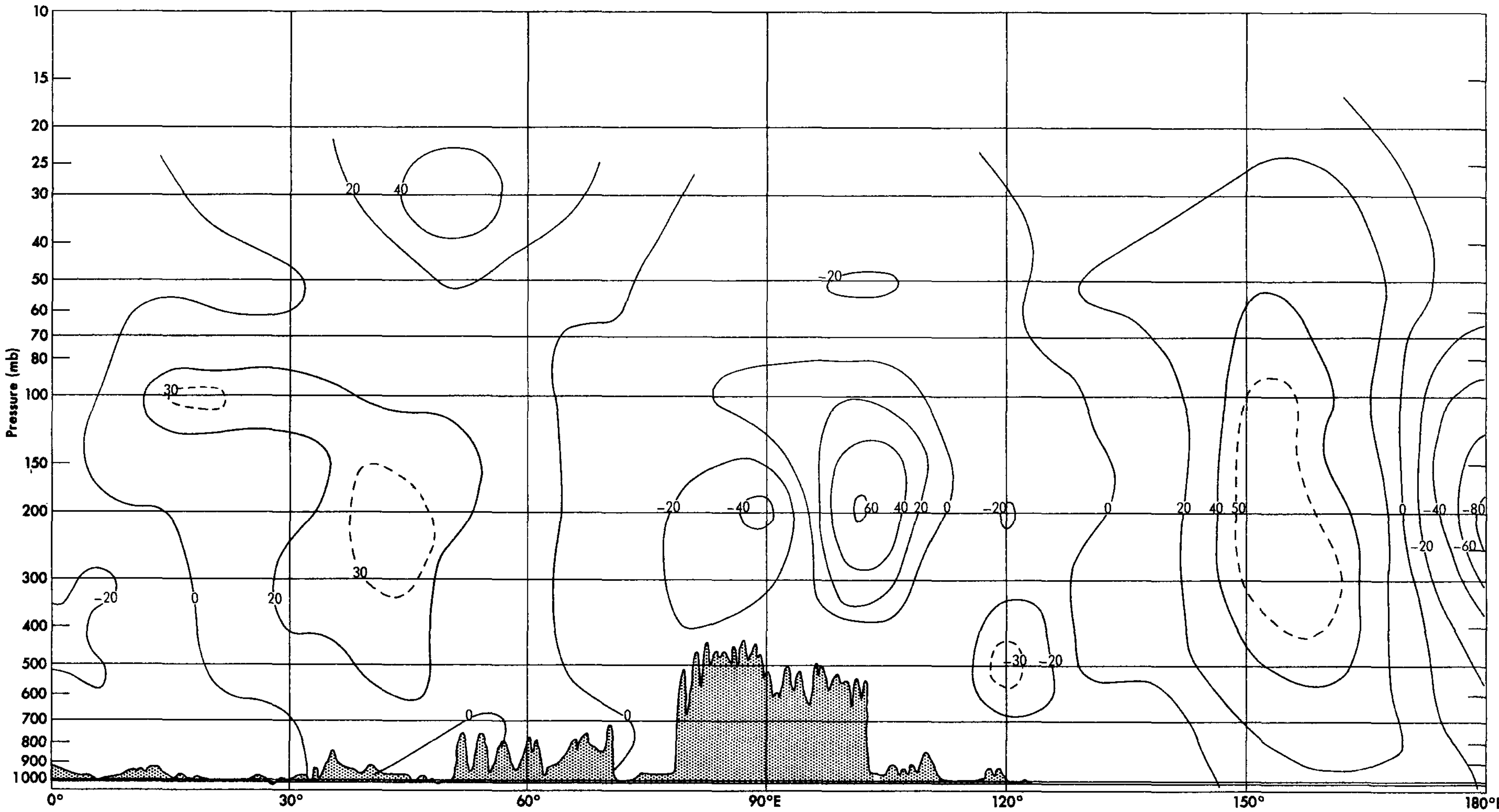


FIGURE 57 (b). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°N FOR MARCH 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

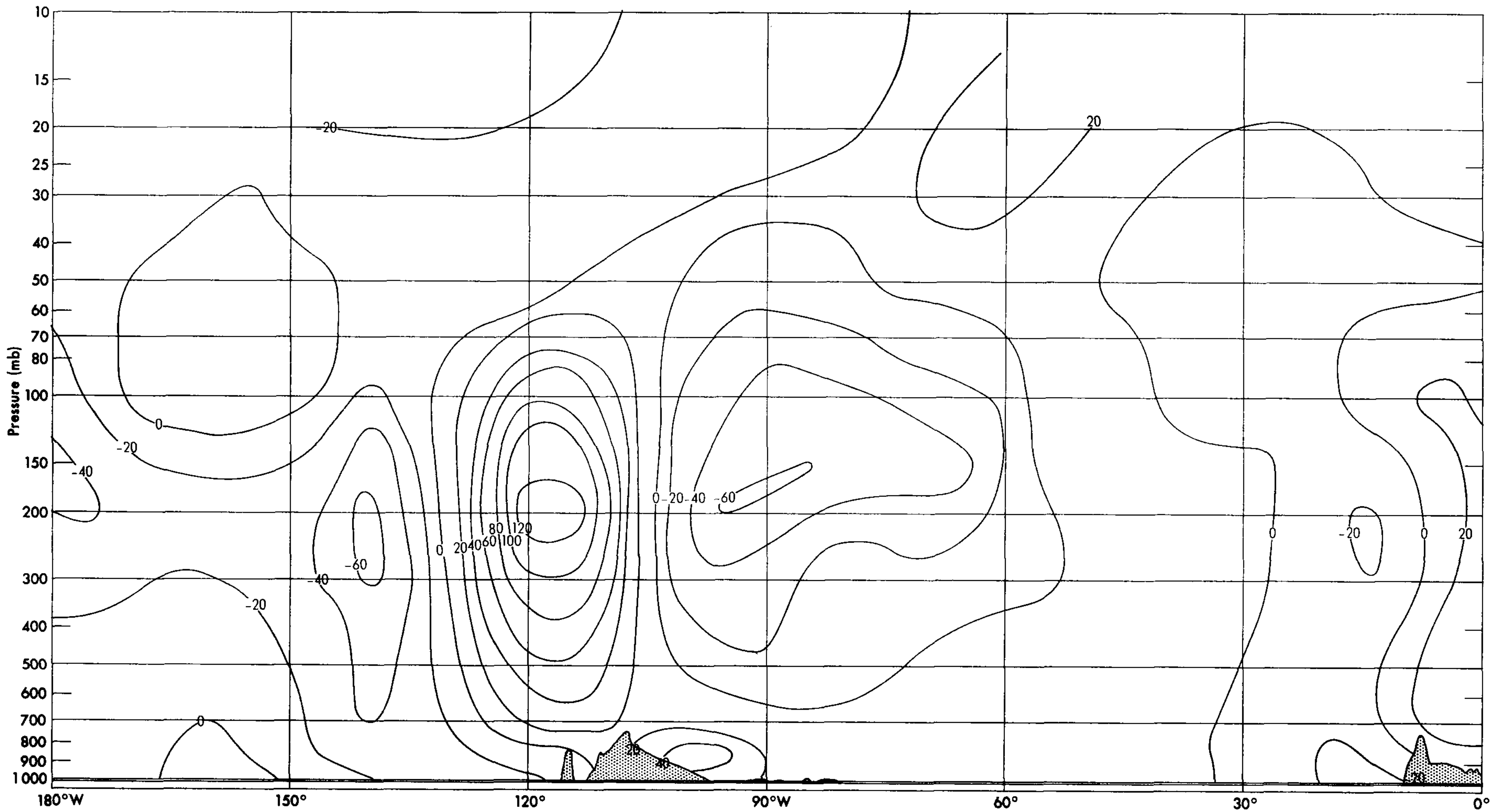


FIGURE 58 (a). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

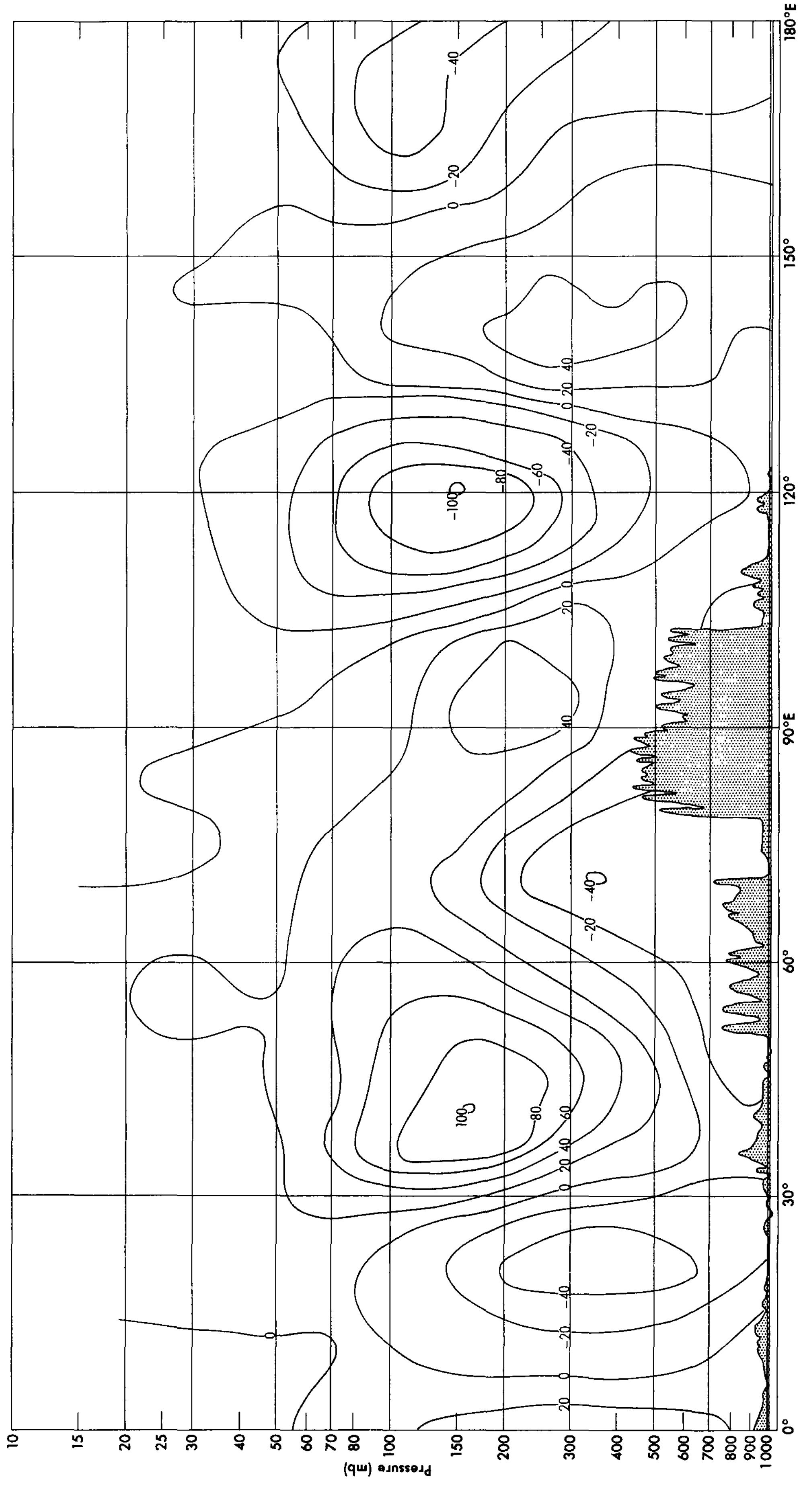


FIGURE 58 (b). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°N FOR JUNE 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

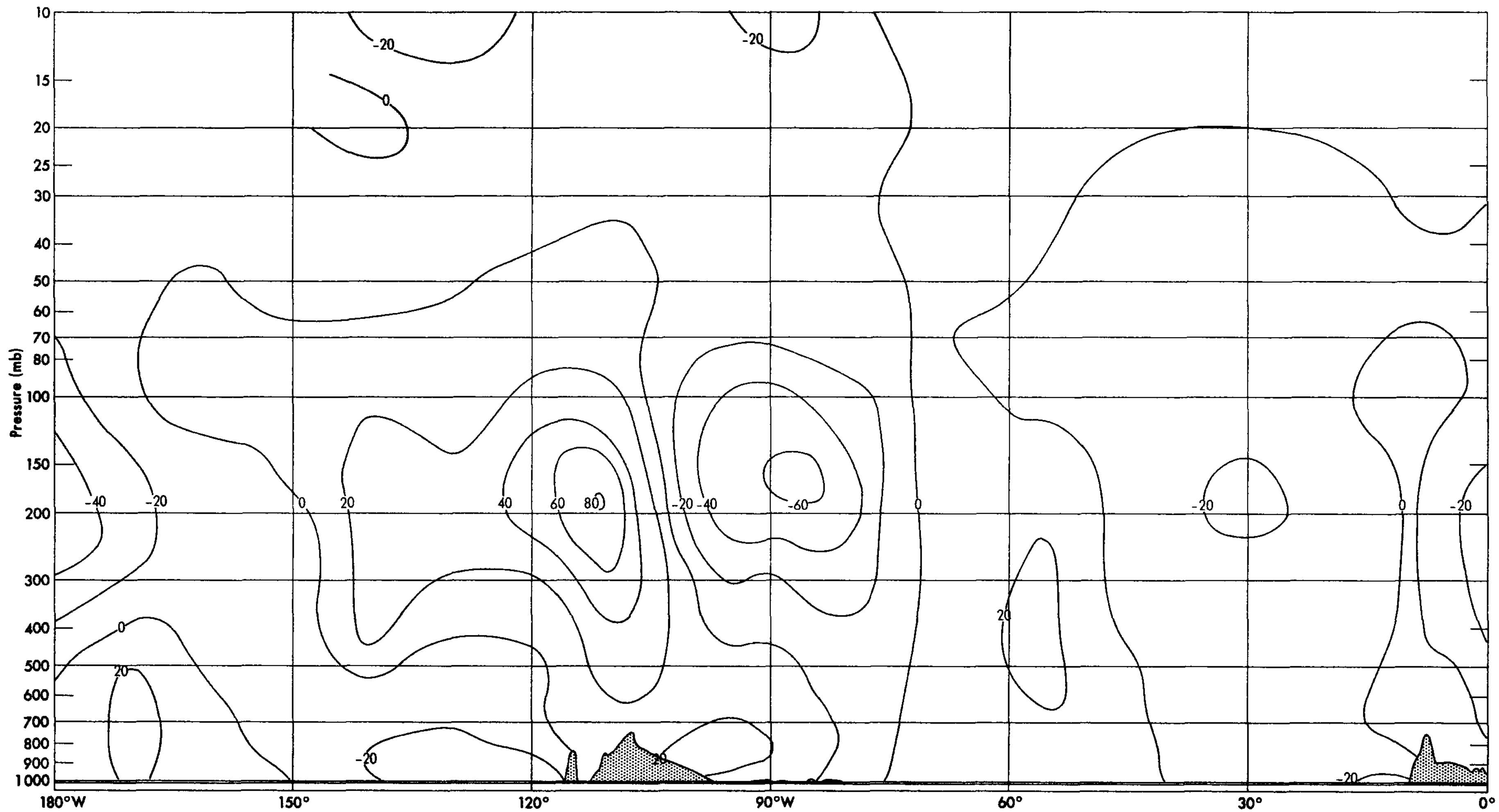


FIGURE 59 (a). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°FOR SEPTEMBER 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

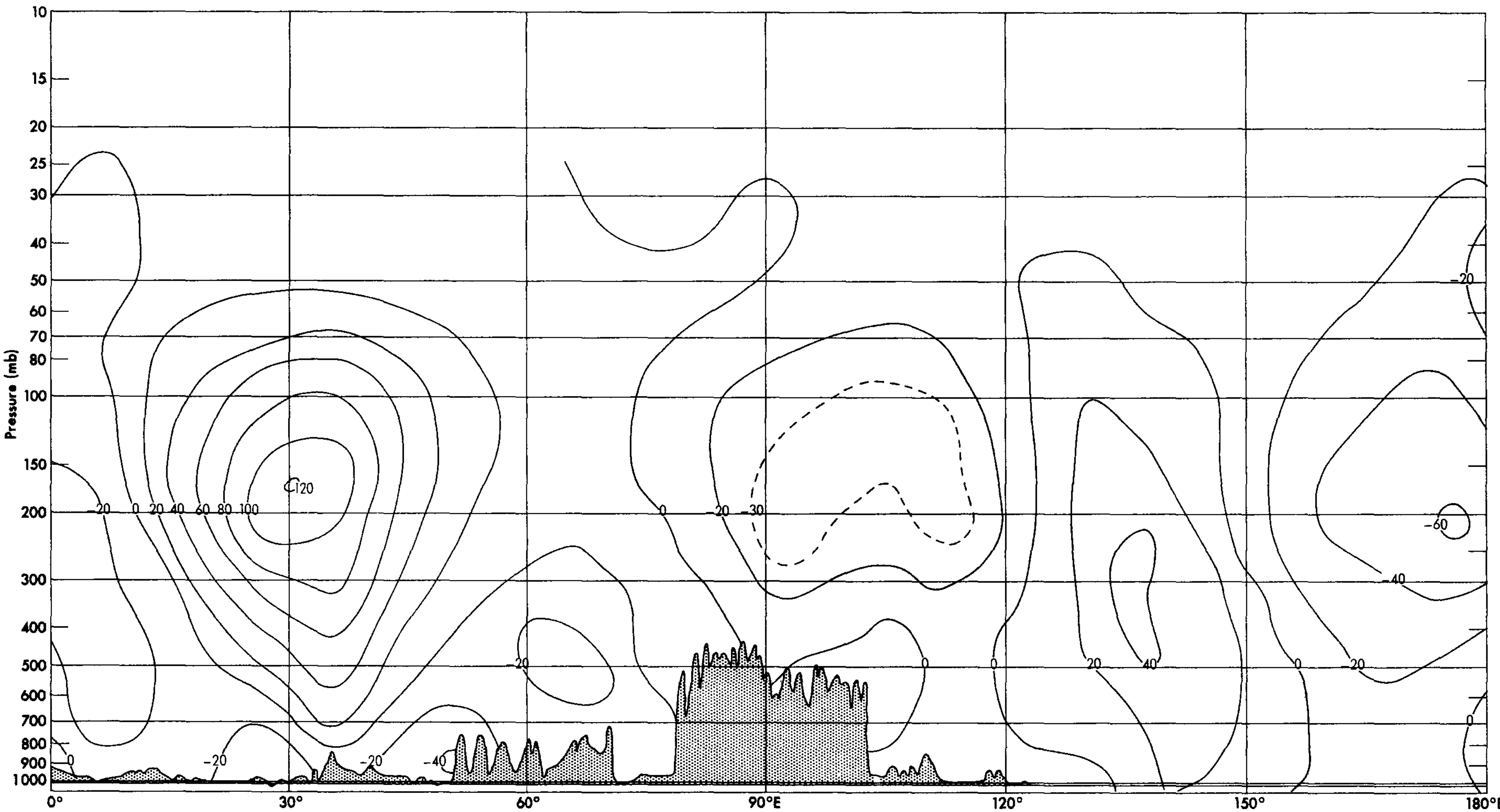


FIGURE 59 (b). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°N FOR SEPTEMBER 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30° N (WESTERN HEMISPHERE)

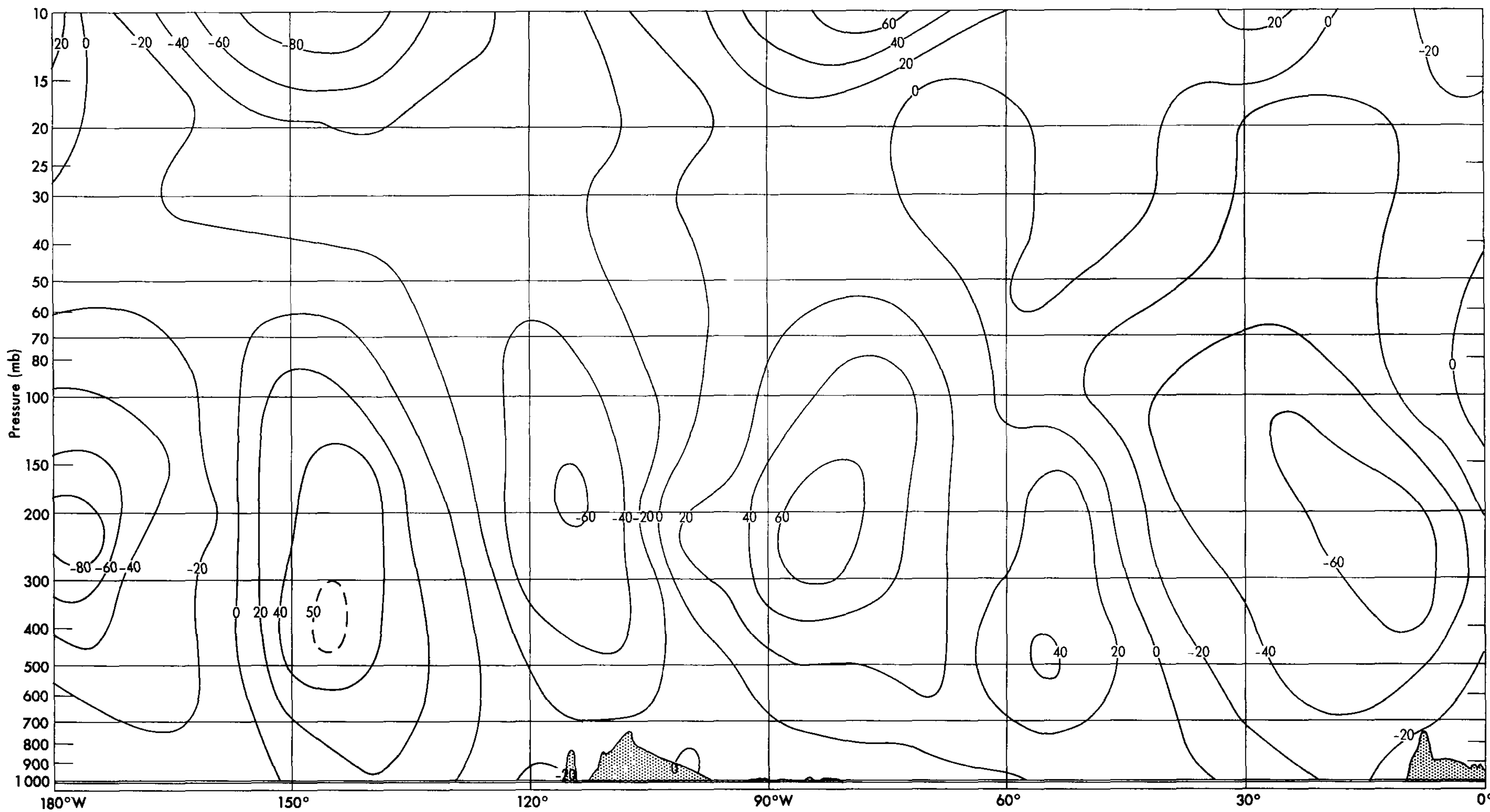


FIGURE 60 (a). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

AEROLOGICAL CROSS-SECTION AT LATITUDE 30°N (EASTERN HEMISPHERE)

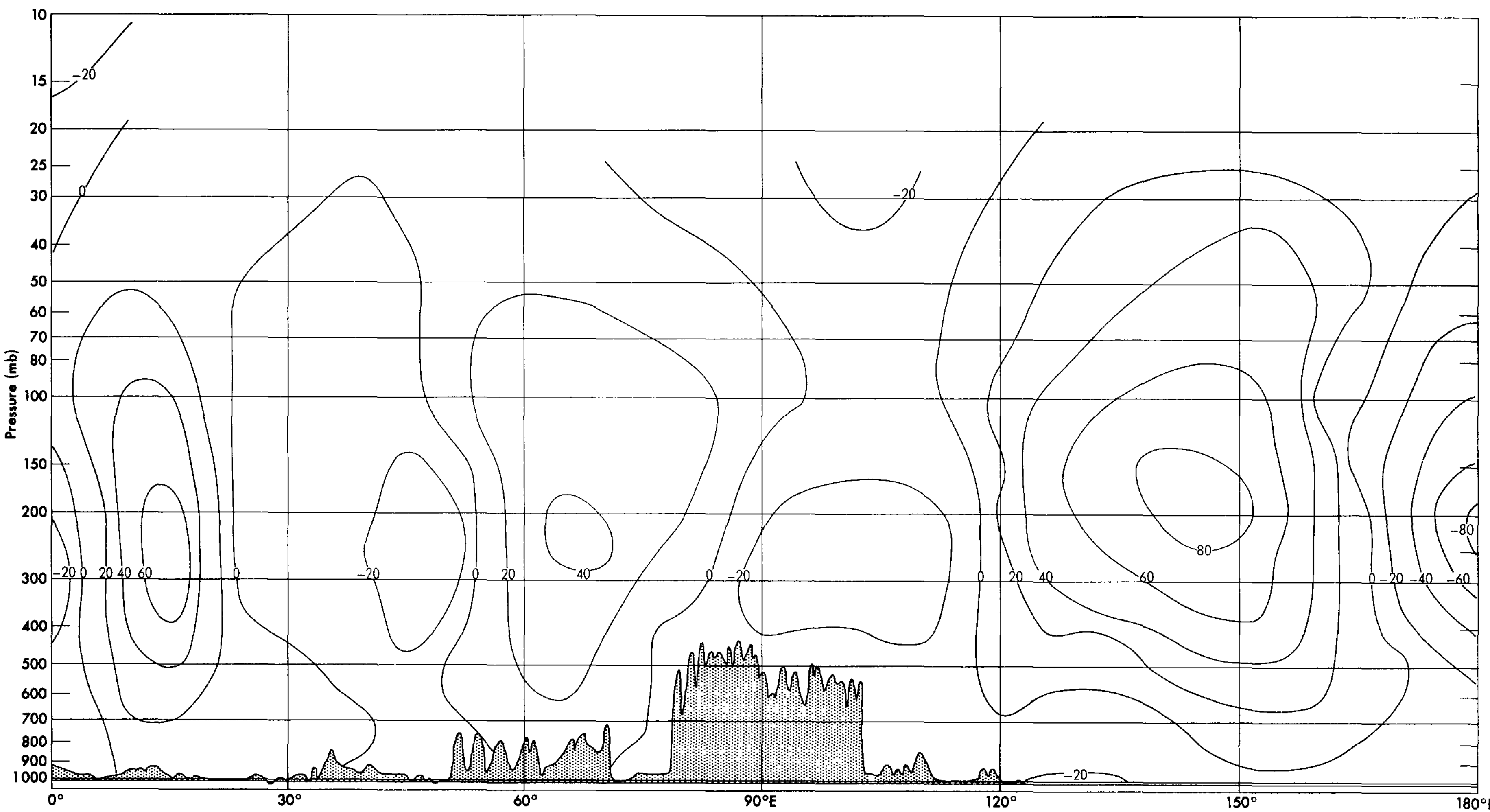


FIGURE 60 (b). TOTAL FLUX OF SENSIBLE HEAT PLUS POTENTIAL ENERGY ACROSS LATITUDE 30°N FOR DECEMBER 1958 IN UNITS OF 10^9 cal/s per mb per degree longitude

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