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ON THE ANNUAL VARIATION OF THE MONTHLY MEAN MERIDIONAL CIRCULATION

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ABSTRACT

Data for a 5-yr period from a dense network of upper air stations have been used to determine the annual cycle in the mean meridional circulation north of 15° S. Only during the transition months April, May and October, November is there some degree of symmetry with respect to the Equator. During the other months of the year, the Hadley cell of the winter hemisphere with a maximum strength of about 23×10^{13} gm sec^{-1} appears always to dominate the circulation. The Hadley cell of the summer hemisphere practically disappears, except possibly near the surface. Maximum meridional velocities connected with the winter Hadley cell are about 2.5 m sec^{-1} near 1000 mb and over 3 m sec^{-1} near 200 mb. Mean vertical velocities attain values of about 5 and 8 mm sec^{-1} in the downward and upward branches of the winter Hadley cells. A rather weak Ferrel circulation (about 4×10^{13} gm sec^{-1}) and a very weak polar circulation (about 1×10^{13} gm sec^{-1}) are computed in middle and high latitudes throughout the year.

With the aid of several diagrams giving the variability of the south-north wind components both in time and space, it is shown that the tropical circulation as presented almost certainly gives a representative picture of the true situation. Much more uncertainty is involved in the circulation at middle and high latitudes.

The transport of angular momentum, potential energy, and sensible and latent heat connected with the calculated mean meridional circulations are presented for January and July. The transports agree quite well with those computed in earlier investigations.

CONTENTS

1. INTRODUCTION

During the more than two centuries since Hadley (1735) published his famous paper on the cause of the trade winds, the character of the mean meridional circulation of the atmosphere has been a topic of great interest and lively debate. Only during the past two decades have aerological data become available in quantities sufficient to settle, qualitatively at least, a number of questions concerning the structure and strength of the tropical Hadley cells and their relative importance in the maintenance of the momentum and energy balances of the atmosphere. However, more detailed information and additional studies are still badly needed to adequately describe many aspects of the meridional flow. These include 1) a more detailed description of the seasonal variations in the mean meridional circulation, 2) a description of the time variability and longitudinal asymmetries of the meridional flow, 3) a detailed description of the mean meridional flow in the deep Tropics, and 4) an accurate evaluation of the weaker portions of the mean meridional flow at middle and high latitudes.

It may, in the long run, prove necessary to resort to indirect computation of certain aspects of the mean meridional flow. For example, in the stratosphere the accuracy and reporting frequency of the radiosonde reports are such that mean meridional velocities computed indirectly from the momentum or heat balance equation probably are better than the directly computed velocities. Such indirect computations have been made for all or part of the Northern Hemisphere by Mintz and Lang (1955), Kuo (1956), Holopainen (1965), Lorenz (1967), and

Vernekar (1967); for the Southern Hemisphere by Gilman (1965); and for the Northern Hemisphere stratosphere by Dickinson (1962), Teweles (1963), and most recently by Vincent (1968). It would, however, be desirable to compute the mean meridional flow directly from wind observations wherever possible, thus avoiding the assumptions involved in an indirect computation. One of the assumptions generally is that one can neglect the effects of vertical eddies and of friction. Thus, it is of interest to note that the indirectly calculated meridional velocities appreciably underestimate the directly "observed" velocities in the lower and upper branch of the Hadley circulation.

The authors have recently completed analyses of the statistics of a large number of general circulation parameters. These statistics derive from several years of data taken at aerological stations over the Northern Hemisphere and Southern Hemisphere Tropics. Included are computations of the mean meridional flow on a mean monthly basis for the atmosphere north of 15° S. The results of these computations together with some statistics on the temporal and spatial variability of the meridional flow are described in this paper.

For extensive tables of the basic mean monthly general circulation statistics, part of which have been used in the present study, the reader is referred to Oort and Rasmusson (1969).

2. PREVIOUS OBSERVATIONAL STUDIES

Numerous observational studies during the past two decades have included estimates of various details of the mean meridional flow. Some of these have been derived from "direct measurement" and others by indirect means. In this nonexhaustive review of the literature, we shall emphasize some of the more important findings of investigators who also attempted to evaluate the mean meridional flow directly from wind observations.

In an early study of the surface wind field over the oceans, Riehl and Yeh (1950) clearly showed the existence of a marked asymmetry of the mean meridional flow about the Equator during the winter-summer season. The surface mean meridional flow of the winter Hadley cell was relatively strong and extended across the Equator into the summer hemisphere. The summer Hadley cell appeared to be a much weaker circulation.

Information on the character of the mean meridional circulation above the earth's surface began to accumulate in the early 1950's, but upper air observations were barely adequate to allow a few tentative conclusions. Starr and White (1954), after an analysis of data from the year 1950, warned that their computed mean meridional wind component could not be taken at face value in view of possible serious bias in their data. They did, however, reach the important conclusion that the mean meridional components are generally quite small, and they interpreted the data to show that any mean meridional component which did exist probably possessed an order of magnitude of less than 1 m sec^{-1}. Aside from the important exception of the wintertime tropical Hadley cell, their conclusion appears to be valid.

Palmén (1957), using 1952 data up to 14,000 ft from a chain of stations centered at 13° N., deduced what appears to be a fairly good estimate of the mass flux by the winter Northern Hemisphere Hadley cell. He found the low-level southward flow to be concentrated below 850 mb.

Palmén et al. (1958), using data from December 1955–February 1956, were able to construct a mean meridional profile at 15° N. that extended upward to 150 mb. The data showed a pronounced southward mass flow in the low levels, little or no meridional flow between 700 and 350 mb, and a concentration of the northward return flow in the upper troposphere. These data were also sufficient to provide a rough description of the longitudinal variation of the wintertime average meridional flow at 15° N. In the lower troposphere, the flow was directed equatorward at nearly all longitudes. In the upper troposphere, the data showed a three-wave structure superimposed on the northward mean meridional flow.

Tucker (1957) extended the work of Riehl and Yeh (1950) by evaluating the surface mean meridional flow over the combined land and ocean areas of the Northern Hemisphere. The inclusion of land areas in the averaging reduced the magnitude of the mean meridional flow at high latitudes. Subsequently, Tucker (1959) investigated the meridional flow over the sector 160° W.–0°–40° E. However, it was difficult to estimate how much the averages for this sector differed from those for the entire latitude circle.

Palmén and Vuorela (1963) and Vuorela and Tuominen (1964) attempted a determination of the mean meridional wind components over the Northern Hemisphere for the 3-mo winter and summer seasons, respectively. Their primary data source was the collection of *Upper Wind Statistic Charts of the Northern Hemisphere* by Crutcher (1959). These charts provided better upper air statistics than had previously been available but were deficient in that they contained no data below the 850-mb level and were based on only a small amount of data south of 15° N. To compensate for this deficiency, the authors used Tucker's (1957) values of surface wind and "characteristic vertical wind profiles" from the surface to 850 mb. A somewhat crude interpolation technique was used to obtain values between the Equator and 10° N. Their results will be compared with those obtained from our data in a later section of this paper.

Defant and Van de Boogaard (1963) analyzed the wind data available for 1 day during the IGY and found surprisingly good agreement with Palmén and Vuorela's results for the winter season. In an earlier study of IGY data, one of the present authors (Oort 1964) computed the mean meridional velocities at 100, 50, and 30 mb.

Obasi (1963) has attempted a direct computation of the mean meridional circulation of the Southern Hemisphere using data taken during 1958. The Southern Hemisphere aerological network at that time was comparable to that which existed over the Northern Hemisphere in 1950, and his results must be viewed in this light.

Early studies of the mean meridional flow across the Equator were made by Rao (1964) and Tucker (1965), but the most comprehensive investigation to date of the circulation of the deep Tropics is that of Kidson et al. (1969). These analyses confirm the dominance of the winter hemisphere Hadley cell and the existence of large mass transfers across the Equator during the summer-winter seasons. The computed mass transfer by the winter Hadley cells was in reasonably good agreement with that computed by Palmén and Vuorela (1963) and Vuorela and Tuominen (1964).

Our results for the Tropics were obtained using mainly the same data sources as those used by Kidson et al. (1969). However, we have attempted to extend their results through a more detailed description of the character and month-to-month variations of the mean meridional circulation.

3. ANNUAL CYCLE OF THE MEAN MERIDIONAL CIRCULATION

Our principal results concerning the seasonal changes in the mean meridional circulation will be presented in this section. The data sources and the method of objective analysis used will be discussed in detail in the appendix. Let us mention here only that the main data set consisted of reports from nearly 600 "good" upper air stations rather well distributed over most of the Northern Hemisphere and over the Southern Hemisphere Tropics down to about 15° S. From the available record of 5 yr (May 1958 through April 1963), 5-mo mean statistics were evaluated. Pictures will be presented for an average January, February, etc.

In the following discussion, we shall use the shorthand notation NH Hadley and SH Hadley for the Northern and Southern Hemisphere Hadley circulations, respectively.

For the mean meridional velocity, we shall frequently use the notation $[\bar{v}]$, where the brackets represent a zonal average and the bar a time average of v, the northward component of the wind.

MEAN STREAMLINES

Streamlines of the mean meridional circulation for each month of the year are given in figure 1. These streamlines were computed from the mean meridional velocities using the continuity equation. They indicate the total transport of mass in units of 10^{13} gm sec^{-1} below the level considered (counted positive if northward). The streamline interval was chosen so that the transport between consecutive streamlines equals 5×10^{13} gm sec^{-1}.

There was only one constraint imposed when computing the mean meridional velocities, that is, no net mass flow was allowed across latitude circles. In other words, the computed velocities were adjusted so that the vertically integrated mass flow was equal to zero. At latitudes south of 30° N., the corrections to $[\bar{v}]$ were very small, and the Hadley cells were thus not noticeably changed. In the next section, the imbalance will be further discussed. Aside from this correction, the flow was not restricted in any way. Mass can, for example, flow freely through the southern boundary.

The streamlines for the annual mean circulation are presented in figure 2. A comparison of figures 1 and 2 shows that the computed annual mean circulation does not give a representative picture of the meridional circulation during either the summer or the winter season.

The following features of the circulation at low latitudes are noteworthy:

a) The reversal of the direction of the circulation from summer to winter season, and the dominance of the Hadley cell of the winter hemisphere. From December to March, the circulation between roughly 10° S. and 30° N. is dominated by an intense NH Hadley cell. From June through September, the circulation between roughly 10° N. and about 35° S. (fig. 4) is determined by the SH Hadley cell, while the NH Hadley cell barely shows up. These findings are in good agreement with the results of Kidson et al. (1969).

b) Only during the transition months between the winter and summer regimes when the NH Hadley and SH Hadley cells are about equally well developed does there exist some degree of symmetry with respect to the Equator. The transition takes place in the rather short time interval of 2 mo (April–May and October–November). During the northern winter (December through March) and northern summer (June through September), the monthly averaged low-latitude circulation remains rather steady.

c) There appear to be certain differences between the NH Hadley and SH Hadley cells. During the northern winter, the low-level branch of the NH Hadley cell has an upward component over all but the extreme poleward portion of the cell. During the northern summer, the streamlines of the SH Hadley cell at low levels stay parallel to the earth's surface until they turn upward rather abruptly at the northern end of the cell. In this paper, a longitude section through the Hadley cells will be discussed, and more will be said about this feature.

d) The computed annual variation in the strength of the Hadley cells and in the latitude of their centers is tabulated in table 1 and is also shown in figure 3 (see dashed curve).

The NH Hadley cell attains a maximum strength of -23×10^{13} gm sec^{-1} during February and is then located at its southernmost latitude of about 2° N. It practically vanishes during the months of June through August (except near the surface, see fig. 4) and reappears in September at about 25° N.

The SH Hadley cell attains, on the other hand, its maximum strength of 24×10^{13} gm sec^{-1} during July–August at a latitude of about 6° S. One cannot obtain a

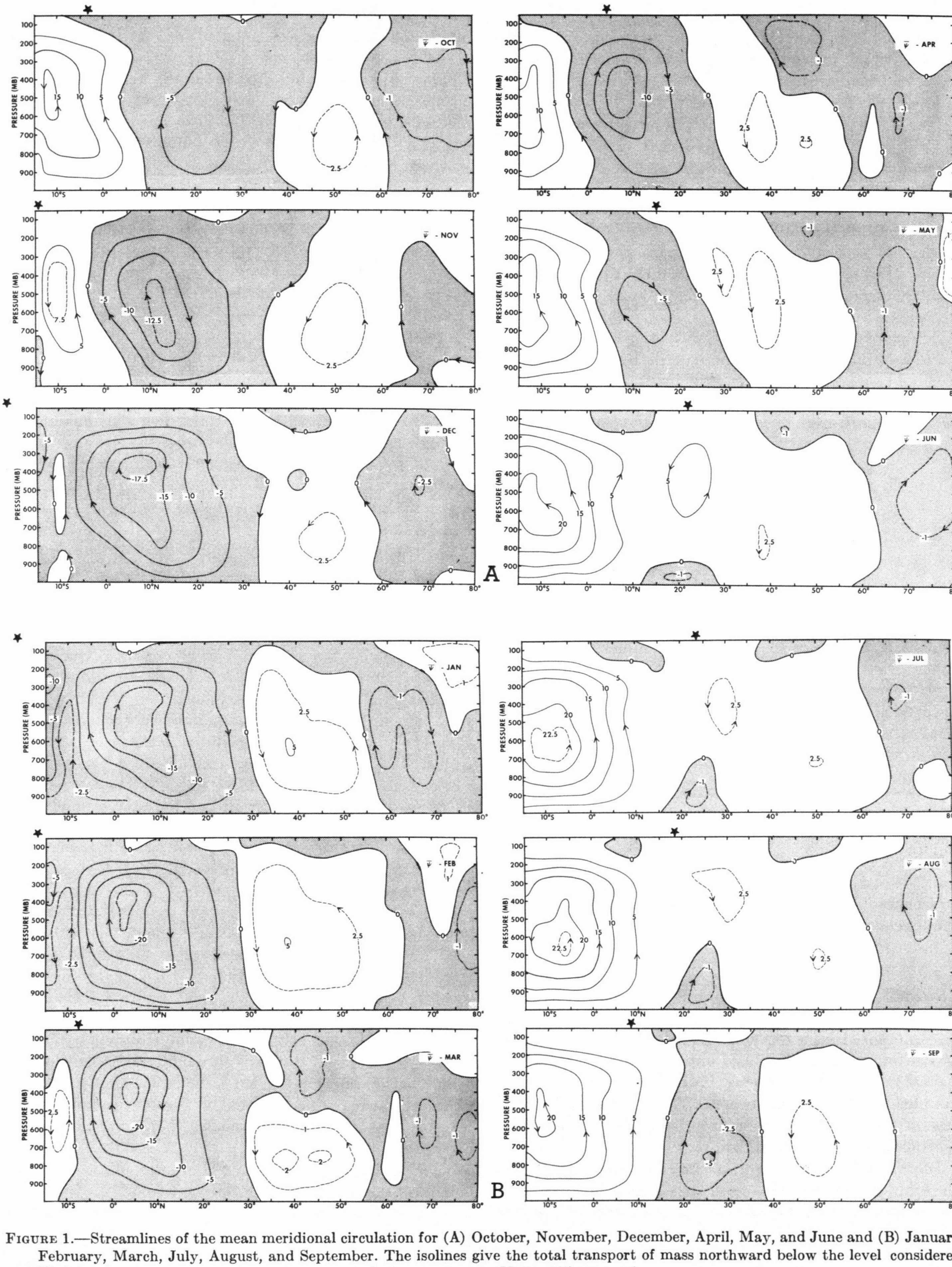


FIGURE 1.—Streamlines of the mean meridional circulation for (A) October, November, December, April, May, and June and (B) January, February, March, July, August, and September. The isolines give the total transport of mass northward below the level considered. The star denotes the mean position of the sun during the month. Units, 10^{13} gm sec^{-1}.

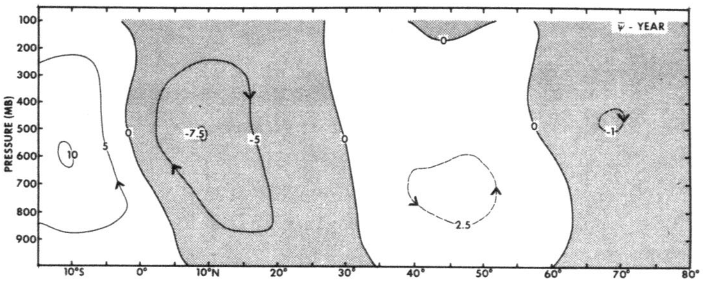


FIGURE 2.—Streamlines of the mean meridional circulation for the annual mean conditions. The isolines give the total transport of mass northward below the level considered. Units, 10^{13} gm sec^{-1}.

clear picture of the seasonal migration of the center of the SH Hadley cell from our basic upper air analyses, since details of these analyses are not reliable south of 10° S. However, the movement of the maximum in the surface $[\bar{v}]$, as shown on figures 3 and 4, suggests a seasonal shift of a magnitude comparable to that of the NH Hadley cell.

A few words may be said about the comparison with results of other investigators as presented in table 1. In general, the agreement is remarkably good, especially with the recent calculations of Kidson et al. (1969). The only major discrepancy appears to be with the latitude found by Palmén and Vuorela (1963) for their NH Hadley cell in winter, that is 11° N. versus our value of about 3° N. This difference largely arises from a difference in the position of the upper troposphere maximum in $[\bar{v}]$. These authors used upper wind analyses by Crutcher (1959) which did not extend south of 15° N. over large parts of the oceans due to lack of data. This might account for more uncertainty in the earlier results (see figure 20 for the much improved radiosonde network used in the present study).

A weak indirect (Ferrel) circulation is in evidence at middle latitudes during most months of the year. Curiously enough, at middle latitudes we have a serious problem concerning an imbalance between the mass flow at low levels and the return mass flow at higher levels. At these latitudes, systematic corrections of up to an average value of 40 cm sec^{-1} had to be applied to the mean meridional velocities at each level to achieve mass balance (note that a vertically averaged flow of mass of generally less than a few millimeters per second is needed to give observed seasonal pressure changes; for further details, see discussion in section 5). With these reservations as to the accuracy of the computed Ferrel circulation, our results suggest that both in intensity and strength the Ferrel cell has a relatively smaller seasonal variation than the tropical Hadley cells and that its average strength is about 4×10^{13} gm sec^{-1}. The center of the circulation is generally located between 40° and 50° N. In the summer months, our calculations show a tendency for two centers, one near 30° N. and the other near 50° N.

At high latitudes, a direct circulation seems to be present throughout the year; but as in the case of the Ferrel circulation, it is weak and not well defined. An order of magnitude estimate of 1×10^{13} gm sec^{-1} can be given for the strength of this polar cell. The computed latitude of its center fluctuates between 65° and 75° N. In the last section of this paper, computations will show that the winter Hadley cell practically dominates the mean north-south exchange of total energy at low latitudes. On the other hand, in middle and high latitudes the mean cells contribute far less to the total transport than the asymmetric (transient plus standing eddy) circulations.

TABLE 1.—*Strength and latitude of the center of the Hadley cells as calculated by different investigators. Units, 10^{13} gm sec^{-1}*

Investigators	Period	NH Hadley		SH Hadley	
		Strength	Latitude	Strength	Latitude
Palmén and Vuorela (1963)	Dec.-Feb.	−23	11° N.		
Vuorela and Tuominen (1964)	June-Aug.	− 3	30° N.	>18	S. of Equator
Kidson et al. (1969)	Dec.-Feb.	−17	6° N.		
	June-Aug.			20	9° S.
Present study	Jan.	−19	5° N.		
	Feb.	−23	2° N.		
	Mar.	−23	4° N.		
	Apr.	−14	6° N.	12	13° S.
	May	− 6	12° N.	17	14° S.
	June			21	12° S.
	July			24	7° S.
	Aug.			23	6° S.
	Sept.	− 5	26° N.	21	12° S.
	Oct.	− 6	22° N.	16	12° S.
	Nov.	−13	12° N.	9	10° S.
	Dec.	−18	7° N.		

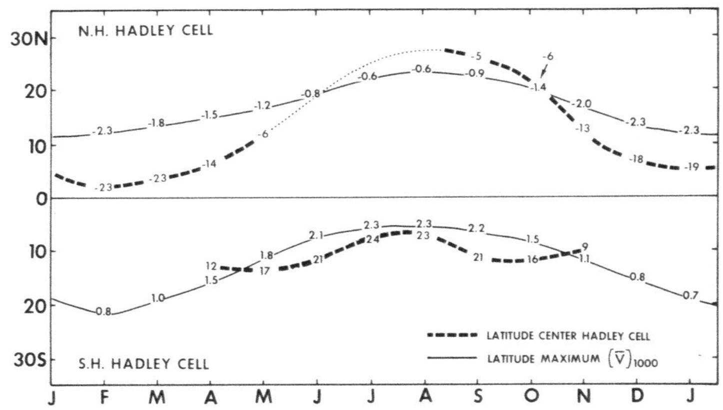


FIGURE 3.—Annual migration of the centers of the Hadley cells (dashed curves) and of the maximum meridional flow at the surface (full curves). The numbers on the dashed curves indicate the strength of the mass circulation in 10^{13} gm sec^{-1}; the numbers on the full curves give the maximum strength of the meridional flow in m sec^{-1}.

The variance of the south-north component of the wind in time and the variance of its time-mean value along a latitude circle are much larger at middle and high latitudes than at low latitudes (see, for example, fig. 14). Both the increased variance in time and the "observed" mass imbalance, which probably indicates systematic sampling errors in space, support our conclusion that the details of the mean meridional circulations as presented here must be taken with reservation at middle and high latitudes.

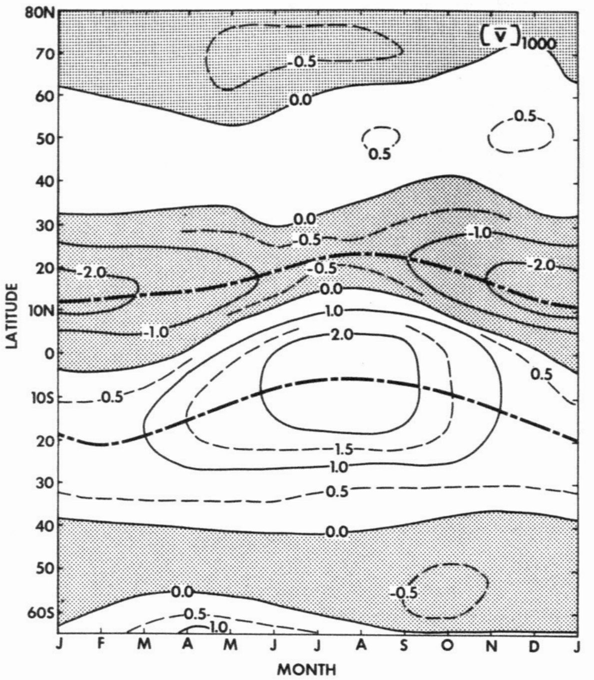


FIGURE 4.—Latitude versus month diagram of the mean meridional wind velocity (positive if northward) at 1000 mb between 65° S. and 80° N. Units, m sec^{-1}.

MEAN MERIDIONAL VELOCITIES

Because of the rather poor distribution of radiosonde stations over the Southern Hemisphere, our basic analyses of aerological data were not extended beyond a latitude of 15° S. However, at the surface there were available to us in a convenient form analyses of the monthly mean wind fields over the equatorial and southern oceans. These wind fields were computed by Miss Martha B. Jackson in a long-term project of the Oceanographic Section of the Geophysical Fluid Dynamics Laboratory for usage in numerical models of the ocean circulation. The basic wind data were taken from the U.S. Office of Naval Operations (1955–1959, 1963, 1965) *Marine Climatic Atlas of the World*, Volumes I–VII, and *Atlas of Pilot Charts* (U.S. Navy Hydrographic Office 1955) for Central American Waters and South Atlantic Ocean and for the South Pacific and Indian Oceans. Zonal averages of the meridional wind component were computed from the analyzed wind fields, assuming zero wind speed over the continents. These results for the Southern Hemisphere could be merged well with the averages previously computed for the Northern Hemisphere.

Figure 4 shows the annual cycle of the computed mean meridional velocities between 65° S. and 80° N. There appears to be a great similarity in the seasonal migration of these velocities in the NH and SH Hadley cells. Perhaps one important difference is the larger latitudinal extent of the SH Hadley cell, especially in winter. The SH Ferrel cell appears to be as weak as its northern counterpart. During the winter and spring months, there is some evidence of a direct antarctic circulation south of 60° S.

The vertical distribution of the mean meridional velocities north of 15° S. is shown in figure 5. The 1000-mb analysis just south of the Equator for the winter months, which is based mainly on radiosonde data, does not agree with the earlier analysis presented in figure 4. Since figure 4 was constructed using extensive surface-data tabulations from the U.S. Navy Hydrographic Office publications, we consider it to be the more reliable of the two. For example, it seems reasonable that there are weak southerlies near the surface during the northern winter south of about 5° S., a remnant of the SH Hadley cell. Again, it is clear that the winter Hadley cell dominates the mean circulation in the Northern Hemisphere. Strong meridional velocities of over 2 m sec^{-1} are observed in the lower branch of the Hadley circulations; these velocities are generally restricted to the lowest kilometer. A strong upper branch return flow of over 3 m sec^{-1} is found between 250 and 150 mb. Its extent in the vertical is limited to a layer 3 to 4 km thick. Between 800 and 300 mb, the mean meridional velocities are weak, generally less than 1 m sec^{-1}.

A peculiar maximum of nearly 2 m sec^{-1} is found in the lower branch of the NH Hadley cell in winter at 700 mb. This feature is connected with the upward slope of the corresponding streamlines we noted earlier in the discussion of figure 1. An important contribution to this feature comes from the strong southward flow over Africa. This flow is probably a part of the much larger monsoon circulation over Asia and Africa (see the longitudinal cross section at the Equator in fig. 11).

The annual mean velocities presented in figure 6 give a more or less symmetric picture with maximum velocities of about 1 m sec^{-1} in the low-latitude Hadley cells.

The different investigators mentioned earlier in the discussion of the streamlines give about the same magnitude and location of the maxima in $[\bar{v}]$. At low levels there are, however, two important qualitative differences between our analyses and those of Palmén and Vuorela (1963). First, our data do not confirm the general increase in $[\bar{v}]$ in the lowest 500 m that these authors propose as a typical profile in the Tropics; we do, however, find that the rapid decrease in speed occurs above the 500-m height. Second, we do not find the deep intrusion northward at low levels of the NH Hadley cell as given in their winter picture; consequently, our Ferrel cell is located about 15° south of their position. The discrepancy in these results can be traced to the use of Tucker's (1957) surface winds by Palmén and Vuorela and our use of the more recent and presumably more accurate surface analyses of Crutcher et al. (1966).

Figure 7 shows the seasonal variation of the mean south-north winds at 200 mb, where the return branches of the Hadley cells attain their maximum intensity. The upper branch of the NH Hadley cell is most strongly

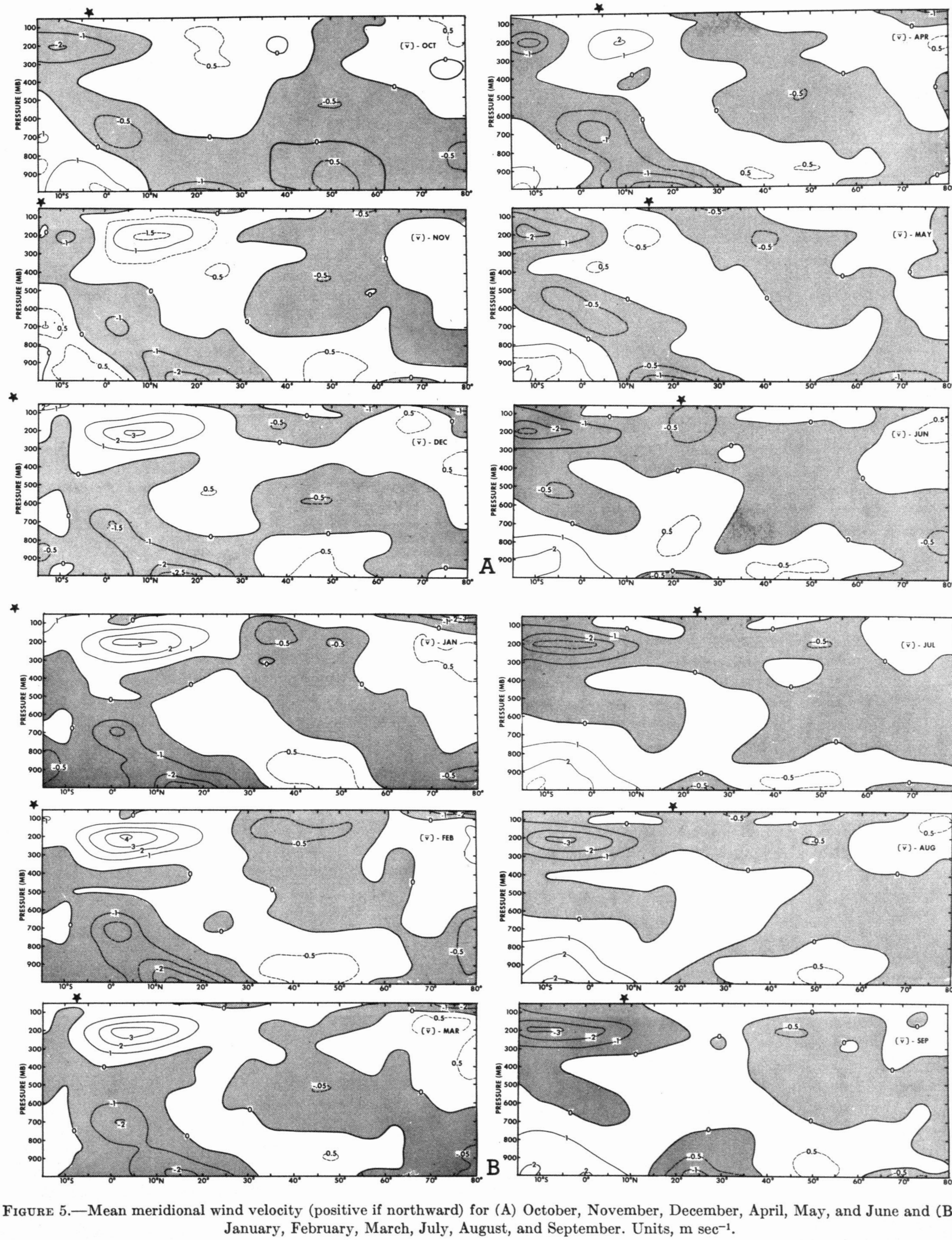


FIGURE 5.—Mean meridional wind velocity (positive if northward) for (A) October, November, December, April, May, and June and (B) January, February, March, July, August, and September. Units, m sec^{-1}.

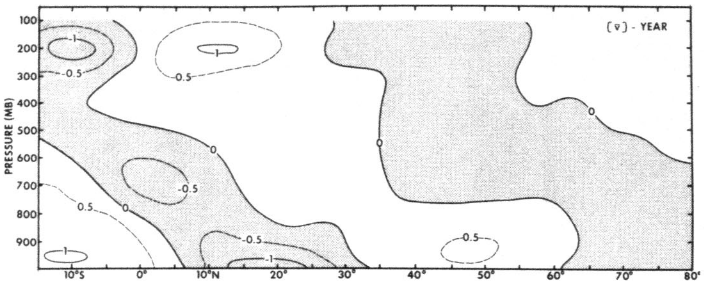


FIGURE 6.—Mean meridional wind velocity (positive if northward) for the annual mean conditions. Units, m sec^{-1}.

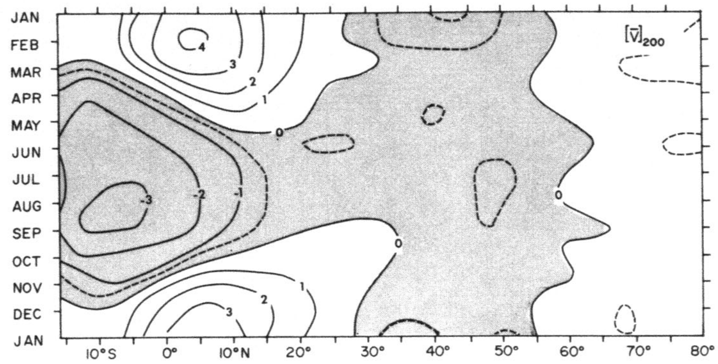


FIGURE 7.—Latitude versus month diagram of the mean meridional wind velocity (positive if northward) at 200 mb. Units, m sec^{-1}.

developed in February and the one of the SH Hadley cell in August.

MEAN VERTICAL VELOCITIES

The monthly and annual mean vertical velocities computed from the measured $[\bar{v}]$ by using continuity of mass are shown in figures 8 and 9 in units of mm sec^{-1}. Throughout the year, rising motion is found in the vicinity of the Equator. In the northern winter, the strongest computed vertical velocities of 10 mm sec^{-1} are found at 4° S. between 400 and 300 mb. In the northern summer, the computed vertical velocities are smaller (maximum values of 0.6 cm sec^{-1}), and the area of rising motion is wider than in winter.

The most interesting seasonal variation is observed in the subtropics. The intense winter Hadley cell causes a strong subsidence in the subtropics between 10° and 30° N. during the months December through April. Maximum values of $[\bar{w}]$ of -6 mm sec^{-1} are calculated in the vicinity of 15° N. However, in summer all vertical motions north of 20° N. are small, generally below 2 mm sec^{-1}. Independent evidence of these seasonal changes in the subtropics may be gained from figure 10, which shows the difference in monthly mean relative humidity between July and January, as calculated from our humidity data. The gross features of the change in vertical motion in the subtropics should be reflected in the pattern of relative humidity. In an area of strong downward motion, one would for example expect to find relatively dry air. The figure indeed shows that in the midtroposphere the relative humidity at 15° N. is more than 20 percent higher in July than in January, while south of 10° S. it is more than 10 percent lower. This agrees well with our pictures of the vertical velocities showing a strong subsiding branch of the Hadley cell *only* in the winter hemisphere. Palmén and Vuorela (1963) calculated for the winter a maximum ascending motion of 9 mm sec^{-1} between 0° and 5° N. and a maximum descending motion in the belt 15°–20° N. of about 7 mm sec^{-1}, both estimates being in surprisingly good agreement with our results.

4. ZONAL ASYMMETRIES

Longitude-height cross sections at the Equator, 16° N., and 40° N. have been constructed to illustrate the zonal asymmetries in the meridional flow (fig. 11). In spite of some uncertainties related to the distribution of observing stations, the cross sections appear to uncover many of the important asymmetries of the meridional flow.

TROPICS

The January flow at the Equator shows a northward component in the upper troposphere at almost all longitudes. Maximum values are found along the longitude belt extending from Africa to the western Pacific. Northward components of several meters per second are also observed at Guayaquil, Bogotá, and Colón, indicating another maximum in the vicinity of South America. The details of the analyses in this area cannot be trusted since the values just west of South America primarily represent an extrapolation by the analysis scheme from stations to the north and east of the area.

The lower equatorial troposphere is dominated by southward flow in January. There are, however, areas of northward flow over the Atlantic and eastern Pacific where the equatorial trough remains in the Northern Hemisphere during the northern winter. The strongest southward flow apparently occurs over the western Indian Ocean, and over Africa, where a maximum is computed around the 700-mb level. Stronger southward transfer at 700 mb relative to 850 mb is also observed in January at a number of other stations near the Equator.

The meridional flow at the Equator in July contrasts sharply with that found in January. Northward flow is now in evidence in the lower troposphere at all longitudes. The direction of the flow over Africa has reversed, and the low-level flow over the western Indian Ocean has changed dramatically. Here, there is general agreement between our analyses and the more detailed analyses of Findlater (1969). However, the relative coarseness of our grid leads to some smoothing of these features. The low-level northward flow over the Atlantic and eastern Pacific has strengthened, particularly in the western Atlantic. Southward flow dominates the upper troposphere, with the strongest transequatorial flow computed over the eastern Indian Ocean and western Indonesia and over the eastern Atlantic. Again, as in January, there is an indication of another maximum over western South America or the eastern Pacific.

Consider now the cross sections at 16° N. The major features of the January cross section are in reasonably

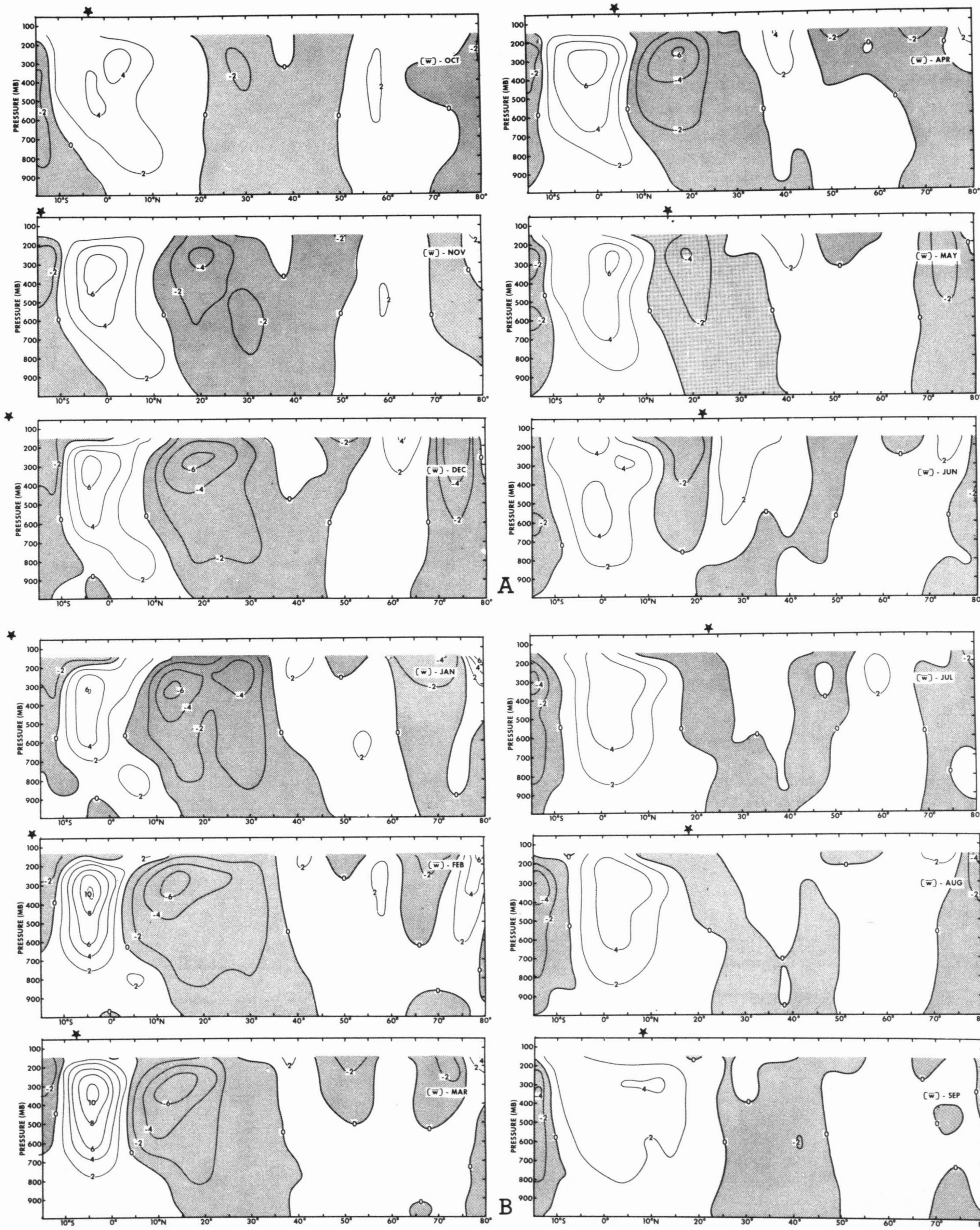


FIGURE 8.—Mean vertical wind velocity (positive if upward) for (A) October, November, December, April, May, and June and (B) January, February, March, July, August, and September. Units, mm sec^{-1}.

good agreement with the winter cross section at 15° N. given by Palmén et al. (1958). Southward flow of varying strength dominates the lower troposphere. In contrast, there exists in the upper troposphere a definite three-wave pattern, which can be traced downward to around the 700-mb level.

In summer, 16° N. roughly marks the northern boundary of the SH Hadley cell. There is, broadly speaking, low-level southward flow over the Western Hemisphere and low-level northward flow over the Eastern Hemisphere, leading to little net meridional transfer across the latitude circle. The main features in the upper levels, namely the southward flow between 65° E. and 150° E. and the northward flow between 30° W. and 65° E. are associated with the summertime high-level easterly jet. This circulation feature develops in the low latitudes of the Northern Hemisphere over the western Pacific, Indian Ocean, and eastern Africa (Flohn 1964).

In summary, there exist, superimposed on the mean meridional component, pronounced longitudinal variations in the meridional component of the tropical wind field. This is true even at low levels in the trade wind latitude belt during winter.

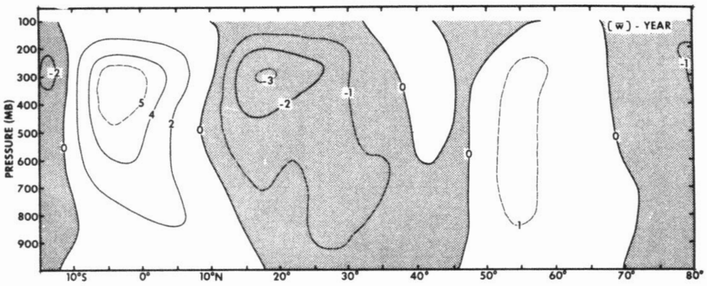


FIGURE 9.—Mean vertical wind velocity (positive if upward) for the annual mean conditions. Units, mm sec⁻¹.

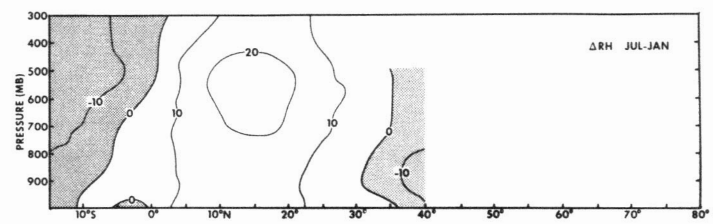


FIGURE 10.—The difference in mean relative humidity (percent) between July and January for the latitude belt 15° S.–40° N.

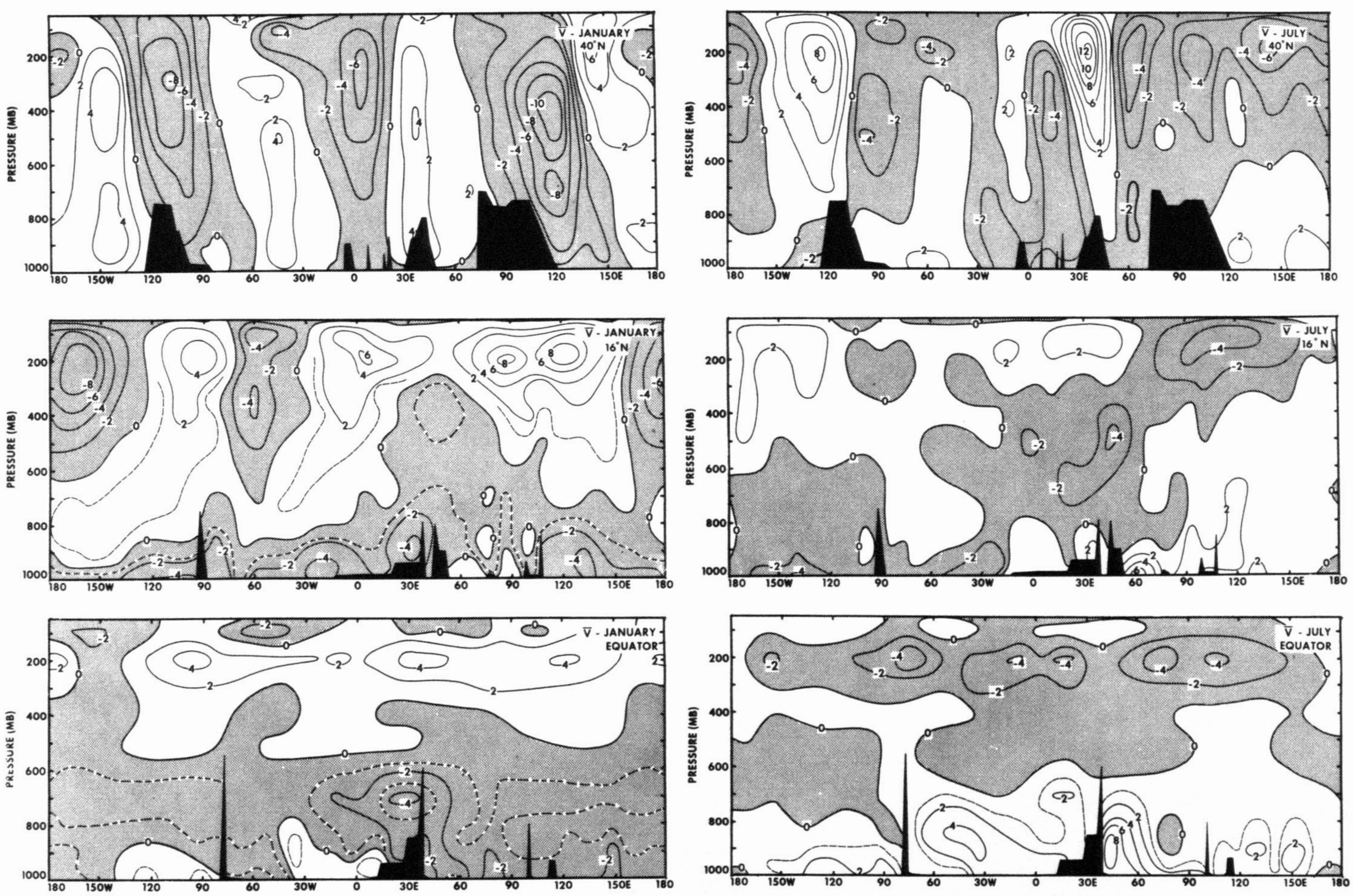


FIGURE 11.—Longitude versus pressure section of the time-mean meridional velocity (positive if northward) for January and July at the Equator, 16° N., and 40° N. Units, m sec⁻¹.

MIDDLE LATITUDES

The situation in middle latitudes changes dramatically in character from that in the deep Tropics, where the flow is relatively uniform with respect to longitude and usually reverses direction between the upper and lower troposphere. At 40° N., the meridional flow changes sign roughly every 60° longitude and has generally the same sign at different altitudes in the troposphere. Maximum velocities are found in the vicinity of 300 mb, the values ranging between 5 and 10 m sec^{-1}. It is evident that a mean meridional circulation computed at this latitude necessarily represents a small statistical residue and consequently must be extremely hard to define.

The January section shows the well-known three-wave structure with troughs located over eastern North America, western Europe, and eastern Asia.

In July, the circulation is generally weaker and not so well defined. One interesting feature is the strong flow from the south over the eastern Mediterranean and Turkey.

As we shall see in the next section, our data gives too much net flow toward the south in the latitude belt 30°–50° N. A comparison with the meridional cross sections constructed by Crutcher (1961) shows, in general, good agreement as to sign and magnitude of the flow with our sections at 40° N. Only during winter over the central Pacific between roughly 160° E. and 160° W. is there major disagreement. Crutcher analyzes at 200 mb one larger area of northward flow between 150° E. and 150° W., while our analysis shows weak southward flow flanked by two areas of northward flow. Undoubtedly, Crutcher's analysis, in which geostrophic estimates were used in regions of sparse data, is closer to the true situation in this area, since we have no wind data in the latitude strip 30°–50° N. between Japan and ship V on the west and ship N on the east (see station configuration, fig. 20). Our objective analysis carries the influence of the Hawaiian Islands and Midway too far to the north and does not give a maximum of northward flow between the Aleutian Islands and Midway-Hawaii as Crutcher's does. His analysis in this area roughly agrees with the geostrophic cross sections presented by Saltzman and Rao (1963) at 45° N.

5. ACCURACY OF THE RESULTS

Because the streamlines and vertical motion patterns were calculated directly from the mean meridional velocities by using the continuity equation without further assumptions, we shall limit our discussion to the errors in the determination of the meridional velocities. These velocities, as mentioned before, represent a straightforward zonal average of the time mean south-north wind component.

MASS BALANCE

It can be shown that a mean meridional drift of only

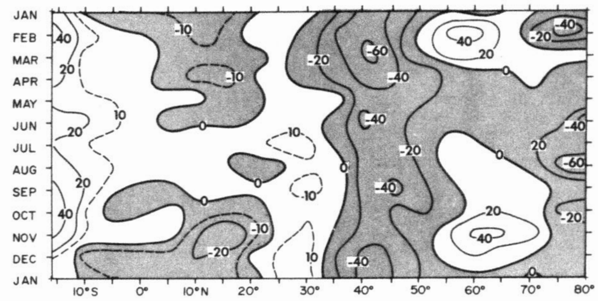


FIGURE 12.—Latitude versus month diagram of the vertical average of the mean meridional velocities, indicating spurious deviations from mass balance. Units, cm sec^{-1}.

a few millimeters per second throughout the depth of the atmosphere will account for the observed seasonal changes in the zonally averaged surface pressure (Gordon 1953). The degree to which the computed meridional velocities satisfy this constraint can be taken as an indication of the magnitude of the errors in the computation. Vertically averaged values of the computed meridional velocities are given in figure 12.

For easy comparison of the conditions at low and middle latitudes, the *unbalanced* meridional velocities at the Equator and 40° N. are shown in figure 13. The numbers at the bottom of the figure indicate the mean imbalance in centimeters per second.

The computed meridional flow yields vertically averaged velocities as high as 40 cm sec^{-1} or more in extratropical latitudes, while values south of 30° N. are surprisingly small. The relatively large errors in middle and high latitudes undoubtedly result from the greater spatial and temporal variability of the meridional wind component at these latitudes as illustrated in figures 11 and 14. The particularly large errors in the latitude belt 35°–50° N., where negative vertically averaged meridional velocities are computed throughout the year, suggest an important systematic sampling bias within this latitude belt. In this regard, it has already been noted that the wind data available over the central Pacific did not provide a proper sampling of the northward flow in that area. Estimates based on geostrophic velocities indicate that a major part of the error in the computed mean meridional velocities at midlatitudes is probably introduced through an underestimation of the strength of this northward flow.

Kurihara (1961) and others have discussed the factors contributing to errors in the determination of the wind. For a number of reasons, these errors increase with height, at least up to the level of the maximum wind. However, the optimum method for reducing the computed vertically averaged meridional velocities to zero cannot easily be determined. Since the computed horizontal velocity divergence is quite sensitive to wind errors, we chose the variance of this quantity as an indicator of the noise level of the wind analyses as a function of height. In particular, significant errors in the wind field are typically reflected on horizontal divergence maps as adjacent "couples" of compensating convergence and divergence. Inspection of the horizontal divergence statistics at the different levels led us to adopt a set of standard weights in applying wind corrections as a function of height. These corrections increased from a minimum at 1000 mb to a maximum at 200 mb. Above 200 mb, the correction remained constant. The ratio of the correction at 200 mb to that at 1000 mb was 2.25.

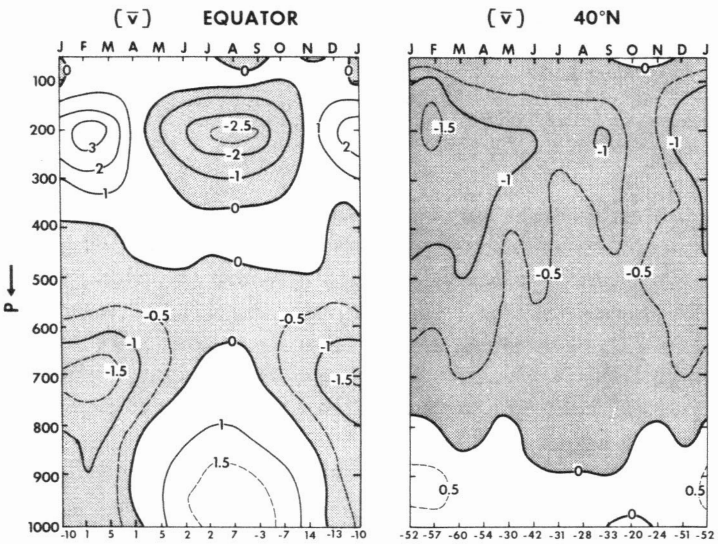


FIGURE 13.—Mean meridional velocities (positive if northward) at the Equator and 40° N. analyzed as a function of month and pressure. Units, m sec^{-1}. Numbers at the bottom indicate mean imbalance in a vertical column in cm sec^{-1}.

ERROR ESTIMATES

Additional information on the character of the meridional flow and the reliability of the calculated mean meridional circulations may be gained from a short description of the computed variances in time and space of v. Figure 14 shows the variance in time $[\overline{v'^2}]$ and the variance in space $[\bar{v}^{*2}]$ both at the surface and at 200 mb. The prime indicates the deviation from the time (bar) mean and the star the deviation from the zonal (brackets) mean.

At the surface in winter, a maximum temporal variance of 40 m^2 sec^{-2} is found in the region of high cyclonic activity around 50° N. This variance increases with altitude to a value of 250 m^2 sec^{-2} between 300 and 200 mb at about 35° N. Between 200 and 100 mb, the intensity in this maximum drops off to less than 100 m^2 sec^{-2}. On the other hand, at the Equator at the surface, the variance is only 4 to 5 m^2 sec^{-2} throughout the year and increases to a value of about 40 m^2 sec^{-2} at 200 mb.

The spatial variance is generally smaller than the temporal variance by an order of magnitude. At 200 mb, there are two distinct maxima in winter, one between 20° and 30° N. and the other between 50° and 60° N., probably connected with the standing waves in the sub-

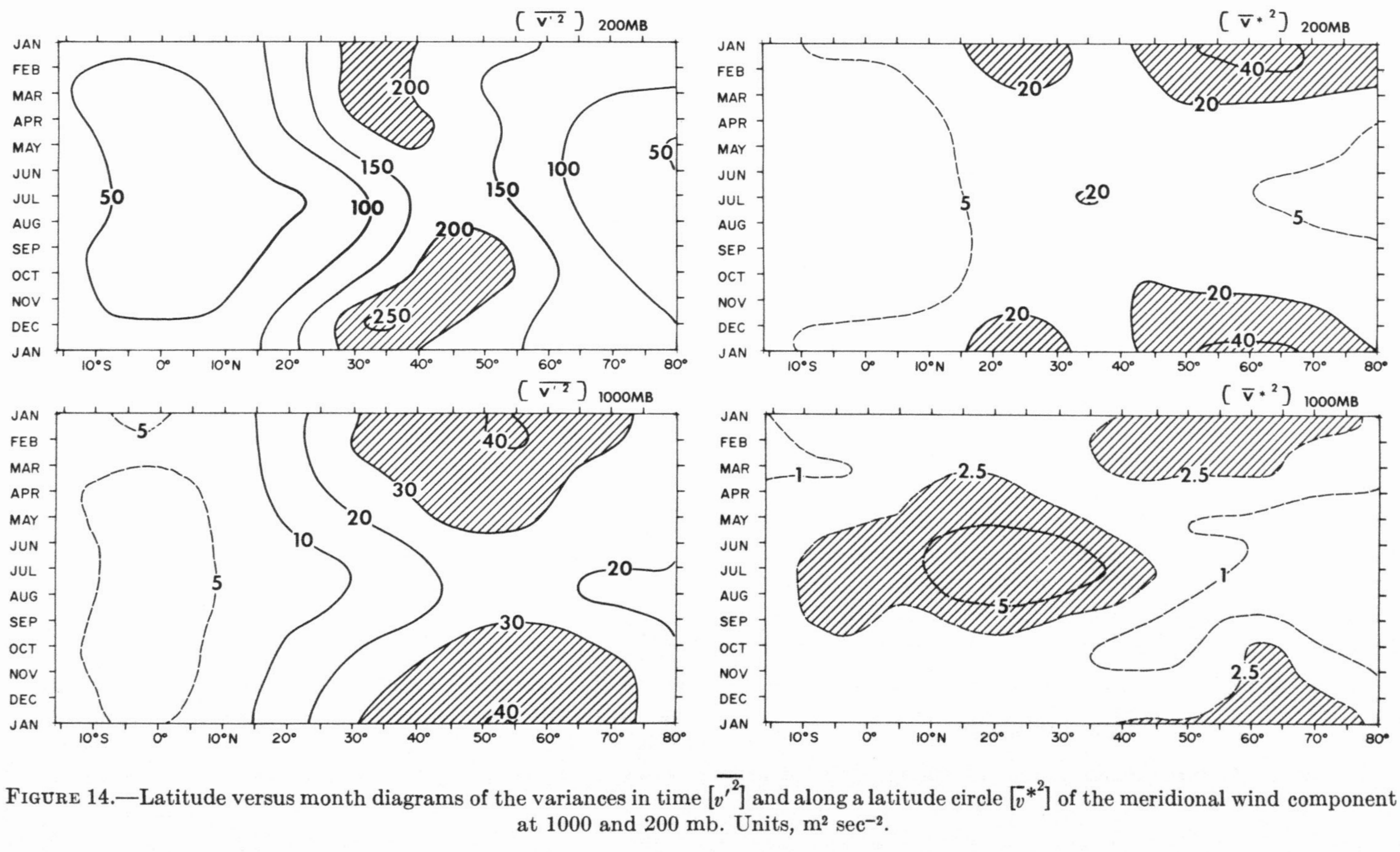


FIGURE 14.—Latitude versus month diagrams of the variances in time $[\overline{v'^2}]$ and along a latitude circle $[\bar{v}^{*2}]$ of the meridional wind component at 1000 and 200 mb. Units, m^2 sec^{-2}.

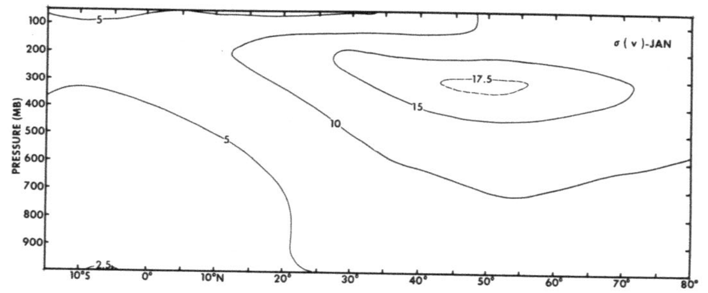


FIGURE 15.—Latitude versus pressure diagram of the standard deviation (both from the time mean and zonal mean) of the meridional wind component for January. Units, m sec^{-1}.

TABLE 2.—*Estimates of the standard error of the mean of* $[\bar{v}]$ *at 1000 and 200 mb. Units, m* sec^{-1}

		1000 mb		200 mb	
		$\sigma(v)$	$[\bar{v}] \pm$ SEM*	$\sigma(v)$	$[\bar{v}] \pm$ SEM
Equator	Jan.	2.6	−0.7 ± 0.2	8.3	3.0 ± 0.7
	July	2.6	2.0 ± 0.2	6.4	−2.6 ± 0.5
20° N.	Jan.	4.1	−2.4 ± 0.3	12.7	1.0 ± 1.0
	July	3.6	−0.4 ± 0.3	7.2	−0.1 ± 0.6
40° N.	Jan.	6.1	0.4 ± 0.5	14.4	−0.5 ± 1.2
	July	4.9	0.5 ± 0.4	13.6	−0.3 ± 1.1
60° N.	Jan.	6.3	0.0 ± 0.5	14.0	0.2 ± 1.2
	July	4.8	−0.1 ± 0.4	11.2	0.0 ± 0.9

*A standard error of the mean of 0.2 for a value of $[\bar{v}]$ of −0.7 m sec^{-1} indicates that one may have 95 percent confidence that the true value of $[\bar{v}]$ falls within the range −0.5 and −0.9 m sec^{-1}.

tropical and polar jet streams, respectively. In summer around 20° N., at low levels the variances in space and time are comparable. As pointed out by Rasmusson (1970), the importance of the standing eddies in summer is related to the prominence of the semipermanent subtropical Highs in this season over the oceans.

The standard deviation of v is given by

$$\sigma(v)=\sqrt{[\overline{(v-[\bar{v}])^2}]}=\sqrt{([\bar{v}^{*2}]+[\overline{v'^2}])}.$$

Values of $\sigma(v)$ for January are shown in figure 15. The standard error of the mean, being an estimate of the confidence one can place in the values of $[\bar{v}]$, is given by $2\ \sigma(v)/\sqrt{N}$.

The choice of the number of independent observations (N) is rather ambiguous. We shall, however, try to gain some idea of the order of magnitude of the standard error of the mean by choosing a rather conservative value of $N=30\times 20$, where 30 is equal to the estimated number of independent observations for an arbitrary station in each 5-mo sample and 20 is equal to the number of independent grid-point values of $\bar{v}$ along a latitude circle. This value of $N=600$ would give for the standard error of the mean $0.082\times\sigma(v)$. Table 2 gives values of this quantity for four selected latitudes. Comparing these error estimates with the values of $[\bar{v}]$, one finds that the low-latitude features are generally statistically significant, with the estimates in the lower branch of the Hadley cells being the more reliable. The upper return flow at these latitudes is rather uniform with longitude (fig. 11), but apparently fluctuates more with time than the low-level flow. Riehl (1954) in his textbook *Tropical Meteorology* already emphasized the apparent restlessness of the high-level flow in the Tropics. In middle and high latitudes, our calculated mean meridional velocities are of the same order as or even smaller than the estimated standard error of the mean, and therefore considerably less reliable than the computed velocities at low latitudes.

6. TRANSPORTS OF ANGULAR MOMENTUM AND ENERGY

A short section in this paper will be devoted to the discussion of the fluxes of angular momentum and energy as computed using our mean meridional circulations. A more detailed discussion will be given in later papers. The main purpose at present is to show that reasonable values of the transports are obtained by using the mean meridional velocities calculated in this paper. The results seem to indicate that it is not necessary or even desirable to resort to indirect methods of calculating these velocities to define, for example, the tropical Hadley circulation.

ANGULAR MOMENTUM TRANSPORT

The flux of angular momentum across a latitude circle is given by

$$F_{AM}=C_1\int_0^{p_0}[\overline{vu}]dp$$

where

$C_1=2\pi a^2\cos^2\phi\ g^{-1}$,
a =radius of the earth,
ϕ =latitude,
p_0 =1012.5 mb=surface pressure,
g =acceleration due to gravity, and
u =west to east component of the wind.

This flux can be partitioned into its mean and transient plus standing eddy components

$$F_{AM}=C_1\int_0^{p_0}[\bar{v}][\bar{u}]dp+C_1\int_0^{p_0}([\overline{v'u'}]+[\bar{v}^*\bar{u}^*])dp.$$

Since our data at 50 mb were poor over Asia, all vertical integrations in this section were carried out only for the layer 1012.5–75 mb. Figure 16 shows the total flux as well as its components for the months of January and July. South of about 30° N. in January and south of 10° N. in July, the computed mean meridional circulations contribute quite significantly to the total flux, while north of these latitudes the eddy contributions dominate. In general, there is good agreement with the fluxes published by Kidson et al. (1969). Only around 30° N., their eddy transport in winter is about 20 percent larger than computed by us for January.

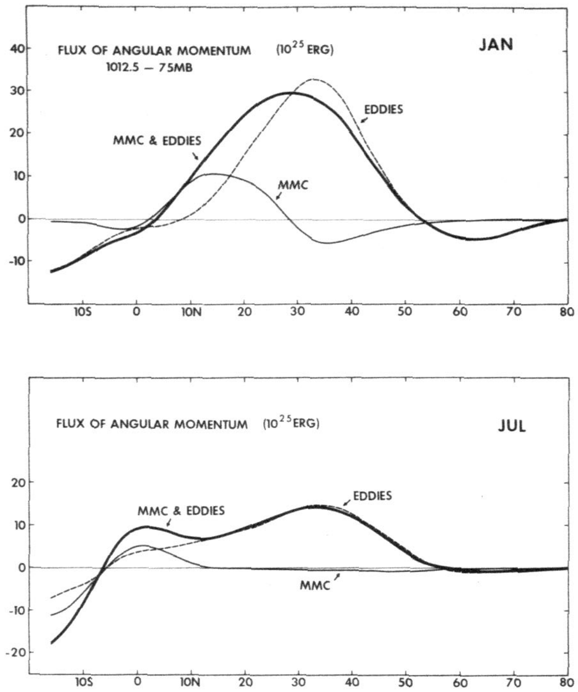


FIGURE 16.—Fluxes of angular momentum due to mean meridional and eddy circulations for January and July. The fluxes are integrated over the layer 1012.5–75 mb. Units, 10^{25} gm cm^2 sec^{-2}.

ENERGY TRANSPORT

The total flux of energy across a latitude circle can be written as the sum of the fluxes of potential energy, sensible heat, latent heat, and kinetic energy:

$$F_{TE}=F_{PE}+F_{SH}+F_{LH}+F_{KE}=C_2\int_0^{p_0}(g[\overline{vZ}]+c_p[\overline{vT}]+L[\overline{vq}]+\tfrac{1}{2}[\overline{v(u^2+v^2)}])dp$$

where

Z =geopotential height,
T =temperature,
q =specific humidity,
c_p =specific heat at constant pressure,
L =heat of condensation, and
$C_2=2\pi a \cos\phi\, g^{-1}$.

These fluxes can again be partitioned into their eddy and mean contributions. We shall discuss presently the vertically integrated fluxes of potential energy, sensible heat, and latent heat by both the mean and the eddy circulations. As pointed out by Starr (1951) and others, the flux of kinetic energy can be neglected in total energy considerations. All the fluxes were computed in our major analysis project; extensive tables of these fluxes at the different levels are in the aforementioned unpublished manuscript of Oort and Rasmusson (1969).

Figure 17 shows the mean and eddy fluxes for January and July. The sign of the energy transports by the mean circulations can be easily deduced by realizing that potential energy has a maximum at high levels in the atmosphere, while both sensible heat and latent heat are concentrated in the lower levels. In January, the strong northward flow at high levels in the NH Hadley cell will result in a strong northward transport of geopotential energy. However, the southward flow of latent plus sensible heat at low levels almost compensates for the potential energy flux. The fluxes change sign in summer, when the SH Hadley cell dominates the circulation with southward flow at high levels and northward flow at low levels. The direction of the total energy flux appears to be determined by the potential energy flux. Thus, the net transport of energy (fig. 18) by the mean meridional circulation at low latitudes is northward in winter and southward in summer. In comparison, the fluxes by eddies (standing plus transient) are negligible at low latitudes. The eddy fluxes play the most important role at middle latitudes. As we have speculated before, the net transport by the indirect (Ferrel) cell in middle latitudes is not very large.

The diagrams clearly show that all three forms of energy must be carefully evaluated when investigating the total energy budget since the final result may represent a relatively small difference of three large terms. For example, the net transport of energy across the Equator is generally very small in comparison with the individual transports of potential energy and sensible plus latent heat.

From the standpoint of total meridional energy exchange, there appears to be some justification for the conclusion that, outside the deep Tropics, the eddy fluxes (standing plus transient) play a more important role than the mean meridional cells. This of course does not mean that the mean meridional overturnings cannot be extremely important in the balance of the individual energy components, even at middle and high latitudes.

In table 3, our numbers for the meridional energy transports at the Equator and 15° N. for January and July are compared with the estimates of other investigators. The agreement, especially with the results of Kidson et al. (1969) for their winter and summer seasons, is quite satisfactory.

All fluxes discussed previously have been integrated over the layer between 1012.5 and 75 mb. To evaluate the *mean* fluxes, we have corrected the mean meridional velocities so that no net north-south mass flow would take place through the layer 1012.5–75 mb or, in other words, that there would be no mean mass flow across the 75-mb level.

Similar calculations were carried out with the top level at 125 and 175 mb to investigate the appropriateness of the assumption of a closed mass circulation below 75 mb. Figure 19 shows the potential energy flux by the mean motions for these three cases for January. It is apparent that 175 mb is not a good choice because an important part of the return branch of the tropical Hadley cell is excluded. However, the results for 125 and 75 mb show a rather close agreement, thus indicating that probably no ap-

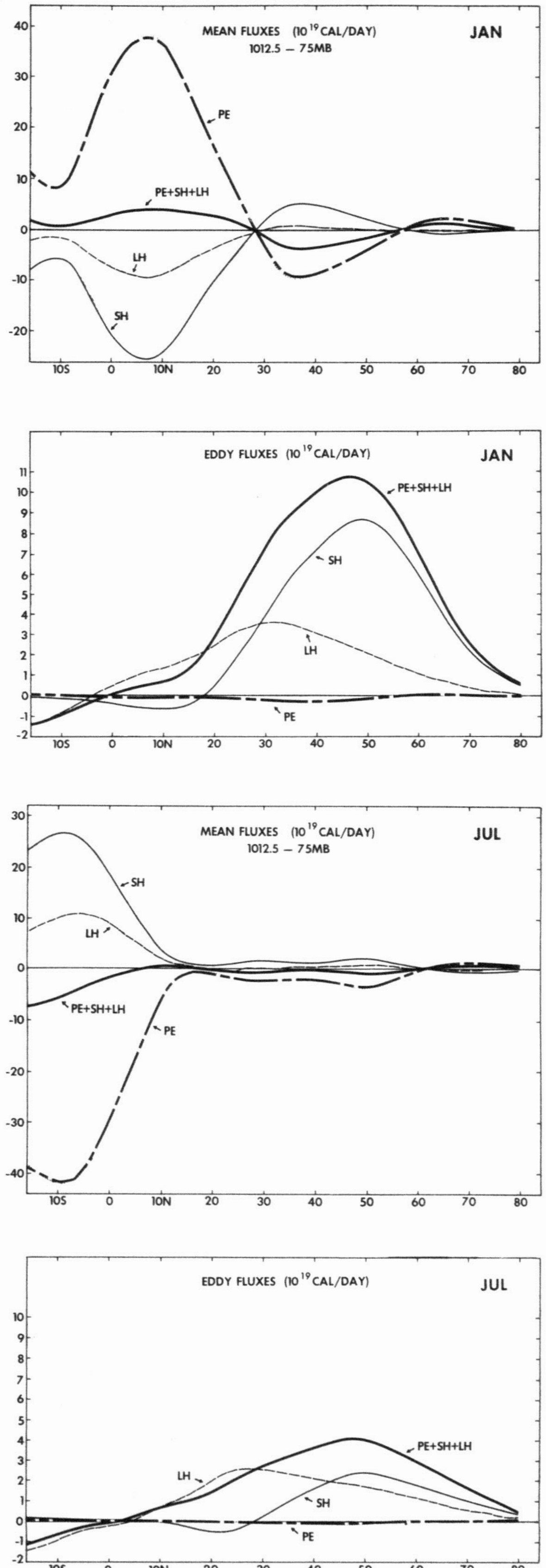


Figure 17.—Mean and eddy fluxes of potential energy (PE), sensible heat (SH), and latent heat (LH) for January and July. Fluxes are integrated over layer 1012.5–75 mb. Units, 10^{19} cal day^{-1}.

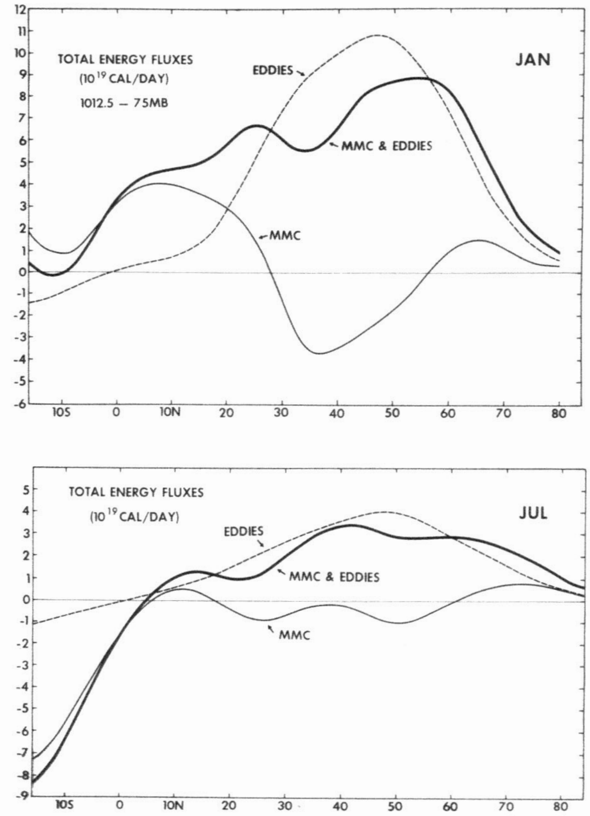


Figure 18.—Fluxes of total energy (potential energy + sensible heat + latent heat) due to mean meridional and eddy circulation for January and July. The fluxes are integrated over layer 1012.5–75 mb. Units, 10^{19} cal day^{-1}.

Table 3.—*Comparison of northward energy fluxes from different investigators across the Equator and 15° N. Units, 10^{19} cal day^{-1}*

Period	Investigator	Lat.	PE	SH	LH	PE+SH	PE+SH+LH
Dec.-Feb.	P, R, V	15° N.				16.1	8.6
Dec.-Feb.	H	Equator				3.0	
		15° N.				12.6	
Dec.-Feb.	K, V, N	Equator	26.2	−17.8	−5.1	8.4	3.2
		15° N.	28.7	−18.6	−5.5	10.1	4.7
Jan.	O, R	Equator	31.4	−20.9	−7.2	10.5	3.2
		15° N.	27.3	−17.4	−6.5	9.9	3.5
June-Aug.	H	Equator				− 6.4	
		15° N.				− 0.6	
June-Aug.	K, V, N	Equator	−33.4	22.0	9.7	−11.4	−1.7
		15° N.	− 4.3	2.2	0.9	− 2.1	−1.2
July	O, R	Equator	−29.8	19.1	9.2	−10.7	−1.5
		15° N.	− 0.7	0.5	0.4	− 0.2	0.3

P, R, V = Palmén et al. (1958).
H = Holopainen (1965).
K, V, N = Kidson et al. (1969).
O, R = present study.

preciable net vertical mass flow occurs across the 75-mb level and that the choice of the layer 1012.5–75 mb appears to be a reasonable one.

In the case of the eddy fluxes, the vertical integrals are rather insensitive to the choice of the top level.

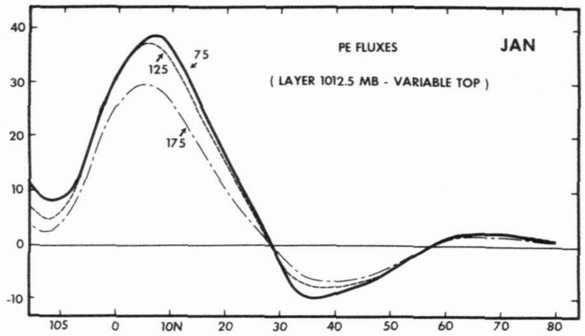


FIGURE 19.—Comparison of the mean fluxes of potential energy computed for three layers with different top levels. Units, 10^{19} cal day^{-1}.

7. SUMMARY AND CONCLUSIONS

One of our important goals has been to describe in some detail the annual cycle in the mean meridional circulations in the atmosphere. In agreement with other investigators, most recently Kidson et al. (1969), a dramatic reversal is found in the tropical circulation from winter to summer. The winter Hadley cell is of overwhelming importance, while the summer Hadley cell practically vanishes except near the earth's surface. Only at the time of the transition months April, May and October, November is there some degree of symmetry with respect to the Equator. During these months, the NH and the SH Hadley cells overturn mass at the rate of about 10×10^{13} gm sec^{-1}. In the midwinter and midsummer months, a maximum mean mass circulation in the winter Hadley cells of 23 to 24×10^{13} gm sec^{-1} is computed. The mean meridional velocities connected with this circulation are about 2.5 m sec^{-1} near 1000 mb and over 3 m sec^{-1} near 200 mb. Mean vertical velocities attain values of about 5 and 8 mm sec^{-1} in the downward and upward branches of the winter Hadley cells, respectively.

At middle latitudes, a rather weak Ferrel circulation is in evidence. Further, there are indications of a very weak direct circulation north of 60° N. At middle and high latitudes, no clearly defined seasonal changes are found in either the position or the strength of the mean meridional circulations. North of 30° N., the computed meridional velocities are generally of the order of or less than 0.5 m sec^{-1}. The relative strength of the mass circulations in the winter Hadley cell, the Ferrel cell, and the polar cell can be given approximately by the numbers 20×10^{13}, 4×10^{13}, and 1×10^{13} gm sec^{-1}, respectively.

Another goal has been to determine to what degree the time-mean and zonal-mean meridional velocities give a representative description of the meridional velocities at each longitude. In this connection, several figures of the temporal and spatial variation of v, the south-north wind component, at the different latitudes are presented. Error estimates (section 5) show that south of about 30° N. the computed mean meridional circulations probably give a fairly accurate picture of the true situation. From longitude versus height sections at the Equator and at 16° N., it is clear that there are certain important zonal asymmetries (for example during the Asian monsoon) superimposed on the basic mean meridional flow. In spite of this, one can certainly conclude from our calculations that the monthly mean meridional velocities at low latitudes are more than a "statistical residue." In fact, these circulations turn out to be of crucial importance in transporting meteorological quantities at low latitudes (section 6).

In middle and high latitudes, the situation is different. Here, the meridional flow changes sign roughly every 60° longitude. Its zonal average is quite small compared to the individual values along the latitude circle, and consequently this average is difficult to evaluate. In addition, we encountered serious sampling problems due to lack of data over the central Pacific Ocean around 40° N., which caused too much southward flow at high levels in the Ferrel cell. Fortunately, one can calculate (section 6) that the vertically integrated fluxes of angular momentum and total energy due to these mean meridional overturnings (except due to the winter Hadley cell) are small compared to the fluxes due to transient plus standing eddies.

The individual fluxes of potential energy, sensible heat, and latent heat by the mean meridional circulations are quite large. However, the character of a mean meridional overturning is such that the flow of potential energy in the upper branch is largely compensated by the flow of sensible plus latent heat in the lower branch. The sign of the potential energy flux generally determines the direction of the flux of total energy. For example, in January maximum transports of potential energy, sensible heat, latent heat, and total energy of 37×10^{19}, -24×10^{19}, -9×10^{19}, and 4×10^{19} cal day^{-1}, respectively, are computed across 5° N. In the case of the eddy circulations, the total energy flux is practically equal to the flux of sensible plus latent heat, the flux of potential energy being quite small in comparison.

APPENDIX

DATA SOURCES

The main data supply for this study came from the MIT General Circulation Library at Cambridge, Mass., which contains daily radiosonde data for about 700 stations over the Northern Hemisphere for the period May 1958 through April 1963. These data were collected and processed by the Travelers Research Center, Inc. (TRC), at Hartford, Conn., for Prof. V. P. Starr at the Massachusetts Institute of Technology (MIT) under the National Science Foundation Grants GP–820, GP–3657, GA–400, and GA–1310X. About 500 of the available 700 stations, being the "good" reporting stations, were used in our analyses.

Data for over 40 tropical stations between 25° S. and 25° N. for the same 5-yr period were very kindly supplied by Prof. R. E. Newell and Dr. J. W. Kidson, also of MIT, and these were added to the basic set of stations.

Data from about 150 pibal and rawinsonde stations were obtained from the U.S. Air Force Environmental and Technical Applications Center at Washington, D.C., to provide additional data below 850 mb and to fill in areas of sparse radiosonde reports between 20° S. and 30° N.

Because of diurnal variability and local effects, once-a-day reports from the operational rawinsonde network are not entirely adequate for the proper evaluation of the 1000-mb mean wind field. This situation was further aggravated by an almost complete lack of 1000-mb wind data over the U.S.S.R. and China in our data library. In order to partly overcome this data deficiency, the 1000-mb wind field north of 5° N. was derived from the $\bar{u}$ and $\bar{v}$ analyses of Crutcher et al. (1966). These analyses are based on both weather ship and merchant ship reports over the oceans and include a large amount of 3-hr data over land areas.

At 50 mb, we had no reports over Russia and China. In general, the analyses deteriorate markedly above 100 mb. Therefore, 50-mb data were not used in the energy calculations reported in section 6.

Table 4 gives a listing of the main data sources used in this study, together with additional pertinent information. The station distributions at 850 and 200 mb are shown in figure 20. It is clear that there are two major regions that are deficient in data. Both are located over the Pacific—one in the latitude belt 35°–50° N. between about 170° E. and 150° W.; the other in the Tropics between 150° W. and 90° W.

TABLE 4—*Main data sources*

(1) V. P. Starr (MIT)-TRC
Period: May 1958–April 1963
Time: 00 GMT
Type: radiosonde
Latitude: Equator–90° N.
Quality:

Level (mb)	Cutoff limit	Number of stations with more than 50 observations	Number of stations with more than 100 observations
1000	50*	180†	100
850	50	526	395
700	50	528	386
500	45	484	333
400	40	448	238
300	40	442	230
200	35	404	171
100	30	326	110
50	30	143	42

(2) J. W. Kidson and R. E. Newell (MIT)
Period: May 1958–April 1963
Time: variable
Type: radiosonde
Latitude: 25° S.–25° N.
Quality: over 40 stations in Tropics with cutoff limits as given under (1)

(3) USAF-ETAC
Period: variable (2 to 25 yr)
Time: variable
Type: primarily pibal, but a few rawins
Latitude: 20° S.–30° N.
Quality: about 150 stations used only at 1000, 950, 900, and 850 mb

(4) Crutcher et al. (1966)
Period: variable, back to 19th century
Time: analyses derived from data taken at various times. These include merchant ship observations over the oceans and 3-hr surface reports over land.
Type: 1000-mb monthly mean wind analyses of the Northern Hemisphere (used in our analyses north of 5° N.)

*The statistics are for the wind components in January. If for the 5 available January months a station had more than 50 wind reports at 1000 mb, it was included in the data sample, otherwise it was rejected.
†The 180 stations have more than 50 observations at 1000 mb.

ANALYSIS PROCEDURES

After various checking procedures (for example, hydrostatic checks), the raw radiosonde data were processed and stored on magnetic tape in the form of time mean and time variance-covariance matrices, such as

$$\begin{matrix} uu & uv & uT & uZ & uq \\ & vv & vT & vZ & vq \\ & & TT & TZ & Tq \\ & & & ZZ & Zq \\ & & & & qq. \end{matrix}$$

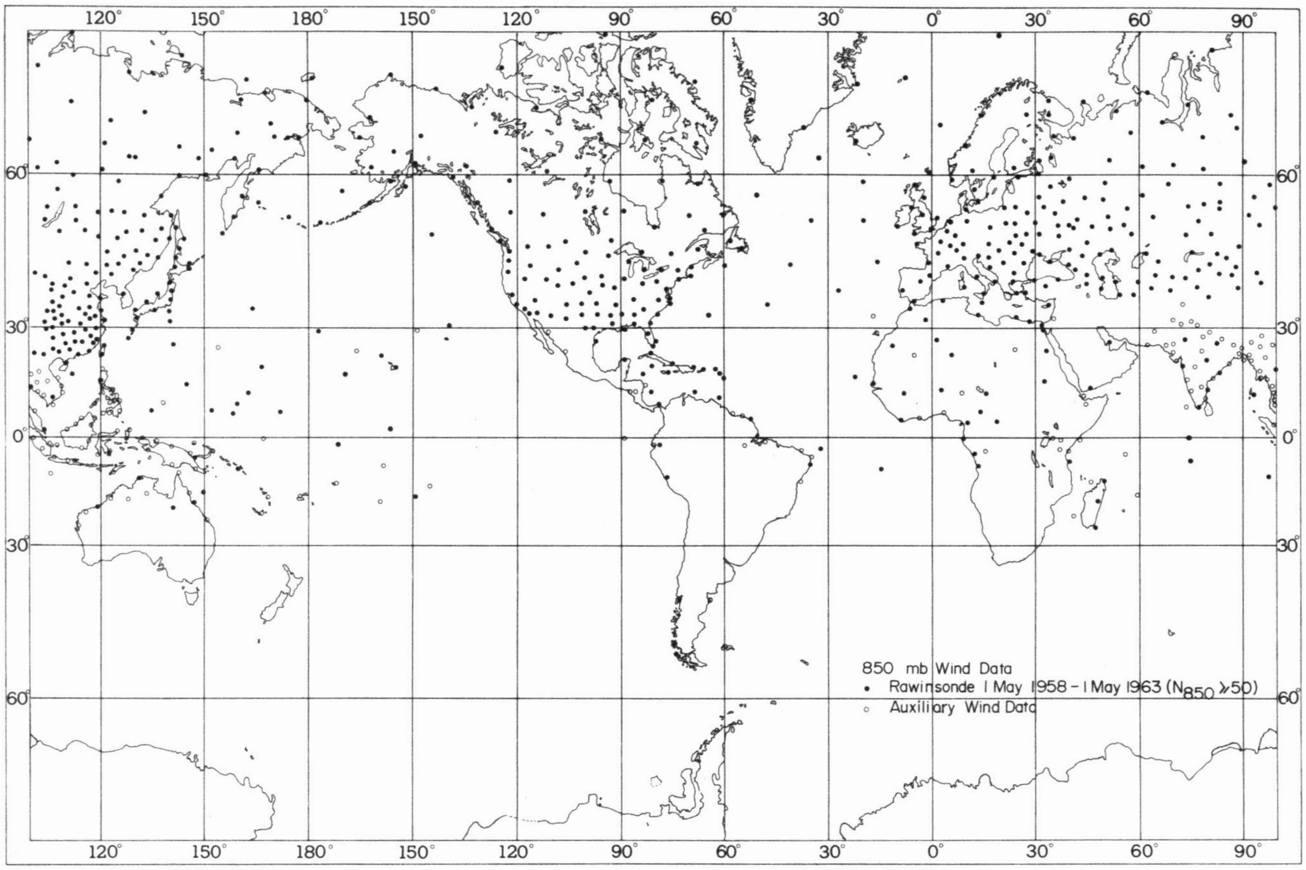
The tapes used in this study contain the parameters summed over 5 mo, that is, five Januaries, five Februaries, etc. In our opinion, the data are probably not quite adequate for individual monthly analyses. Therefore, we set as our goal the determination of the general circulation statistics for an average January, an average February, etc.

The processing of the data from sources (1) and (2) (table 4) was done by Messrs. Howard M. Frazier, Jim G. Welsh, and Ed R. Sweeton of TRC under contract from Prof. Starr at MIT. The Univac 1108 computer at the Geophysical Fluid Dynamics Laboratory, ESSA, was used for all calculations. Data from sources (3) and (4) were merged with the MIT data at the time of analysis.

We wrote an objective analysis procedure using the advanced computer language "ANAL68" developed by J. G. Welsh (Frazier et al. 1968) at TRC. The operators used in ANAL68 perform computations on two-dimensional arrays. Its effectiveness lies in the ability to formulate the analysis directly in terms of fields rather than for individual grid-point values. The maximum array allowed by the program and used by us consists of 47 by 51 points. The analyses were performed on a modified JNWP-grid, the grid distance being 1.5 times the JNWP-distance. The North Pole was located in the center of the grid and the y-axis along the Greenwich meridian. At the left and right sides, the analysis extended southward to 6° S., at the bottom and top to 11° S., and in the corners to 27° S. The grid was so oriented that those areas north of 15° S. that fell outside the grid contained practically no data. Thus, the effect of not including these areas in the analysis was minimized.

After an extensive period of testing, the following basic analysis scheme was adopted:

a) An initial guess field was constructed consisting of a smoothed zonal avarage of all data. The technique is very similar to that described by Eddy (1967).



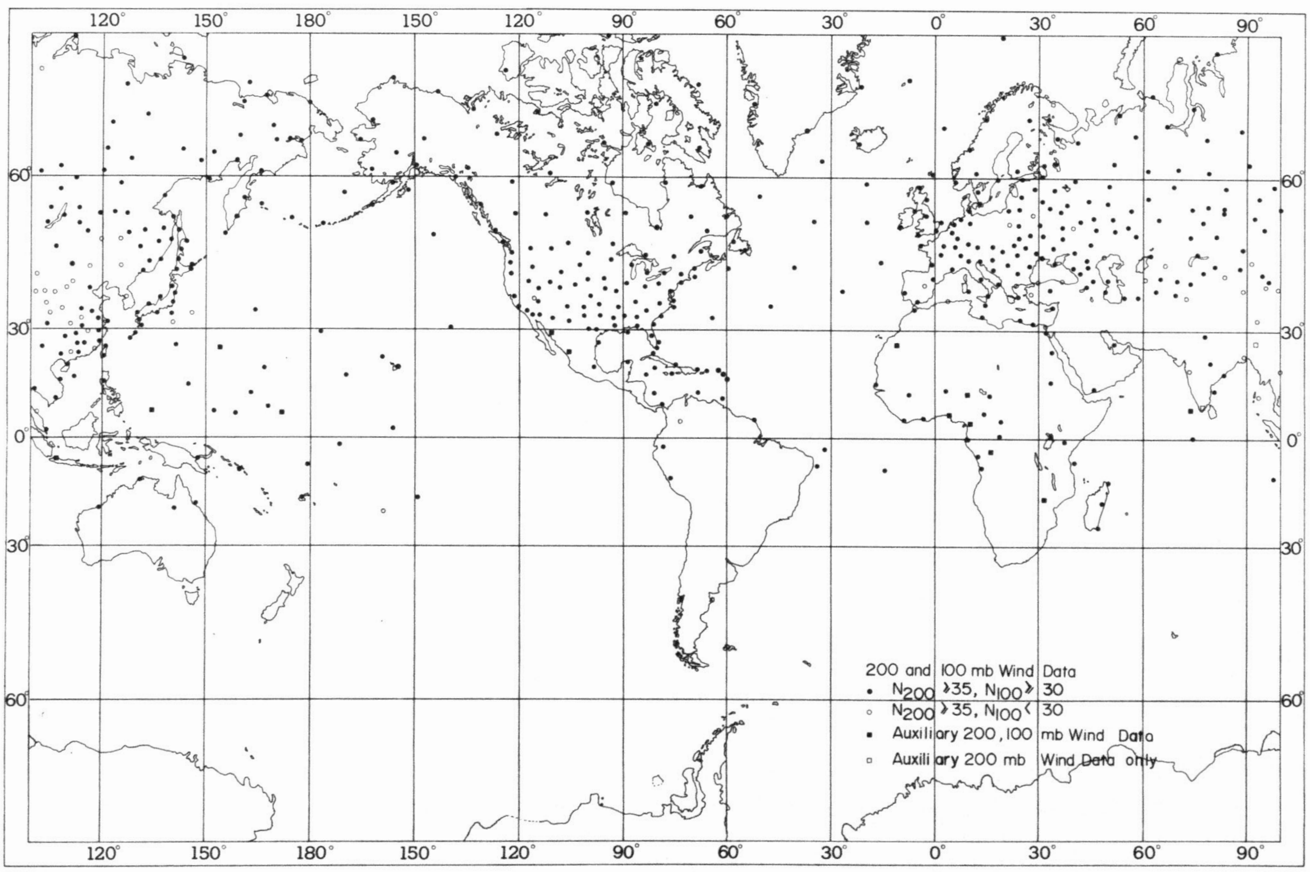


FIGURE 20.—Maps of the location of stations used for analysis at 850 and 200 mb. At 850 mb, the black dots indicate the main radiosonde stations from data sources (1) and (2) in table 4 in the appendix; the open circles give additional climatological stations from source (3). For 200 mb, the explanation is given on the map itself.

b) A new analysis was obtained by analyzing the difference between the actual data points and the zonally symmetric field and adding this to the symmetric field. If a data point deviated by more than a certain limit from a smoothed analysis, its value was printed out and checked for possible errors. Next the analysis was repeated.

c) For the $\bar{u}$- and $\bar{v}$-fields, the divergence was calculated; and if it was larger in absolute value than 5×10^{-6} sec^{-1}, the $\bar{u}$- and $\bar{v}$-analyses were adjusted. In general, these corrections were very small. The final analysis was visually checked for possible errors. A comparison of these objectively analyzed maps with hand-analyzed maps using the same data gave quite satisfactory results.

The zonal symmetric first-guess field described under step *a*) was generally found to be an improvement over a constant value first-guess field in that it tended to give the meteorological features an elongated east-west shape. This is of importance especially in areas of sparse data such as the southeastern part of the North Pacific. When using a constant value as first guess, we found that the analysis was influenced too much by data at higher latitudes. The anisotropy of the mean fields appears to be one of the major difficulties in using simple interpolation and extrapolation schemes.

As we have discussed before with regard to the height-longitude sections of $\bar{v}$, our analysis did not do too well at the higher levels in the central Pacific between Midway-Hawaii and the Aleutian Islands. In the case of the $\bar{v}$-field, step *a*) in the analysis does not offer much advantage, at least in middle latitudes where the zonally averaged $\bar{v}$-field is quite small compared to the zonal asymmetries.

We also tried to analyze by using the shape of the field at the lower level, thereby relating the analysis between levels. This, however, did not improve the analysis. Thus, we adopted the scheme discussed above where the analysis at each level depends only on the data at that particular level.

The different parameters were analyzed for the levels 1000, 850, 700, 500, 400, 300, 200, 100, and 50 mb in this way. At 950 and 900 mb, where the number of reports is considerably smaller than at the mandatory levels, the weighted average of the 1000- and 850-mb levels was used as a first-guess field.

At 1000 mb, the analyses published by Crutcher et al. (1966) were substituted north of 5° N., since our data sample does not include 1000-mb winds over Russia and China.

In our calculations, a *smoothed topography* was taken into account by zeroing out those areas on the map that were below terrain.

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