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MONTHLY MEAN VALUES AND SPATIAL DISTRIBUTION OF MERIDIONAL TRANSPORT OF SENSIBLE HEAT

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ABSTRACT

Monthly mean values of meridional transport of sensible heat by the atmosphere in the layer 850–500 mb. over the Northern Hemisphere poleward from the subtropics are analyzed for a period of 3½ years. The latitudinal values of this transport exhibit an annual cycle which is characterized by a rapid buildup from August to November and a slightly less rapid decline from February to June. Dissimilarities among the transport patterns for the same calendar months in different years are generally small; however, the month of December has marked variability. The longitudinal makeup of heat transport across latitude 45° N. in the cold season is dominated by three contributing regions which are associated with two of the three major waves observed in monthly mean flow patterns. The most sharply defined region of contribution to the heat transport across latitude 45° N. is associated with cold air moving southward to the rear of the trough line along the east coast of Asia. At 60° N., however, pronounced heat transport zones are generally absent except for the occasional appearance of a maximum over the eastern Atlantic and western Europe.

1. INTRODUCTION

There is a poleward flux of energy in the earth's atmosphere and oceans associated with the differential radiational heating between the equator and the poles. From the general physical energy equation and the equation of motion, Starr [15] showed that this energy is transported mainly in the form of sensible heat, latent heat, potential energy, and energy within the oceans.

An examination of the relative magnitudes of each of these quantities indicates that the sensible heat term represents the most important heat transport mechanism at almost all latitudes. Calculations of oceanic heat transport by Sverdrup [17] show that the oceanic contribution is about one-third as large as the sensible heat transport in the atmosphere. Computations by Benton and Estoque [1] and others show that the heat transferred by the flux of latent energy is about the same magnitude as the oceanic transport, 25 to 35 percent of the measured atmospheric sensible heat transport. Computations by Mintz [9] indicate that the geopotential term may be as significant as the atmospheric sensible heat term in low latitudes. Poleward of 25° N. the geopotential term is normally quite small when compared to the transport of sensible heat. A more detailed discussion of the comparative magnitudes of these different quantities has been presented by Jung [5].

Since the atmospheric meridional flux of sensible heat is the most important variable in the large-scale poleward transport of energy, it is important to know more about its temporal and spatial variations. Heat transport has direct significance in energy conversions, specifically the conversion of zonal available potential energy into eddy available potential energy as defined by Lorenz [7] and others. As greater amounts of radiation data are obtained from satellite measurements it will be important to know how the heat transport and energy conversions react to variations in the differential heating between high and low latitudes. For instance, as pointed out by Winston [19], it will be of interest to determine just how far down the time scale the relationship between poleward heat transport and differential radiation between high and low latitudes is maintained (e.g., seasons, months, or even shorter periods).

Many investigations of the meridional transport of sensible heat by the atmosphere have been made in the past, notably by White [18], Lorenz [8], Starr and White [16], Mintz [9], Pisharoty [14], and Peixoto [13]. Except for the work of Starr and White, and Peixoto, these studies were confined to rather short time intervals, usually one to four months. Also most investigators concerned themselves only with latitudinal aspects of sensible heat transport and ignored the longitudinal variations. This paper gives a summary of sensible heat transport data, computed geostrophically, for the layer 850–500 mb. in the period October 1958 to March 1962. It presents not only latitudinal data, but also examines the longitudinal variations at 45° and 60° N. These data, therefore, may provide a good approximation to a climatic distribution of this variable.

2. LATITUDINAL CONTRIBUTIONS TO POLEWARD TRANSPORT OF SENSIBLE HEAT

COMPUTATIONAL METHOD

The northward transport of sensible heat, H, across a given latitude circle, ϕ_0 between two constant pressure surfaces, p_1 and p_2, may be expressed as follows:

$$H=\frac{c_p a \cos \phi_0}{g}\int_{p_1}^{p_2}\int_0^{2\pi} vTd\lambda dp, \qquad (1)$$

where a is the radius of the earth, c_p is the specific heat at constant pressure, g is the acceleration of gravity, v is the meridional wind component, T is the temperature and λ is longitude. The longitudinal integral may be approximated by a sum of the product of v and T taken at intervals of 5° of longitude, around the latitude circle. The pressure integral may be approximated by using mean values of v and T in the layer to form the product. With these approximations the heat transport in a given layer between p_1 (top) and p_2 (bottom) is evaluated as follows:

$$H=\frac{c_p a \cos \phi_0 (p_2-p_1)\Delta\lambda}{g}(\Sigma vT), \qquad (2)$$

where the summation is for 72 intervals of $\Delta\lambda$ equal to 5° of longitude, around the latitude circle, and v and T are now average values in the layer. The mean temperature, T, is derived from the thickness between p_1 and p_2. Furthermore, the geostrophic approximation is used to obtain v, so that v is a function of the difference over an interval of 5° of longitude of the average heights of p_1 and p_2.

The use of the geostrophic wind automatically eliminates the possibility of measuring transport associated with meridional cells. Also, even if there were no mean meridional motions, the neglect of the ageostrophic component of the wind could be serious, but probably mainly at lower latitudes. The findings of Jordan [3, 4] indicate, however, that the geostrophic approximation is substantially valid at least as far equatorward as latitude 20°, particularly above the surface layers.

To compute the total transport across a latitude circle, equation (2) would have to be evaluated for a whole series of layers between the surface (or approximately 1000 mb.) and the top of the atmosphere. A program has been coded for electronic computation by means of equation (2) of northward heat transport at every 5° latitude circle northward from 20° N. for a layer between any two designated standard constant pressure surfaces. Furthermore this machine program has been designed to accept objectively-analyzed height data which are available in the National Meteorological Center (NMC) so that the computations are automated to the fullest extent. In these calculations the heights at the grid points in the NMC octagonal grid must first be interpolated to yield heights at standard latitude-longitude intersections. Since objective analyses by NMC for levels other than 850 and 500 mb. were not available until January 1961, fully automatic calculations of heat transport for the entire period since October 1958 have been feasible only for the layer 850–500 mb. However, as some test calculations showed (Winston [19]), the heat transport in the layer 850–500 mb. provides on the average a rather good representation of the transport throughout the entire troposphere.

Heat transport values were computed once a day from 850-mb. and 500-mb. height data for 0000 GMT. All values presented in this paper are for monthly or seasonal periods which have been obtained by simple averaging of these daily values.

In August 1961 NMC made a change in their objective analysis procedure which has some effect on the heat transport values presented in this paper. This change was toward less smoothing in the analysis of the height fields, and it increased to some extent the smaller-scale components of the flow, particularly in areas of sparser data. (In regions of dense data coverage the particular smoothing procedure formerly in use did not have much influence on the final height analysis.)

To determine how much this change in the smoothing procedure might affect the computed heat transport values, 850-mb. and 500-mb. height fields were obtained by both old and new analysis methods and the transports were computed from each for a sample of eight days in March and April 1962. It was found that the transport values computed by the newer procedure (using less smoothing) were generally larger by from 4 to 9 percent between 30° N. and 70° N. Practically no change was found at 20°–25° N. and changes of 10–15 percent were found at 75°–80° N. However, there is evidence that this difference varies with synoptic flow patterns as well as latitude so that these differences might not be representative of other months of the year or the same months of other years. Thus because a more extensive comparison (which in machine time is very expensive to obtain) was lacking, it was decided to make *no* adjustments in the

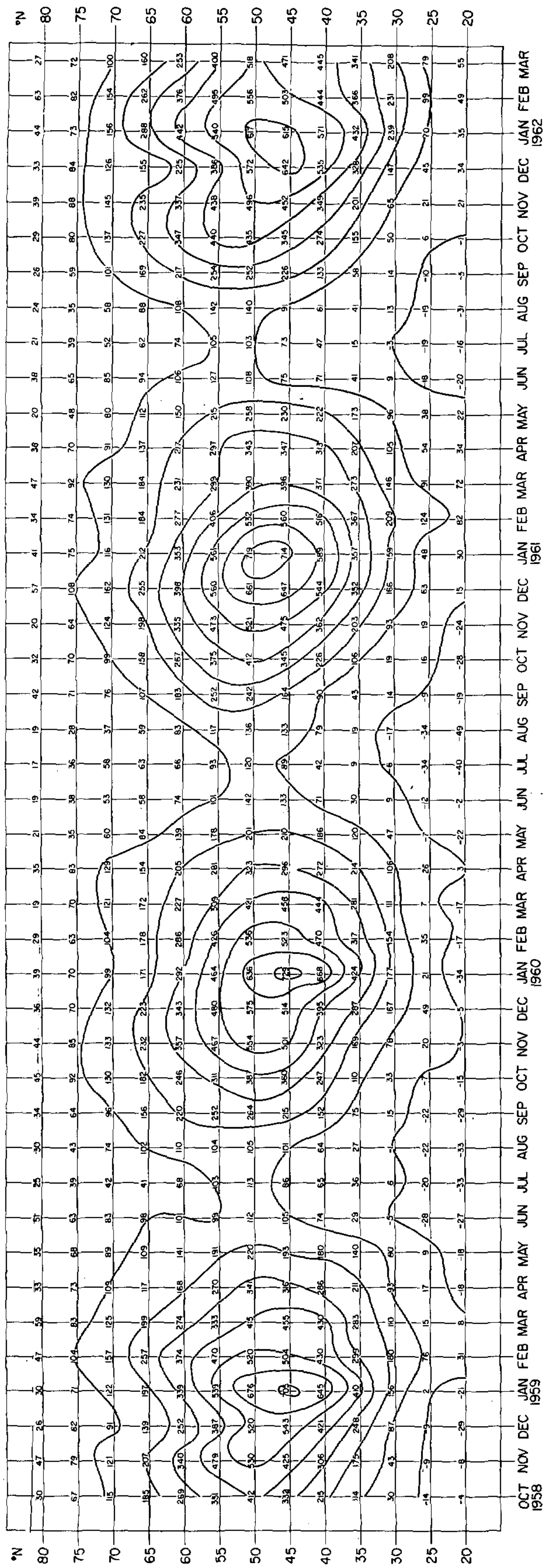

FIGURE 1.—Time-latitude chart of monthly mean values of poleward transport of sensible heat in the layer 850–500 mb. for the period October 1958–March 1962. Units are 10^{12} cal. sec.$^{-1}$

data prior to August 1961. It should be borne in mind, however, in utilizing these data for comparative purposes that most of the values prior to August 1961 are probably at least 5 percent larger than shown, on the presumption that the newer analysis method is more nearly correct.

TEMPORAL AND LATITUDINAL VARIATIONS OF THE NORTHWARD HEAT TRANSPORT

Latitudinal values of the 850–500-mb. meridional sensible heat transport for the entire period, October 1958 to March 1962, are given in figure 1. The most prominent feature of this diagram is the annual cycle, with large amounts of transport at middle latitudes in the colder portion of the year and relatively small amounts in summer. The maximum values for the year generally occur in January between latitudes 45° and 50° N. (In 1961–62, however, the highest value occurred in December at 45° N.) The latitudinal maximum of heat transport varies over only a limited range of latitudes (about 45°–55° N.) throughout the year, tending to be farther north in summer and fall. In terms of the annual variation of heat transport at each latitude circle there seems to be some tendency for the maximum to be reached in late autumn or early winter north of 50° N. and in late winter south of 40° N., but exceptions to this are quite apparent. For example, in 1958–59 at higher latitudes the major annual maximum occurred in February, but there was a secondary maximum in late autumn and a relative minimum in December. Incidentally it should be mentioned that the annual course of heat transport in general bears some resemblance to the annual course of monthly mean zonal wind speed at 700 mb. (Klein [6]), but the axis of maximum westerlies throughout the year is located on the average about 5°–10° of latitude south of the axis of maximum heat transport. Thus maximum heat transport takes place generally on the north (or cyclonic shear) side of the strongest westerlies as might be expected from the general location of major cyclonic activity to the north of the jet as shown also by Klein [6].

The annual course of heat transport and some year-to-year differences in the various months are highlighted in figure 2 where the monthly mean heat transport values averaged for all latitudes (20° N.–80° N.) for each of the years are shown. The strong annual trend in the transport is, of course, very evident, and the differences between average values in adjoining months from August to November and from January to June are generally larger than any inter-annual difference between the same months. However, some months do exhibit a moderate variability from one year to another. December is most striking in this respect, since in December 1960 the heat transport was about the same as the January 1961 value while in December 1958 it was as low as the November 1958 value. The other two Decembers were in between, but generally closer to the preceding November values than to the following January values.

This greater variability of heat transport in December as compared with other months raises some questions as to why this should be so and as to what significance it has relative to the overall heat transport and other features

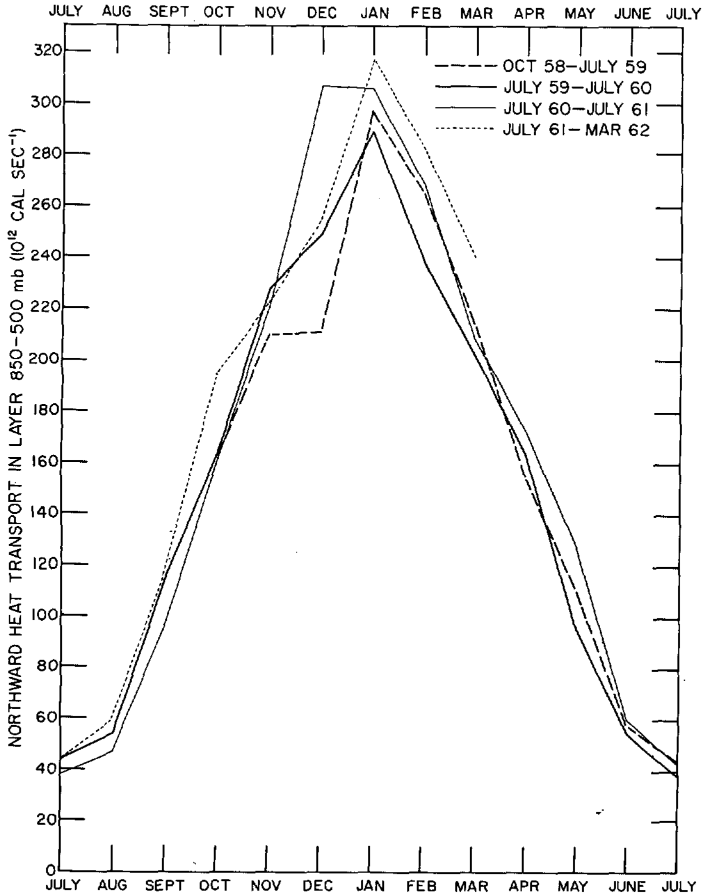

FIGURE 2.—Annual course of poleward transport of sensible heat in the layer 850–500 mb. for four different periods, October 1958–March 1962.

of the general circulation and its energetics. Despite the fact that our heat transport values represent perhaps the largest sample yet computed, it is still much too small to make any firm conclusions about year-to-year variations and it is probably unwise to assume that December is especially unique in variability of heat transport.

Nevertheless it is of interest to note that the very high value of transport in December 1960 was preceded by seven consecutive months (May–November 1960) in each of which the heat transport was lower than for the corresponding month in the preceding year. (Values for January–March 1960 were also lower than those of the previous year.) In fact the net cumulative monthly deficit in heat transport from May through November 1960, as compared with May–November 1959, totaled 59×10^{12} cal. sec.$^{-1}$, while the December 1960 transport was 58×10^{12} cal. sec.$^{-1}$ higher than the December 1959 value. This rapid balancing of the previous seven months' deficit of heat transport which was effected during December 1960 leads to speculation as to whether the cumulative effects of low heat transport over a long period such as this would essentially be responsible for a sudden surge in heat transport. Certainly a smaller amount of heat transport should lead to greater than normal north-south thermal gradients (providing the north-south differential heating remained relatively unchanged). This was indeed the case during these months since values of the zonal available potential energy, which is a function of the variance of latitudinal mean temperatures, were also higher than the preceding year during this same period of May–November 1960. Then in December 1960 the zonal available potential energy dropped to very low values as the strong heat transport acted to decrease sharply the north-south thermal gradient. Thus the long-period deficit in heat transport was reflected in an increased north-south thermal gradient which undoubtedly led to a large-scale dynamic instability in the westerlies. An inspection of the monthly mean flow patterns of November and December 1960 (O'Connor [12] and Gelhard [2]) suggests that a huge breakdown of strong zonal flow in November into a very large amplitude wave pattern over the area from the central Pacific eastward through the Atlantic in December occurred quite suddenly. In fact the circulation breakdown was so drastic that there was virtually no continuity in locations of centers of height anomaly, an occurrence which is not usual in month-to-month flow changes (Namias [10]).

Further comparison among the heat transport amounts for the four Decembers is afforded in figure 3, where the latitudinal profiles of transport for each of the months can be examined more readily than in figure 1. Note that December 1960 has greater transport values than the other Decembers at all latitude circles but a few subtropical ones. However, from 45° N. southward the December 1960 profile is virtually identical with (although consistently slightly greater than) the profile for December 1961. The latter, however, shows considerably lower transport values than the former at all latitudes northward of 45° N. At the higher latitudes the December 1959 values most closely approach those of December 1960.

Despite the differences among the heat transport values of these four Decembers their latitudinal profiles all bear a strong resemblance and the slopes of the curves are generally quite similar at lower and higher latitudes. Thus the overall patterns of the convergence of heat transport (fig. 4), as derived from the distributions in figure 3, have the common characteristics of considerable convergence north of about 52° N. and sizable divergence south of about 47° N. There are nevertheless moderate variations among the four Decembers at specific latitudes in several instances. For example, through the mid-latitude zone of rapid transition the values for December 1961 are as much as 0.9° C. day^{-1} greater than those for December 1959. On the other hand, between 65° and 70° N. the values for December 1959 are 0.8° C. day^{-1} larger than the December 1961 values. These differences may represent significant yearly latitudinal changes in heat flux convergence for the month of December. Expressed in heating units, the heat flux convergence in December 1960 and 1961 near 60° N. reached values as high as 120 ly. day^{-1}. For a steady state these large convergences must be compensated partially, of course,

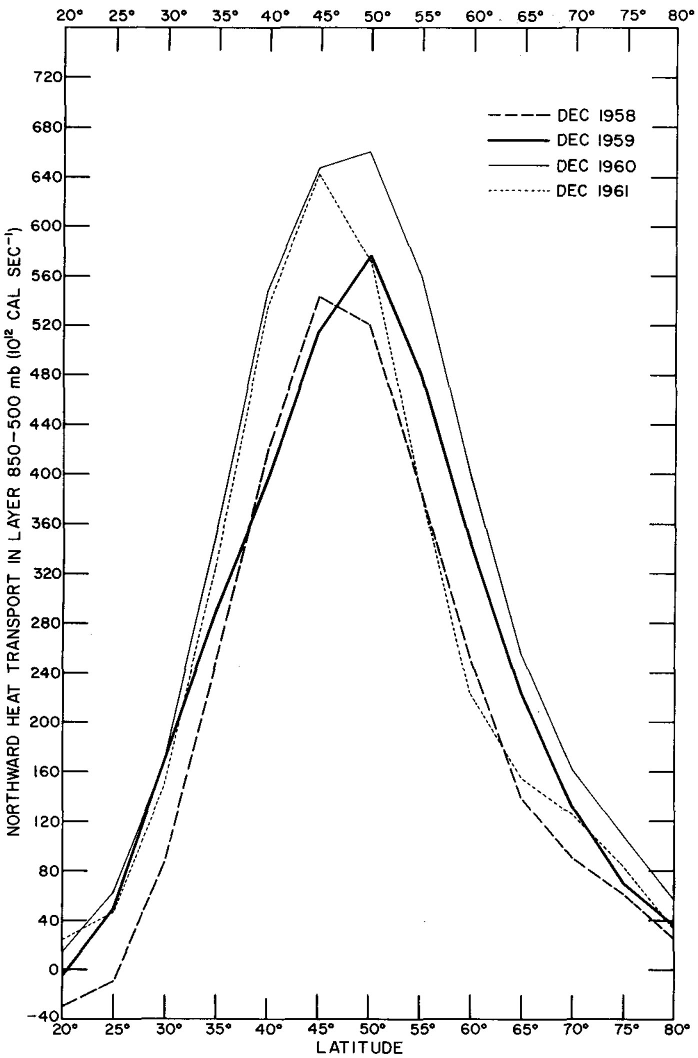

FIGURE 3.—Latitudinal distributions of poleward sensible heat transport in the layer 850–500 mb. for four consecutive Decembers, 1958–61.

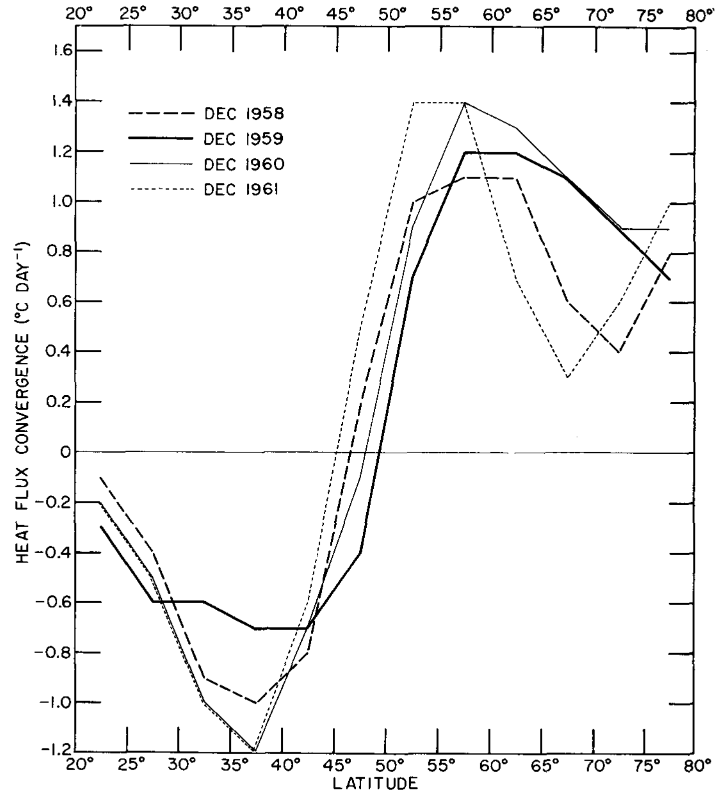

FIGURE 4.—Latitudinal distributions of poleward sensible heat flux convergence for four consecutive Decembers, 1958–61. Convergence is expressed in terms of the temperature change (positive for convergence, negative for divergence) that would occur in each 5° latitude belt if heat flux convergence alone were operating.

by adiabatic cooling due to a mean upward motion, but also largely by infrared cooling.

Examination of the latitudinal distribution of heat transport over the entire cold seasons (October–March) of the four years (fig. 5) indicates that year-to-year variations are observable at all latitudes, but the latitudinal profiles for each year agree very well, and in each season the maximum transport is found in the vicinity of 45°–50° N. However, it is apparent that the 1960–61 cold season had more total northward transport at all latitudes than either of the preceding two winter seasons. These higher transport amounts are to a great degree due to the very high values recorded during December 1960. During the 1961–62 winter season there was greater transport at high and low latitudes than in previous seasons. On the other hand the heat transport at middle latitudes during this period was less than it was during the 1960–61 season. The high values at most latitudes during 1961–62 were a reflection of the fact that four of the six months, when averaged over all latitudes, showed the greatest heat transport amounts if one compares them to the same months in other years. Most of this may be the result of the changes in the objective analysis procedure which was discussed in the section on computational methods.

A comparison of these four years of cold season data with other published heat transport values is given in table 1. Values for 1010–200 mb. were computed from day-to-day calculations of sensible heat flux made by Pisharoty [14]. The 700–500-mb. and 1013–700-mb. heat transport data were evaluated by White [18] and later recomputed by Lorenz [8] using a different computational procedure. Lorenz's data are used in the table, although taken as a whole the two sets of figures differ only slightly. The White-Lorenz studies were done at four latitudes, 35°, 45°, 55°, and 65° N. Therefore, in order to make other values comparable, Pisharoty's and our data were tabulated for these same four latitudes. Although these three studies are for different years, the general trends of the values are in good agreement. With the exception of the 1013–700-mb. layer, the sensible heat transport increases in all instances until January and then decreases. The difference in the monthly variation of heat transport in the 1013–700-mb. layer may be a true anomaly or may be due to a fictitious computational component introduced because of the irregularities of the earth's surface and the use of artificially reduced sea level pressures. An exten-

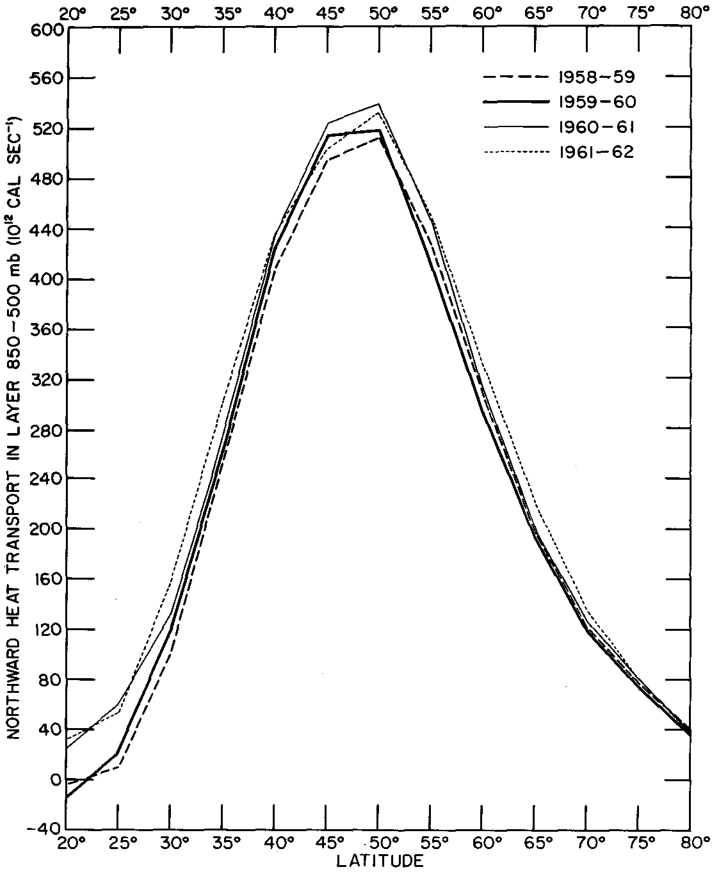

FIGURE 5.—Latitudinal distributions of poleward sensible heat transport in the layer 850–500 mb. for four consecutive cold seasons (October–March)

sive comparison of the figures in table 1 is probably not justified, however, because the studies were done for different years as well as different pressure surfaces and consequently are difficult to adjust.

3. LONGITUDINAL CONTRIBUTIONS TO POLEWARD TRANSPORT OF SENSIBLE HEAT

COMPUTATIONAL METHOD

An analysis of variables v and T in equation (2) in terms of mean values for a latitude circle and deviations may be written as:

$$v=[v]+v^* \text{ and } T=[T]+T^*,$$

where [ ] represents an average value over a latitude circle and * indicates a deviation from this latitudinal mean. If these expressions for v and T are substituted in equation (2), recognizing that $[v]$ is identically zero for geostrophic flow and that the summation of the product of a constant times a deviation from the mean is also zero, then the heat transport across an entire latitude circle can be expressed as follows:

$$H=\frac{c_p a \cos\phi_0(p_2-p_1)\Delta\lambda}{g}\sum v^*T^*, \quad (3)$$

TABLE 1.—*A comparison of monthly mean sensible heat transport calculated in three different studies. All values are averages over four latitude circles, 35°, 45°, 55°, and 65° N. Units are 10^{12} cal. sec.$^{-1}$*

	Present study 850–500 mb.				White [18]-Lorenz [8] 1013–700 mb. 700–500 mb. 1945–46		Pisharoty [14] 1010–200 mb. 1949
	1958–59	1959–60	1960–61	1961–62			
October	246	241	246	292			
November	322	342	337	332	289	131	
December	329	376	454	368	498	146	
January	463	447	461	469	422	158	928
February	383	361	379	407	489	119	803
March	318	305	288	343			

where the summation is again for 72 intervals of $\Delta\lambda$ or 5° of longitude around the latitude circle. Thus there is a net northward transport across a latitude circle only if there is a positive covariance of meridional flow and temperature.

Positive contributions toward the total northward heat transport across a latitude circle occur at each longitude where the temperature is above the latitudinal average in southerly flow and where the temperature is below the latitudinal average in northerly flow. The other combinations, southerly flow with below-average temperatures and northerly with above-average temperatures, contribute negatively to the net northward heat transport across the latitude circle. In view of the dependence of the net poleward heat transport for each latitude circle on this single term, it was decided to compute and analyze v^*T^* for each 5° longitudinal interval along each latitude circle. This calculation is part of the machine program for heat transport calculations mentioned earlier. It is made once a day using the NMC 850-mb. and 500-mb. height data for 0000 GMT. The monthly mean values presented here were obtained by averaging the daily values for each 5° longitude at latitude 45° N. and also at 60° N.

LONGITUDINAL TRANSPORT VARIATIONS AT LATITUDE 45° N.

A time-longitude chart of the average monthly contributions in each 5° longitude zone to the northward heat transport across latitude 45° N. from October 1958 to March 1962 is given in figure 6. A well-marked annual variation with pronounced longitudinal maxima and minima is readily apparent. In the early part of each fall season the longitudinal transport contributions increase rather abruptly in certain preferred longitudinal zones and continue to increase until the highest values are reached in the winter season. There are marked decreases in early spring, and by late spring there are relatively few high transport maxima around the latitude circle.

During the colder portion of the year there are roughly three longitudinal zones in which the bulk of the contributions to the northward heat transport across latitude 45° N. occur. These are eastern Asia (90° E.–150° E.), the central and eastern Pacific (170° E.–130° W.), and eastern North America and the Atlantic (90° W.–20° W.). This is summarized for each of the four cold seasons (October–March) by the graphs of average seasonal values

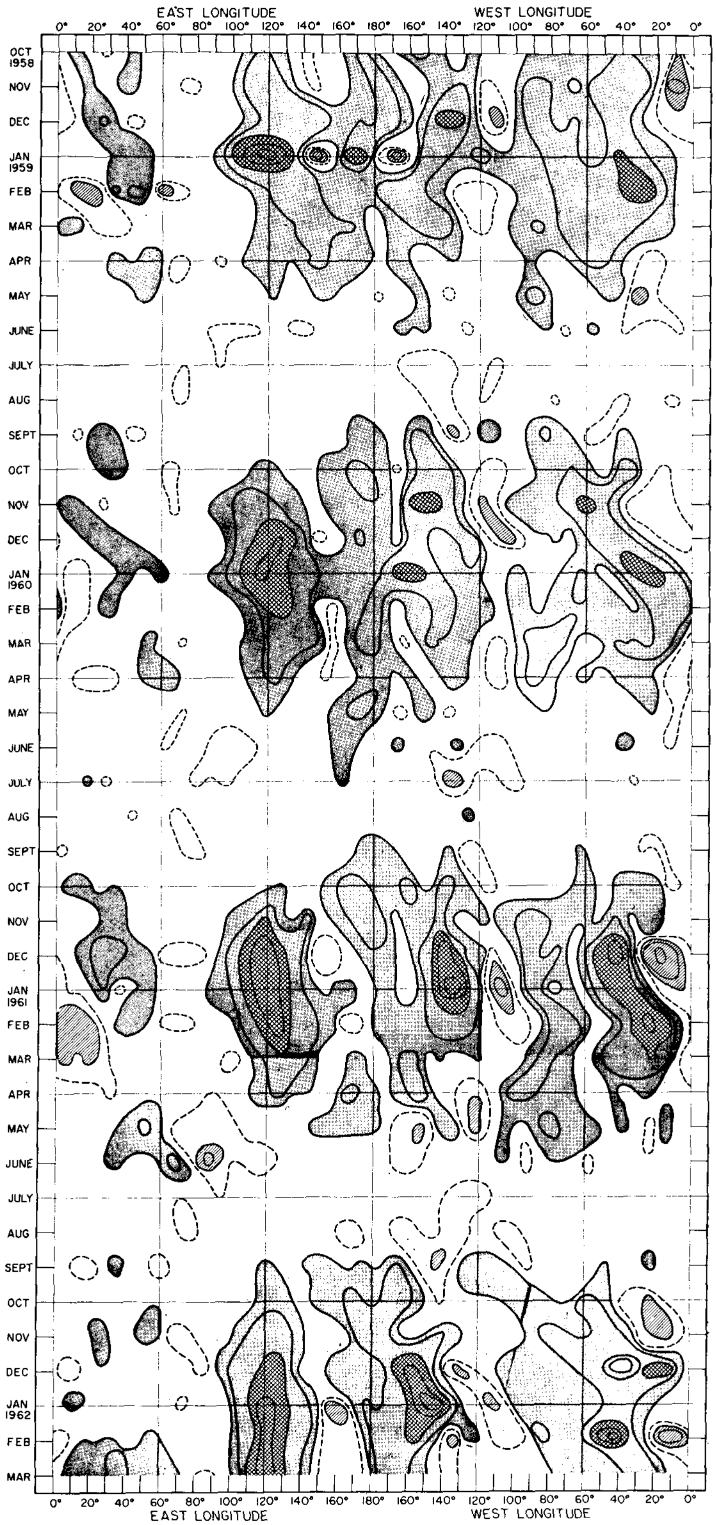

FIGURE 6.—Time-longitude chart of monthly mean contributions in each 5° longitude zone to the net poleward transport of sensible heat across latitude 45° N., October 1958–March 1962. Isopleths are drawn at intervals of 100×10^{11} cal. sec.$^{-1}$ with the $\pm 50\times10^{11}$ lines also included. Zero lines are dashed. Areas of positive values between 50 and 200 units are in smooth stippling. Areas in excess of 200 are cross-hatched. Areas of values more negative than −50 units are hatched.

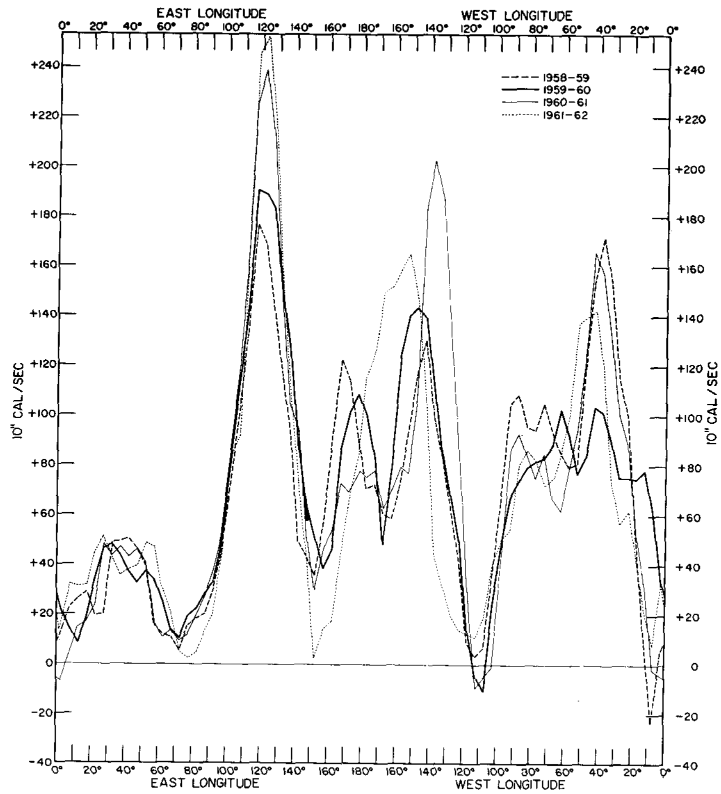

FIGURE 7.—Averages for four consecutive cold seasons (October–March) of contributions in each 5° longitude zone to poleward sensible heat transport across latitude 45° N.

in figure 7. Although there is a tendency toward another maximum over eastern Europe and western Asia (10° E.–50° E.) it is much weaker than the others and generally the European to central Asian sector contributes little to the heat transport across latitude 45° N.

From both figures 6 and 7 it is apparent that the eastern Asia maximum is rather narrowly confined longitudinally and exhibits the sharpest peak values (near 120° E.) most consistently. Note that this maximum remains closely anchored longitudinally throughout the cold season in each of the years (fig. 6). Generally the maximum in the eastern Pacific also shows only slightly more month-to-month longitudinal motion. On the other hand the eastern North America-Atlantic sector more often exhibits a tendency toward a gradual eastward shift across the Atlantic over a period of 3 to 4 months.

These zones of pronounced contribution to the heat transport across latitude 45° N. and their persistence and continuity from month to month are closely related to the locations and strength of the large-scale monthly mean wave patterns. This is illustrated by the time-longitude chart of monthly mean geostrophic meridional 700-mb. wind speed (fig. 8) which shows a predominance of about three major waves around latitude 45° N., particularly in the colder portion of the year. Comparison of figures 6 and 8 shows that basically only two of these major waves are connected with the major contributions to northward heat transport across latitude 45° N. The northerly flow to the rear of the trough line in the western Pacific and the southerly flow to the rear of the ridge over western North America are associated with the first two zones of

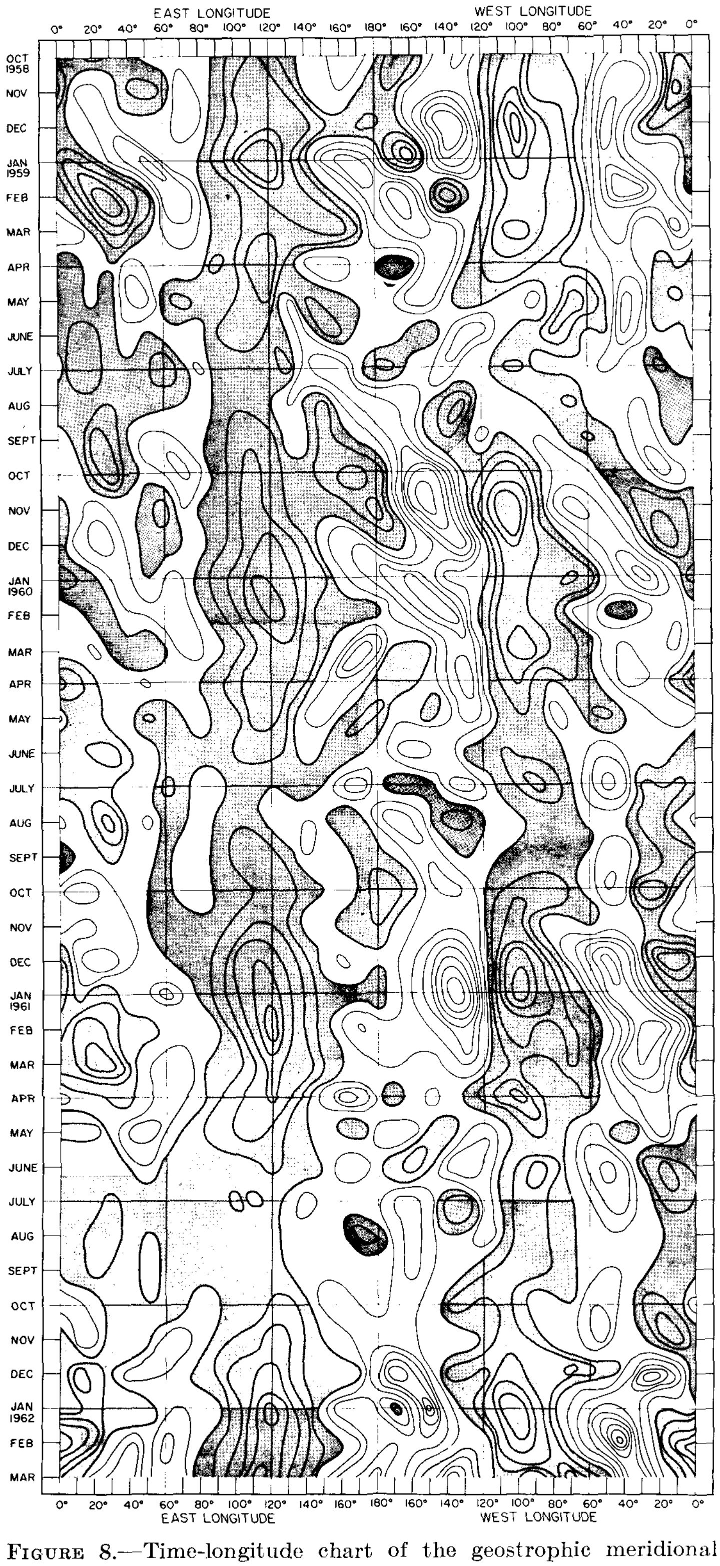

FIGURE 8.—Time-longitude chart of the geostrophic meridional wind at 700 mb. for each 10° longitude along latitude 45° N. derived from monthly mean 700-mb. height data obtained from the Extended Forecast Branch, U.S. Weather Bureau. Isopleths of wind speed are drawn at height gradient intervals of 5 ft./deg. long. (about 3.6 kt.). Areas of northerly flow are stippled, and areas of southerly flow are unshaded.

sizable transport contributions. Thus the eastern Asia maximum is associated with northerly components of flow of cold air from the Asian continent, while the high values in the central and eastern Pacific are the result of southerly flow of warm Pacific air.

The zone of strong transport contributions over the Atlantic occurs in the southerly winds ahead of the trough near the east coast of North America. Generally there is also a sizable contribution in the eastern portion of the northerly flow (i.e., the portion closest to the trough line) in eastern North America, but this is certainly not as striking as the strong maximum over eastern Asia. One sees that the eastward motions of the heat transport maxima in the North America-Atlantic region are connected with the eastward motions of this trough over eastern North America.

It is interesting that the strongest components of northerly flow over western and central North America, (i.e., the portion closest to the ridge line over western North America) are usually associated with a minimum (sometimes even negative) of contributions to the latitudinal heat transport. This is also generally the case when strong northerly flow is found over the eastern Atlantic and Europe. In these cases the air moving southward to the east of a well defined ridge is relatively warm. Another area of minimum contributions is found in the southerly flow immediately east of the eastern Asia trough, where obviously the air moving northward close to this trough line is of recent continental origin and is relatively cold. Many of these features were also evident in the time-longitude charts of heat transport and meridional flow on a daily basis presented by Winston [19].

Some striking differences among the longitudinal contributions to heat transport in the cold season are apparent in figure 6. For example, over eastern Asia in 1958–59 the values were relatively weak through December, then increased abruptly in January and then just as abruptly weakened in February. In each of the other three cold seasons the values built up more rapidly in the fall and remained at rather sustained high values throughout the winter before falling off again in the spring. Figure 8 indicates that the northerly wind flow components over this region correspond rather closely with these transport variations.

In the two cold seasons of 1960–61 and 1961–62 the longitudinal transport values over the eastern Pacific and the Atlantic similarly showed more rapid buildups in the fall and more sustained high values through the winter than in the two earlier winters. During the last two winter seasons the high transport contributions were concentrated in narrower longitudinal zones and were offset by stronger minima. Thus the values for the total heat transport across latitude 45° N. in these four cold seasons showed a range of less than 10 percent (fig. 5). However, as pointed out earlier in this paper, some months, particularly December, exhibited marked variations in total latitudinal transport (figs. 2 and 3) and these differences are mainly accounted for by variations in the three zones of major longitudinal contributions to the northward transport.

In order to get a better idea of the spatial transport arrangement at 45° N. during periods of very intense heat transport, we made the following study. The transport values for twenty selected winter-season days having high values were averaged at each 5° of longitude around the latitude circle. The resultant transport pattern looked very much like that in figure 7 with two exceptions. The amplitude of the maximum at 120° E. was damped somewhat and the eastern Pacific high transport area had only one peak, extremely strong, centered at about 140° W. Similar averages were also made on 20 selected winter days of fairly low heat transport. This time the spatial pattern showed only one major maximum region, the area of the eastern Asian coast, with a peak centered at about 120° E. These rather interesting results suggest that frequently throughout the winter season the amount of heat transported in the western Pacific shows relatively small variance from day to day. Consequently periods of high heat transport at middle latitudes apparently depend largely upon the prevailing synoptic conditions over the eastern Pacific and to a lesser extent, over the Atlantic

These same types of longitudinal transport patterns undoubtedly exist at other middle latitudes such as 40° and 50° N. and, therefore, have not been investigated. Data at two other latitudes, 60° N. and 30° N. are being examined even though the total (geostrophic) transport at each of these latitude circles is considerably less than in middle latitudes (fig. 5). At this writing, analysis of monthly mean longitudinal values at 30° N. has not been completed, but the data at 60° N. have been examined to some degree. In general the sharp peaks of heat transport contributions at various longitudes which are so evident at 45° N. are lacking at 60° N. However there are times when very high longitudinal peaks of transport do occur at 60° N. This is illustrated in figure 9 where the distributions for the three winter months of 1958–59 are given. Note the sharp peak of northward heat transport contribution near 20° W. in February. During this period blocking action, associated with a prominent high pressure cell at 700 mb. which averaged 500 ft. above normal for the month, persisted over western Europe (O'Connor [11]). Strong southerly flow in the eastern North Atlantic brought warm, maritime air into high latitudes and produced intense heat transport and warming in this near-Arctic region. Consequently, in this area the heat transport contribution during February was more pronounced at 60° N. than it was at 45° N.

An examination of 60° N. data during other years indicates that when there is a period of intense transport along this latitude circle, it usually occurs within this region. Therefore, the amount of heat advected into the Arctic region appears to depend strongly upon the state of the circulation over the eastern Atlantic and western Europe.

4. SUMMARY AND CONCLUSION

The annual cycle of meridional transport of sensible heat by the atmosphere in the Northern Hemisphere has been delineated clearly by the 3½ years of heat transport data presented in this paper. In middle latitudes this cycle is characterized by a rapid buildup from August to November, peak values generally in January, a decline from February to June which is somewhat less rapid than the fall buildup, and lowest values in July. Differences among the transport totals for the same calendar months in different years of this period are generally small, except for the month of December when the heat transport values exhibit marked variability as compared with the other months. Examination of the very high values in December 1960 (relative to the other Decembers) leads to some interesting speculation about the influence of a cumulative deficit of heat transport, which had developed over several consecutive preceding months, in forcing this large-scale heat transport through the abnormal buildup of large-scale dynamic instability in the planetary flow.

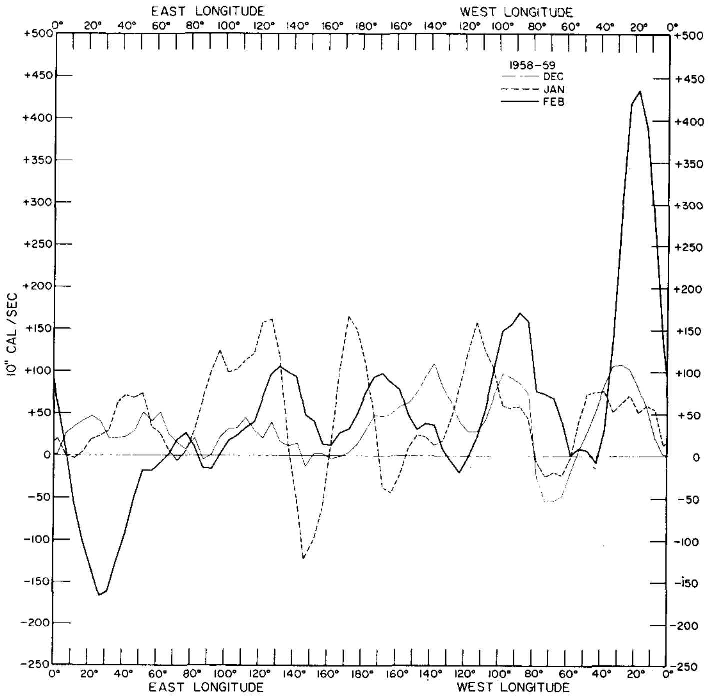

FIGURE 9.—Monthly mean contributions in each 5° longitude zone to poleward sensible heat transport across latitude 60° N. in the winter of 1958–59.

The latitudinal distribution of heat transport shows a strong maximum at latitudes 45°–50° N. in the cold season with maximum heat flux convergence in latitudes 55°–65° N. and maximum divergence concentrated in latitudes 30°–40° N.

Longitudinally there are generally three main regions making major contributions to the northward heat transport across latitude 45° N. These three regions are mainly associated with just two of the three major waves observed in monthly mean flow patterns. The best defined region of strong contribution to the poleward heat transport occurs to the rear of the trough line along the east coast of Asia where air colder than the latitudinal average moves southward. The other two longitudinal zones of large amplitude are not as firmly anchored as the eastern Asia zone, but are generally found over the central and eastern Pacific and over eastern North America and the Atlantic. The eastern Pacific zone is associated with warm air flowing northward on the west side of the semipermanent ridge line over western North America. The eastern North America-Atlantic zone results primarily from warm air flowing northward to the rear of a ridge over the Atlantic with some contribution on the western edge of this zone from the southward flow of cold air to the rear of the trough along the east coast of North America. This pattern does not hold at 60° N., however, where there are usually no pronounced areas of strong transport. But in some winter months a very high longitudinal maximum is found, and in the period of study this occurred over the eastern Atlantic and western Europe where warm air flowed poleward to the rear of a strong blocking anticyclone.

Calculations of heat transport are being made on a continuing basis so that a more complete climatological analysis of this quantity should be possible within a few years. It will be of interest, of course, to see how well some of the features noted for the 3½ years of data presented in this paper maintain themselves over a longer period. In addition, in the next few years it is anticipated that some comprehensive data on global radiational heating will be obtained by weather satellites. Examination of these radiation data and heat transport data over various time periods may provide some clearer physical reasons for the temporal and spatial variations in meridional heat transport and associated energy conversions. Some preliminary examination of outgoing long-wave radiation data from TIROS II in relation to energy changes in the Northern Hemisphere circulation has been encouraging (Winston and Rao [20]), but needless to say we are only at the threshold of comprehensive studies of such relationships.

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