

## SOME NEW DATA ON THE LONGITUDINAL DIMENSIONS OF PLANETARY WAVES

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### ABSTRACT

Statistics of planetary wave number and wave length as observed on 5-day mean 700-mb charts are presented for each ten degrees of latitude between 30N and 70N for each month of the year. These statistics show that there tend to be fewer waves around latitude circles in the colder half of the year. As might be expected from the variation in the length of latitude circles, there are more waves at lower latitudes than at high latitudes, but wave lengths are actually longer at middle and low latitudes than at high latitudes. The monthly and latitudinal variations in the longitudinal dimensions of waves are explained to a moderate degree by variations in physical parameters suggested by theoretical and laboratory models. Specifically, it has been found that wave length exhibits a direct relationship to thermal Rossby number, zonal wind speed in mid-troposphere, and static stability.

### 1. Introduction

Wave number (or wave length) is one of the basic parameters used to characterize the planetary flow pattern in mid-troposphere. To a great extent, it has been employed as a gross measure of circulation type; *i.e.*, low wave number (long average wave length) is generally characteristic of strong westerly flow, while high wave number (short wave length) is more characteristic of weaker westerlies with greater dominance of meridional flow. Thus, wave number is frequently cited in descriptions of observed hemispheric flow patterns (*e.g.*, Namias and Clapp, 1951) and also in treatments of laboratory (*e.g.*, Fultz, 1956; Fultz *et al.*, 1956; Hide, 1956) and theoretical (*e.g.*, Fleagle, 1957; Kuo, 1953; Kuo, 1956; Thompson, 1953) models of the general circulation. Of course, wave number is of considerable importance in the realm of short- and medium-range prediction through its relationship to wave motion, as clearly indicated, for example, by the now classical Rossby equation (Rossby and collaborators, 1939). Changes in wave number are especially significant since they generally result in some radical adjustments in hemispheric flow (Cressman, 1948; Namias and Clapp, 1944). In view of this widespread importance of wave number as a general-circulation parameter, it is believed that the new wave-number statistics presented here will be of general interest to those concerned with planetary circulations.

These statistics consist of frequency distributions of planetary wave number and wave length for each month of the year for every 10 deg of latitude between 30N and 70N. These data, which were derived from 5-day mean 700-mb charts as a by-product of a recent

study of trough and ridge frequencies (Klein and Winston, 1958), are believed to represent the most comprehensive information (both in time and space) on wave number yet collected. Earlier published values of average wave length for 5-day mean 700-mb (10,000-ft) charts (Namias and Clapp, 1944) were for latitude 45N only and were based on only 2½ yr of selected data over a limited sector of that latitude circle (*i.e.*, trough locations from 130W eastward to 30W). Later values of 5-day wave lengths were based on more than 6 yr of data, but they were restricted to 45N and longitudes 110W eastward to either 60W (Bortman, 1949) or 30W (Clapp, 1948). Average wave length figures for latitudes 40N and 50N for 30-day mean charts (Klein, 1952) were based on 19 yr of data but were limited to the North American area.

More-recent data on wave number (Essenwanger, 1953; Glaser, 1956; Jung *et al.*, 1956) have been derived for the entire longitudinal breadth of the hemisphere and for fairly extensive time periods, but for limited latitudinal zones. However, these data were derived from daily 700- or 500-mb charts where the difficulties of defining the long or planetary waves are well known. These latter studies attempted to eliminate some minor waves, but, particularly in the work of Glaser (1956) and Jung *et al.* (1956), this elimination procedure appears to be quite subjective. It is well recognized that 5-day mean charts generally provide a good representation of long or planetary waves so that the latter may be counted rather simply on an objective basis. However, it is realized that 5-day means are occasionally imperfect filters of minor waves, too.

Much analysis of wave numbers has also been accomplished in terms of zonal harmonics of the height

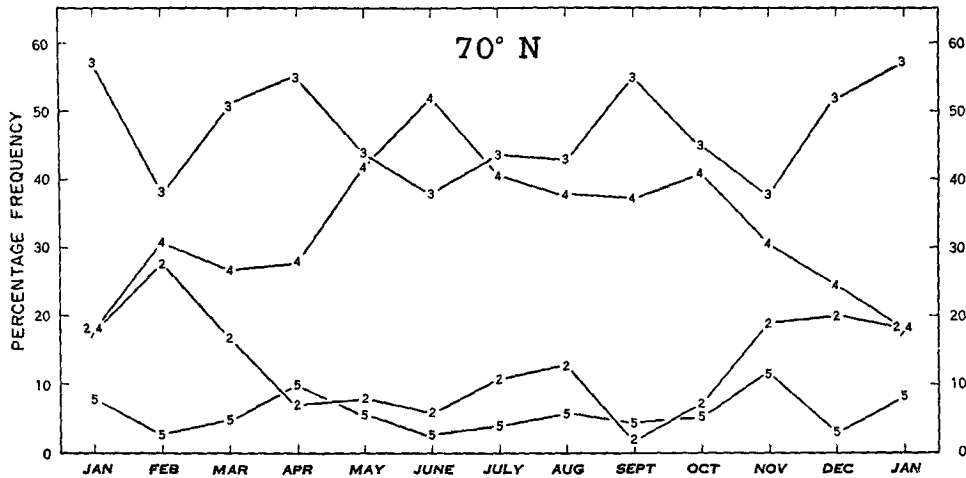


FIG. 1. Annual variation of percentage frequencies of 5-day mean planetary wave numbers at 700 mb for latitude 70N. Distribution for each wave number is identified by appropriate wave number plotted at each monthly frequency value. Frequencies less than 2 per cent not shown.

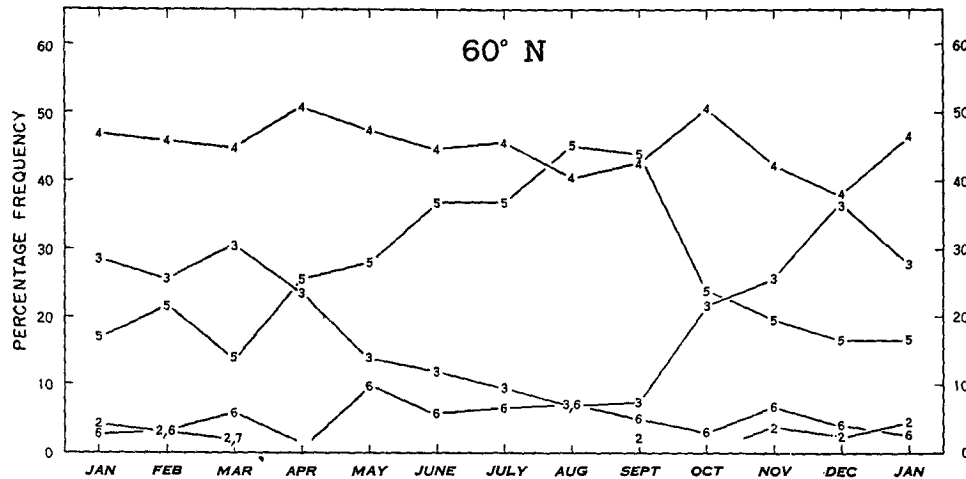


FIG. 2. Annual variation of percentage frequencies of 5-day mean planetary wave numbers at 700 mb for latitude 60N. See legend to fig. 1.

profile along latitude circles (Eliassen, 1958; Saltzman, 1958; White and Cooley, 1956). This procedure yields some interesting information on amplitudes and energies of various component wave numbers, although the physical reality of these components may be open to question (White and Cooley, 1956). In any event, comparison of the wave number of the actual height profile (as obtained in this study) with the amplitudes and energies of the harmonic components is difficult at best and no attempt has been made to do so here.

**2. Derivation of data**

Wave numbers were extracted from 5-day data recorded for use in the aforementioned trough-ridge frequency study (Klein and Winston, 1958). For each month and each 10-deg-lat circle between 30N and 70N, all years where height data covered a complete

latitude circle were used. (Complete hemispheric coverage at all latitudes was not available on these 700-mb charts until as late as 1949.) Data for latitudes 50N to 70N were derived from the period November 1947 to August 1955, while data for latitudes 30N to 40N cover the period January 1949 to August 1955. Thus, the number of years for a given month and latitude varies from 6 to 9, with most values representing 7 to 8 yr of data. Inspection of the entire set of data suggested that these differences in the length of period would tend to have little effect on the validity of comparisons of average wave dimensions for the various months and latitudes.

Latitudinal wave numbers were obtained by counting the number of ridges observed along latitude circles for each map. For a given longitudinal height profile along a latitude circle, each height maximum is defined

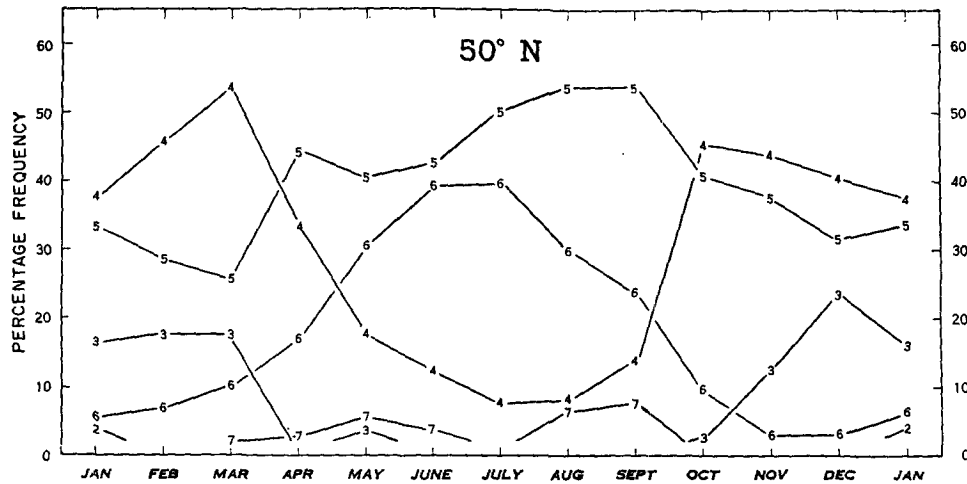


FIG. 3. Annual variation of percentage frequencies of 5-day mean planetary wave numbers at 700 mb for latitude 50N. See legend to fig. 1.

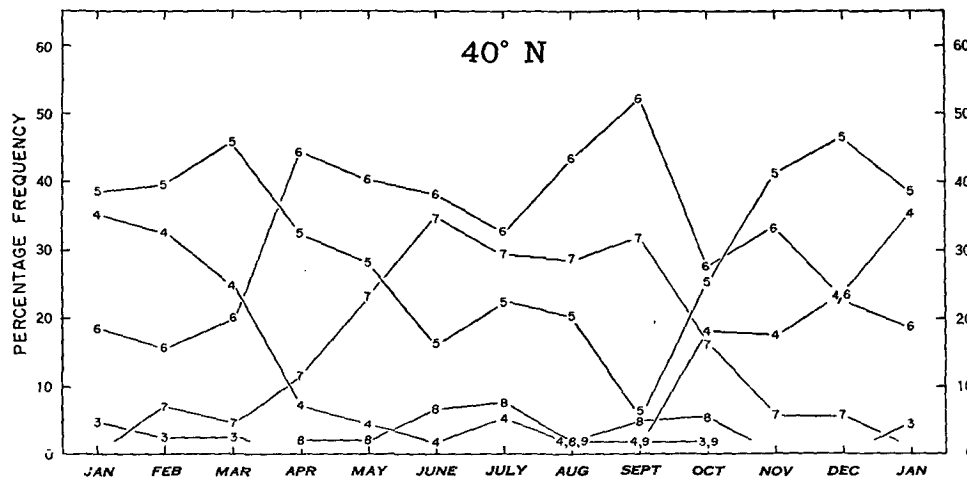


FIG. 4. Annual variation of percentage frequencies of 5-day mean planetary wave numbers at 700 mb for latitude 40N. See legend to fig. 1.

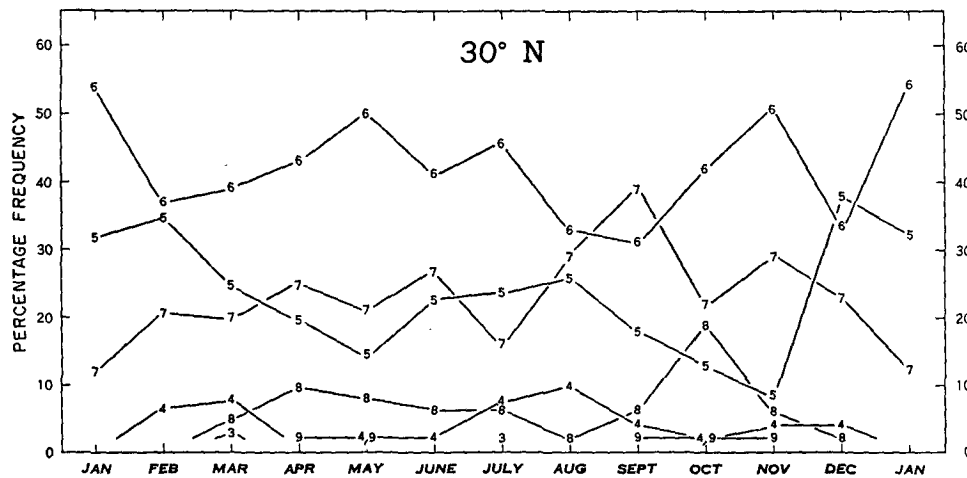


FIG. 5. Annual variation of percentage frequencies of 5-day mean planetary wave numbers at 700 mb for latitude 30N. See legend to fig. 1.

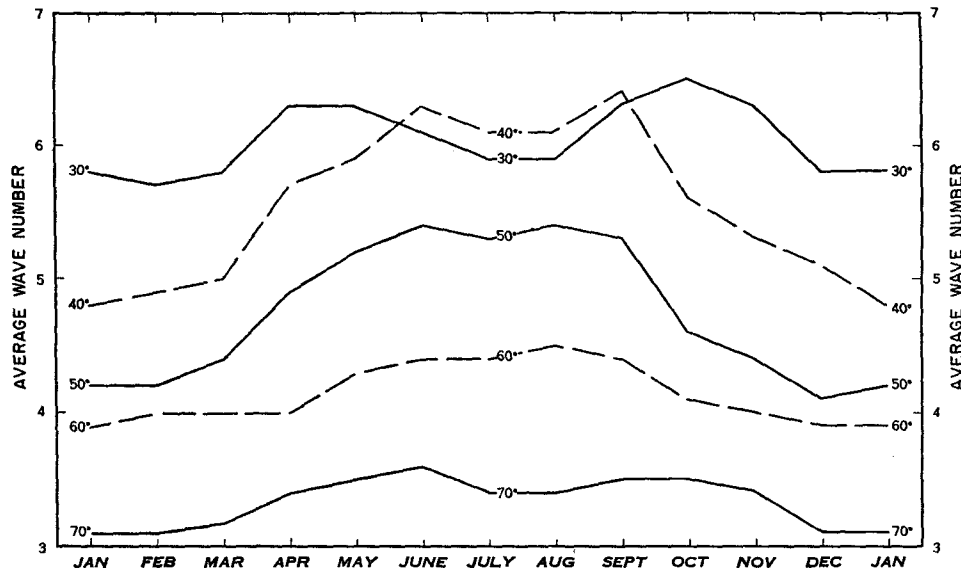


FIG. 6. Annual variations of average 5-day mean planetary wave numbers at 700 mb for various latitude circles.

as a ridge. The only exception to this simple definition is that minor ridges, with both intensity (height difference between trough and ridge along latitude circle) 10 ft or less and latitudinal extent less than 10 deg lat were omitted. A count of troughs along latitude circles would have yielded virtually identical wave-number data since troughs are defined as the inverse of ridges (*i.e.*, height minima along latitude circles).

### 3. Monthly and latitudinal distributions of wave number

The primary results of this study are presented in a series of diagrams for each latitude circle showing the month-to-month distribution of percentage frequencies of wave numbers observed on 5-day mean charts (figs. 1-5). At all latitudes, lower wave numbers are generally more frequent in the colder half of the year, while higher wave numbers are more frequent in the warmer half of the year. This variation between cold and warm seasons is most pronounced at middle latitudes (50N and 40N; figs. 3 and 4) where the wave numbers dominant in winter decrease considerably in frequency in the summer months and vice versa. The most extreme example of this is wave number 4 at 50N which has a wide variation in frequency between warm and cold seasons. It is notable that most of these variations in frequencies of wave number in middle latitudes do not take place gradually from winter to summer, or vice versa, but occur rather abruptly, mainly between March and April and between September and October.

At higher latitudes (figs. 1 and 2), some of these rapid transitions in frequency of occurrence of wave numbers are also in evidence, but they are not as sharply concentrated between the specific months indi-

cated at middle latitudes. In general, however, at each of the higher latitudes the dominant wave number of the cold season maintains a relatively high frequency all through the year even though higher wave numbers do tend to have increased frequencies in the warm season.

At 30N (fig. 5), wave number 6 occurs most frequently in all but two months of the year. The tendency toward smaller wave numbers in winter is evident in that wave number 5 is very nearly of equal frequency to wave number 6 between December and February. In contrast to other latitudes, however, the highest wave numbers of the year are most prevalent in the fall season (September-November) rather than in summer. Some of this may be associated with the high frequency of troughs of tropical origin in this season. On the average, however, the annual variation in wave number at 30N is the least clearcut of the latitudes studied.

Comparison of wave-number data among the various latitudes during the year is facilitated by the graphs of average wave number for each of the latitude circles (fig. 6). The generally higher average wave numbers at low as compared with high latitudes are readily apparent in all months, the number of waves at 30N being roughly double the number at 70N. The only exception to this basic north-south increase in wave number is found in June through September when the value at 40N is slightly higher than at 30N. The differences in seasonal variations of wave number at the different latitude circles are also highlighted quite clearly in fig. 6, but with much less detail than can be obtained from figs. 1-5. Minimum average wave numbers occur in one of the winter months at all lati-

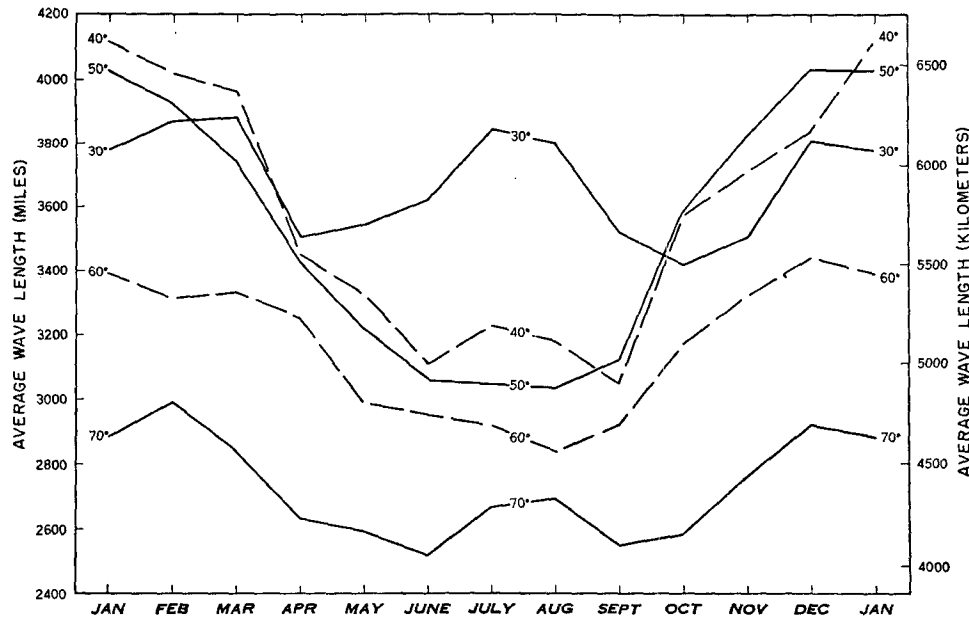


FIG. 7. Annual variations of average 5-day mean planetary wave lengths at 700 mb for various latitude circles.

tudes, and maximum average wave numbers occur in summer months at 50N to 70N and in September and October at 40N and 30N, respectively. The tendency toward secondary maxima at these latter latitudes is also apparent in spring (30N) or early summer (40N).

#### 4. Average wave length

Although comparisons of wave numbers for the various latitude circles are of definite interest, variations of this parameter do not conveniently portray the true latitudinal differences in wave dimensions. A more straightforward measure of wave size is the average wave length in actual length units (*i.e.*, not degrees of longitude). These average wave lengths were derived by individually converting each wave number to wave length and then multiplying each by its frequency of occurrence. Thus, arithmetic means of wave length were obtained rather than the harmonic means which would have resulted from direct conversion of the average wave numbers to wave lengths. The month-to-month variations of average wave lengths for each of the latitude circles are shown in fig. 7.

It is notable that in the colder half-year (October to March) the average wave length increases by about 1000 mi from latitude 70N to latitude 50N and then remains relatively constant southward to 30N, although the length at 30N is slightly smaller than at 40N and 50N through virtually all of the cold season. In the warmer half-year (April to September), wave length generally increases by some 1000 mi from 70N southward to 30N, with the greater differences occurring between 70N and 60N and between 40N and 30N.

TABLE 1. Comparisons of average wave lengths obtained in the present study with average wave lengths for 5-day, daily, and monthly periods obtained in earlier investigations. All data for 700 mb except Essenwanger's (500 mb). Units are statute miles.

Source	Period	Latitude (N)	Season			
			Winter	Spring	Summer	Fall
Present Study	5-day mean	45	4,000	3,519	3,109	3,475
Clapp (1948)	5-day mean	45	4,165	3,528	2,989	3,430
Klein (1952)	Monthly mean	45	4,966	—	—	—
Present Study	5-day mean	55	3,688	3,324	2,975	3,322
Essenwanger (1953)	Daily	55	3,102	2,784	2,585	2,863

Latitudes 40N and 50N exhibit the least differences in average wave length both during the warm season and through most of the remainder of the year as well.

It is of interest to compare the average wave lengths obtained in this study with some of the previously derived data for 5-day and also daily and monthly periods. For purposes of comparison, the average wave lengths for the months and latitudes shown in fig. 7 were averaged further to obtain seasonal values for latitudes 45N and 55N. The various data are shown in table 1. It will be noted that the earlier 5-day data of Clapp (1948) are rather similar to the values obtained in this study in spite of the fact that Clapp's data were for such a restricted longitudinal interval (troughs located from 130W eastward to 30W). Monthly mean wave lengths (data available for winter only) average appreciably longer than 5-day lengths as pointed out in an earlier comparison by Klein (1952). On the other hand, average wave lengths on daily charts at 55N are

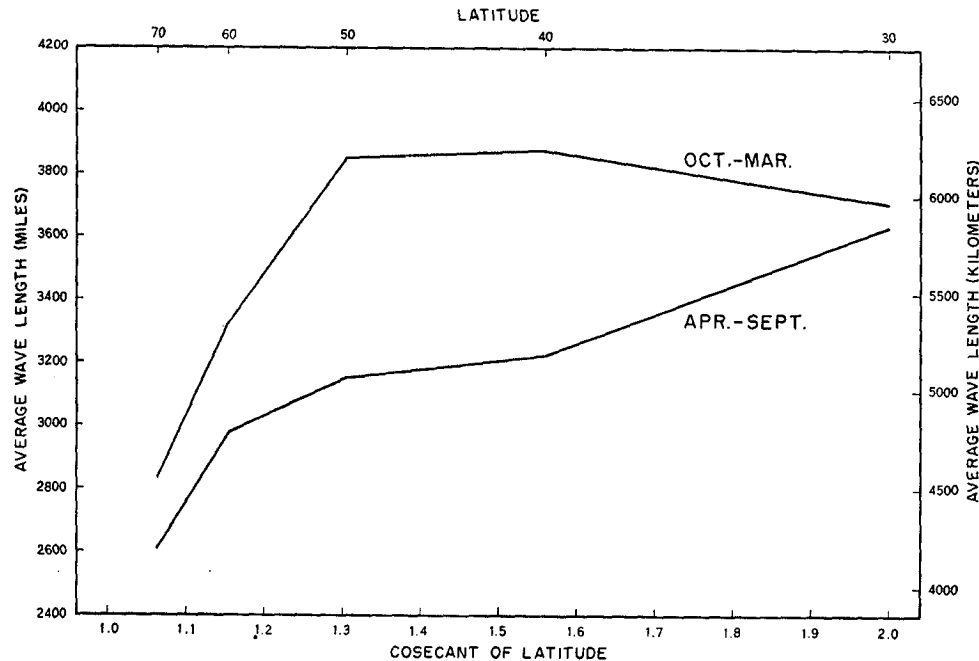


FIG. 8. Relationship between average wave lengths for colder and warmer halves of year and cosecant of latitude.

shorter than on 5-day charts, but certainly not by as outstanding an amount as might be expected.

### 5. Relationships to physical parameters

The question naturally arises as to whether these observed monthly and latitudinal distributions of average wave dimensions can be explained physically. Recent experimental (dishpan) (Fultz, 1956; Fultz *et al.*, 1956; Hide, 1956) and theoretical (Kuo, 1953; Kuo, 1956) studies have shown that two basic parameters which exert an influence on wave number, or length, are the latitudinal thermal gradient, which is maintained by differential heating, and the rate of rotation. This theoretical-experimental relationship between thermal gradient and wave length is direct (*i.e.*, the stronger the thermal gradient, the longer the wave length) and, of course, inverse for wave number. On the other hand, the rate of rotation should be inversely related to wave length (*i.e.*, the greater the rate of rotation, the shorter the wave length) and directly related to wave number.

In the actual atmospheric case, unlike the dishpan, the rotation rate cannot be varied at will, but the rotation on earth about the local vertical (*i.e.*,  $\Omega_E \sin \phi$ , the vertical component of the earth's angular velocity  $\Omega_E$  at latitude  $\phi$ ) does of course vary (with latitude); thus, the analogy to the dishpan's controlled rotational variations is readily apparent and this has been pointed out in the literature (*e.g.*, Bolin, 1952; Riehl, 1954). Thus, the observed general decrease in average wave

length<sup>1</sup> with latitude may well be explained on the basis of rotational influence on wave dimensions. The variation of observed wave lengths relative to the inverse of rotation at each latitude (*i.e.*,  $\csc \phi$ ) for the warmer and colder halves of the year is given in fig. 8, where a fair dependence of average wave length on  $\csc \phi$  is in evidence.

The relationship between average wave length and the other important parameter, thermal gradient, was also investigated. The measure of thermal gradient considered here was the northward gradient of 1000- to 700-mb thickness measured over a 10-deg-lat interval centered at each given latitude and based on monthly normal thickness data (U. S. Weather Bureau 1952). Normal data were assumed to be representative of the average monthly and latitudinal values of thickness for the period of the wave-length data, even though some significant departures from normal of actual thickness may have existed during this period. The plot of this thermal gradient *vs* the average wave length for each month at each latitude (60 cases) is shown in fig. 9, where it is evident that the relationship, although not outstanding, is in the expected direction; *i.e.*, longer wave lengths tend to be associated with stronger thermal gradients. The linear correlation coefficient between these parameters is +0.55. Incidentally, it may be noted that four cases toward the upper left corner of fig. 9 (*i.e.*, large wave lengths with

<sup>1</sup> Wave length alone will be considered henceforth in view of its more direct representation of actual planetary wave dimensions than wave number, as pointed out earlier.

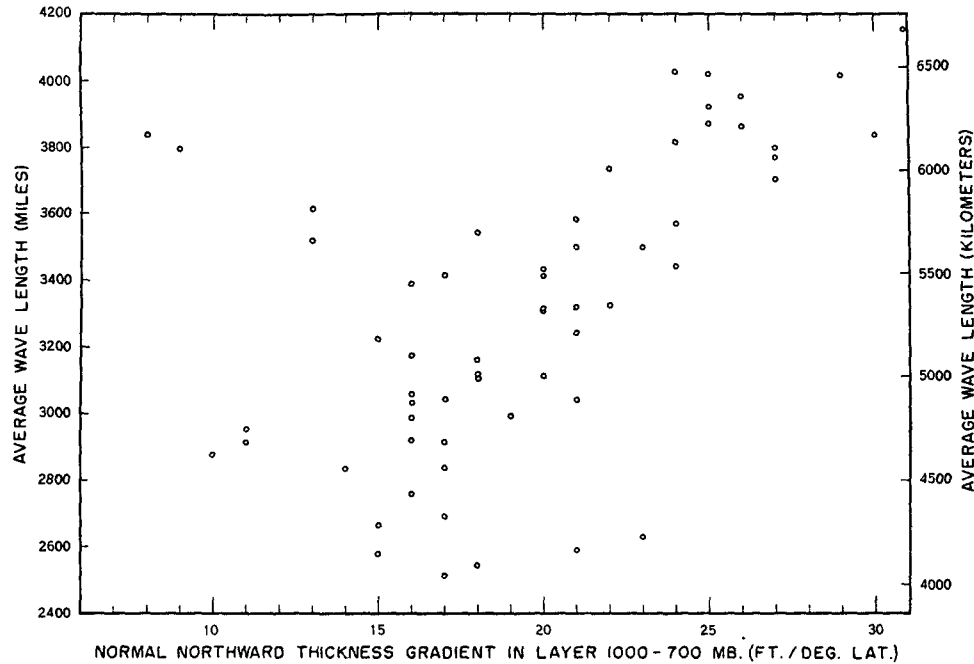


FIG. 9. Relationship between average wave lengths for each month and latitude and north-south 1000- to 700-mb thermal gradients based on normal height data.

small thermal gradients) are rather far out of line from the other points. These cases are for latitude 30N in the months of June to September, and it is apparent that thermal gradient exercises little control over wave length in the warm season at this latitude.

As pointed out by Fultz (1956) and Kuo (1956), the total effect of rotation (or latitude) and differential heating (or thermal gradient) is expressible in terms of a single parameter, the thermal Rossby number  $R_{0T}$ , which is conveniently written in the following form, as given by Fultz (1956):

$$R_{0T} = \frac{u_T}{A\Omega}, \quad (1)$$

where  $u_T$  is the thermal wind,  $A$  is a suitable horizontal length parameter, and  $\Omega$  is the basic rotation which is equal to  $\Omega_E \sin\phi$ .  $R_{0T}$  was evaluated for each month and latitude using thermal winds computed from the normal thickness gradient data mentioned above. The quantity  $A$ , which Fultz chose to be a constant related to the radius of the fluid in his dishpan experiments, was also taken here as a constant, equal in this case to the overall average wave length, or about 90 per cent of the radius of the earth. The relationship of thermal Rossby number to wave length is shown in fig. 10, which demonstrates a fairly good relationship, the correlation coefficient being +0.69. Thus, it appears that the thermal Rossby number does explain a goodly portion (*i.e.*, about half) of the latitudinal and monthly variation of average wave length on 5-day mean charts.

Other parameters suggested by theory were also investigated. One of these was static stability which, in baroclinic models (*e.g.*, Eliassen, 1952; Kuo, 1956), tends to determine the most favored wave number. The particular parameter evaluated here was the quantity  $S$  as studied by Kuo (1956), which is defined as follows:

$$S = gsd^2(2\Omega a)^{-2}, \quad (2)$$

where  $g$  is the acceleration of gravity,  $s$  is static stability,  $d$  and  $a$  are the vertical and horizontal scales of the motion, and  $\Omega$  is the rate of rotation. Stability for each month and latitude was estimated from the difference in normal thickness (U. S. Weather Bureau, 1952) between the layers 700 to 1000 mb and 500 to 700 mb. The correlation coefficient between this stability parameter and average wave length was +0.63. This correlation is in the expected direction (*i.e.*, the greater the stability, the longer the wave length) and lies somewhere in between similar correlations obtained for two sets of data on daily maps by Breistein and Parry (1954). The joint relationship of the thermal Rossby number and the stability parameter,  $S$ , with wave length was also briefly investigated, but the multiple linear correlation coefficient was only +0.69, which is the same as the correlation between thermal Rossby number and wave length alone. This is attributable to the fact that thermal Rossby number and the static stability parameter are too closely correlated (+0.85 in the normal data used here) so that virtually no additional information is obtained by considering

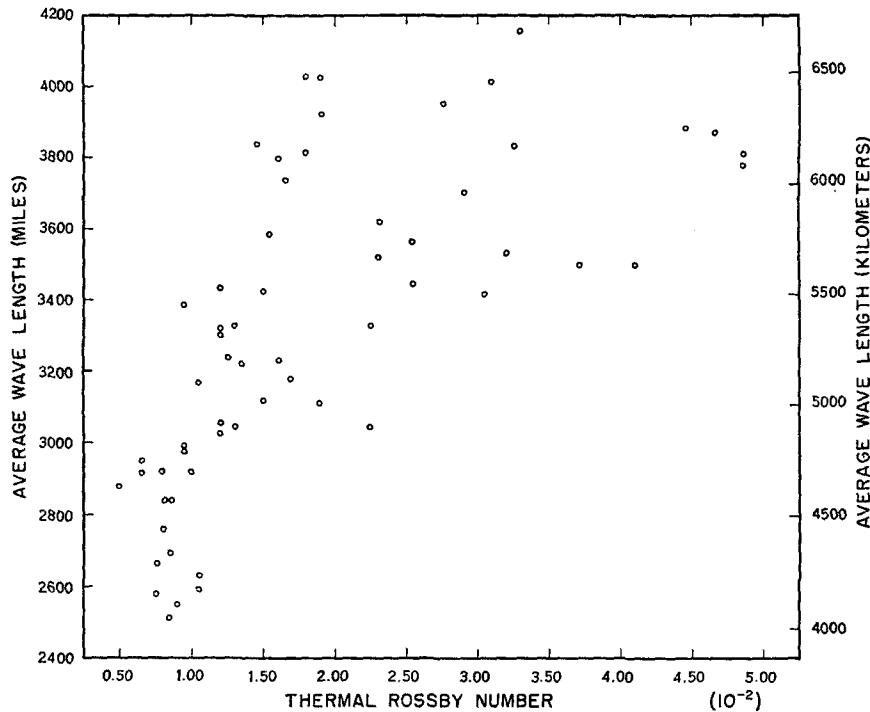


FIG. 10. Relationship between average wave lengths for each month and latitude and thermal Rossby number.

static stability. This agrees with Kuo's (1956) discussion in which he pointed out that the latitudinal thermal gradient is closely related to static stability (the stronger the horizontal thermal gradient, the greater the vertical stability).

The relationship of wave length to normal latitudinal values of zonal wind speed at 700 mb was also looked into. Wind speed was chosen on the basis of its appearance as a major parameter in Rossby's well-known barotropic treatment of planetary waves (Rossby and collaborators, 1939). The correlation between wave length and zonal wind speed [as obtained from 700-mb data presented in fig. 28 of Klein (1957)] was  $+0.71$ , which is very similar to the correlation with thermal Rossby number. Incidentally, this correlation is considerably higher than the values obtained by Bortman (1949) for latitude 45N, but his correlations were for individual 5-day mean waves rather than long-period average values.

The joint relationship of thermal Rossby number and zonal wind speed with wave length was also looked into. In this case, a multiple linear correlation coefficient of  $+0.76$  was found. This shows that the thermal Rossby number and zonal wind speed taken together explain somewhat more of the behavior of wave length than either parameter taken alone (56 per cent of the variability *vs.* 49 per cent), despite the fact that thermal Rossby number and zonal wind speed are fairly well correlated ( $+0.70$ ).

Finally, it was of interest to actually compare the observed average wave lengths with those that may be computed from the Rossby wave equation, which, when solved for wave length  $L$ , is

$$L = 2\pi(U - c)^{1/2}\beta^{-1/2}, \quad (3)$$

where  $U$  is the zonal wind speed (taken at 700-mb in our calculations here),  $c$  is the wave speed, and  $\beta$  is the northward variation of the Coriolis parameter. This equation of course stems from a highly simplified barotropic treatment of planetary waves. Unfortunately, values of  $c$  were not derived from the data in this study nor are they available from other data for all latitudes and seasons. Available data (Clapp, 1948) for latitude 45N indicate that the average speed of waves on 5-day mean charts varies between about 1.0 and 1.5  $\text{m sec}^{-1}$  over the various seasons of the year. As compared with normal monthly values of  $U$  at 700 mb for latitudes 40N and 50N, these values of  $c$  are small (less than about one-fourth the values of  $U$ ). It was decided, therefore, to compute  $L$  from (3) with the assumption that  $c = 0$ ; in other words, the Rossby stationary wave length was obtained. Since  $c$  is generally positive, this stationary wave length is actually longer than wave lengths which would be computed if wave motion were considered in (3).

It was found that the computed stationary wave lengths and the average observed wave lengths were rather poorly correlated (coefficient of  $+0.26$ ). Com-



puted wave lengths for latitude 30N in the warmer half of the year were most poorly related; the computed values showed a very distinct minimum in summer, whereas the observed wave lengths (fig. 7) actually displayed a secondary maximum. The observed values at 30N were between two and five times larger than the computed values between June and September. This is considerably larger than the average ratio of about 1.3 for the remaining 56 pairs of wave length values. These were the same cases which were also so poorly related to thermal gradient, as mentioned above in the discussion of fig. 9. Apparently, summertime wave dimensions in the subtropics are under a basically different type of physical control than represented by most of the parameters studied here.

The general findings about the shortness of Rossby stationary wave lengths (some 900 mi shorter on the average) agree with those of Namias and Clapp (1944), who found that the Rossby stationary wave lengths computed from 700-mb zonal winds were shorter than the observed stationary 5-day mean wave lengths. A choice of  $U$  at some level higher than 700 mb and closer to the average level of non-divergence (*i.e.*, about 600 mb) would have yielded larger values for the Rossby stationary wave lengths, but this would probably have had little influence on the correlation coefficient since the ratio between normal winds at 600 and 700 mb is roughly a constant. It should also be pointed out that considerations of simple baroclinic effects such as included in a study by Sutcliffe (1951) would yield stationary wave lengths which are longer than the Rossby stationary wave lengths.

## 6. Conclusions

In summary, certain well-marked climatological features of planetary wave dimensions have been revealed by the data presented here. Basically, these concern the monthly and latitudinal variations in wave number and/or length as follows:

(a) Wave numbers tend to be smaller in the colder half of the year and larger in the warmer half of the year, but the difference averages only a little more than one wave even for middle latitudes (40N to 50N) where the variation is greatest.

(b) Wave numbers generally increase from high to low latitudes (about twice as many waves at 30N as compared with 70N). However, this increase is not as great as the southward increase in the length of the latitude circles. In other words, wave lengths at middle and lower latitudes are longer than at high latitudes.

These monthly and latitudinal variations in wave length are explained to a considerable extent by the variations in parameters suggested by theoretical and laboratory models. Thus, wave length exhibits a direct

relationship to thermal Rossby number, which expresses the combined influences of the earth's rotation and the north-south thermal gradients, to zonal wind speed in mid-troposphere and to static stability. These parameters are by no means independent, however, and all three are basically functions of differential heating between higher and lower latitudes. In view of this, it will be of much interest to determine observationally the relationships between wave length and radiational data, which will become available from satellite measurements in the next few years.

The investigations here have shown that only slightly more than half of the latitudinal and monthly variability in wave length can be explained by the parameters studied. It is probable that some of the remaining variability could be explained through some considerations of the longitudinal-variable features of the underlying surface in the Northern Hemisphere. Such influences as orography and differences in temperature between land and ocean very likely have some marked influence on average wave length or wave number. Radiational differences in the longitudinal direction may play one of the important determining roles in such influences too.

As yet, the basic 5-day data, from which the average values of wave length and wave number presented here have been derived, have not been examined from the point of view of variations between individual 5-day periods or over individual months or years. Further investigation of these variations would be of much interest, particularly in regard to the corresponding fluctuations of such physical parameters as those studied here and parameters related to the longitudinal-variable influences just mentioned. It is believed that less of the shorter-period fluctuations in wave length would be determined by the very large-scale, hemispheric parameters studied here and more would be explained by more localized longitudinal-variable parameters. Also, lag relationships, rather than contemporary relationships, might come to the fore. This implies that the relationships between the large-scale parameters and average wave length may be at their best for long-period averages of the type presented in this paper. In other words, the large-scale thermal and rotational effects may essentially determine the statistics of the wave patterns but not their detailed behavior.

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