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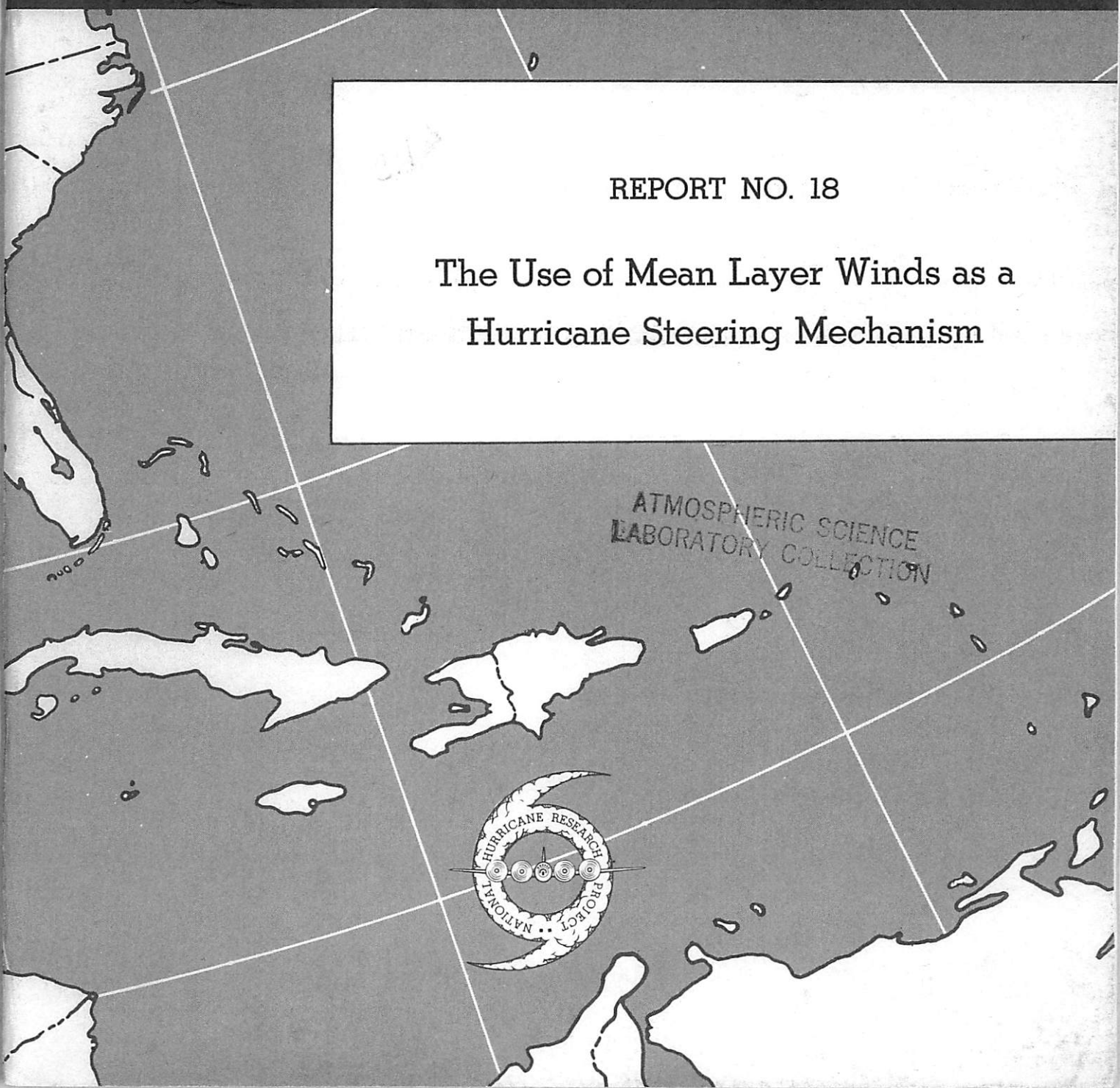
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The Use of Mean Layer Winds as a Hurricane Steering Mechanism

ATMOSPHERIC SCIENCE
LABORATORY COLLECTION



U. S. DEPARTMENT OF COMMERCE
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WEATHER BUREAU
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NATIONAL HURRICANE RESEARCH PROJECT

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The Use of Mean Layer Winds as a Hurricane Steering Mechanism

by

Banner I. Miller

Weather Bureau Office, Miami, Fla.



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THE USE OF MEAN LAYER WINDS AS A HURRICANE STEERING MECHANISM

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ABSTRACT

The mean wind around a tropical cyclone is determined for several layers of various thicknesses extending from the surface to 16 km. This is done by combining wind observations from a large number of storms in order to obtain a composite picture of the hurricane circulation. The resultant wind for each layer is calculated over a ring extending 2° - 6° of latitude from the center of the hurricane. This resultant is compared with the mean motion of the storm in an effort to establish the layer whose mean flow corresponds most closely to the motion of the hurricane. The data indicate that for moderate to intense storms the best steering layer is the 500 to 200-mb. layer. Finally an effort is made to develop a constant pressure chart which will represent the mean flow for a deep layer. This is done by averaging the standard constant pressure heights for the bottom, the middle, and the top of the layer. The geostrophic components are calculated from the mean chart and these components are compared with the actual mean wind for the layer. It is concluded that the standard constant pressure chart at the middle of the layer affords as good an approximation of the mean wind for the layer as does the mean chart.

1. INTRODUCTION

Various efforts have been made to relate the motion of a tropical cyclone to the basic current in which the cyclone is embedded. The difficulties are many and obvious. The width of the steering current as well as the depth through which the mean wind flow must be integrated undoubtedly vary with the intensity of the storm, the relative barotropicality of the atmosphere, the latitude, and the cycle of development through which the cyclone is passing. These could be determined if sufficient wind observations could be obtained from the area of the cyclone. However, there has never been available enough wind data extending through a deep layer to permit a detailed analysis of even one individual hurricane.

There is, of course, no reason to assume a priori that the hurricane moves with the speed of a steering current, however defined, since the internal forces of the storm itself may well make a substantial contribution

to the motion, particularly to the meridional component. There is evidence [6] to indicate that such is the case. Experience has shown the value of the steering principle, although most forecasters, lacking the necessary wind observations to enable them to determine the mean flow through a deep layer, have been forced to depend upon a steering level [1] rather than a steering layer. The height of the steering level apparently depends upon the intensity of the storm, usually ranging from 30,000 to 50,000 feet.

Riehl and Burgner [5] suggested that the steering current be defined as a belt 5° of latitude in width, extending from the surface to 300 mb., but they did not have the data to investigate their hypotheses. Later E. Jordan [2] prepared a set of composite charts of the hurricane circulation at several levels extending from 4,000 to 45,000 feet, from which she computed the steering as "...the pressure-weighted mean flow from the surface to 300 mb. and extending over a band 8 deg lat in width and centered on the storm." The average speed of the storms used in her study was 11 knots, and the steering current as she defined it indicated 9.7 knots.

The objectives of this present investigation were two-fold: (1) To extend the work of E. Jordan by making use of the larger number of wind observations made in the vicinity of tropical storms since 1952; (2) To attempt to determine the steering current by the use of mean layer winds without the necessity of pressure-weighting the data.

2. PREPARATION OF THE COMPOSITE CHARTS

The preparation of the composite charts used in the computation of the steering current has been discussed in a previous [3] report, but will be summarized briefly here. All data used were from Atlantic hurricanes. In order to be included within the tabulation, data had to meet the following requirements: (1) The central pressure of the storm was 985 mb. or less; (2) The center of the storm was south of 35°N . latitude; (3) The rawinsonde balloon reached an elevation of at least 6 km. All reports that fell within a grid covering 12° latitude both ahead and behind the storm and 8° to the right and the left were tabulated by 2-degree squares. The hurricane was at the center of the grid, which moves with the storm. The size of the grid was deliberately chosen to exceed that of the hurricane in order that the mean flow just outside the hurricane circulation might be investigated in relation to the storm's motion.

The grid and the number of observations, tabulated by 2-degree squares, are shown in figure 1. The total at 6 km. was 1047; this had decreased less than 10 percent at 10 km., but had dropped to 659 at 16 km. The persistence of the data at 6 km. is also shown in figure 1. Persistence is a measure of the steadiness of the wind and is defined as the ratio of the vector mean to the scalar mean.

Prior to tabulating the data the tracks of the storms were plotted on a Mercator projection and the positions of the centers at 3-hour intervals were indicated. The grid of figure 1 was constructed on a transparent overlay. The size of the 2-degree squares on the overlay represented the true map scale at 22.5°N ., which was about the middle latitude of the region of interest.

The arrow at the left of figure 1 (and subsequent illustrations) indicates the direction of the motion of the storm. The overlay was placed on the map with the arrow parallel to the storm track and the center of the grid over the position of the storm. The square within which the observation station fell was noted and the data tabulated in that square. The direction and speed of the motion of the storm were averaged over a 12-hour period, 6 hours before and 6 hours after the time of the wind observation. The direction from which the storm was moving was determined and the rotation that would be required to orient the track to a direction common to all storms was tabulated. This same correction was then applied to the wind observations pertinent to that storm and time.

In working up a winds aloft observation, the usual procedure is to average the balloon travel over a 2-minute interval for the lower levels and a 2- to 4-minute interval for the higher levels. For example, the wind direction at the end of the first minute is assumed to be the direction of the balloon from the observer at the end of the second minute, and the speed is the horizontal distance of the balloon from the observer divided by the time; i.e., 2 minutes. In this investigation a similar procedure was applied to deep layers.

The original winds aloft records were obtained. The direction and horizontal distance of the balloon from the observer at 1, 3, 6, 10, 12.5, and 16 km. were noted. The mean wind direction for each layer, 0-1, 0-3, 0-6, and 0-10 km. was assumed to be the direction of the balloon from the observer at the top of the layer. The mean wind speed was the horizontal distance divided by the time of ascent.

After the tabulations were completed, the vector means were determined for each square. The mean motion of the storms was then subtracted from the vector mean, and the radial and tangential components were determined. These components were smoothed by plotting the average for four adjacent squares at the intersections of these squares. Below 10 km. very little smoothing was required within about 6° of the storm. Above 10 km. more smoothing was required. After smoothing, the radial and tangential components were then recombined with the mean motion of the storms to obtain the mean wind field for each layer. The 0-1, 0-3, 0-6, and 0-10 km. layer means were determined in this way.

To obtain the means for the intermediate layers, the mean for each layer was converted back into a mean horizontal distance by multiplying by the average time of ascent. To obtain the average of the 1-3, 3-6, and 6-10 km. layers, each of the three lower layers was subtracted vectorially from the next higher layer. For example, the 0-1 km. distance was subtracted from the 0-3 km. distance. The result is the 1-3 km. distance, which was then converted back into the mean wind speed for the layer. The 3-6 and 6-10 means were similarly derived.

Above 10 km. a different technique was used because the data were not completely homogeneous. The individual 10-12.5 and 12.5-16 km. winds were derived in the conventional manner, i.e., by differentiating the individual observational curves (by finite differences), although this process was applied

to deeper layers than is normally used. The averages for each square were then obtained by combining the individual winds in a manner similar to that described above. To obtain the 6-12.5 km. layer means the 6-10 and 10-12.5 km. layers were added. For all layers a somewhat different technique [3] was used to derive the means for the four inner squares, but these data were not used in the computation of the steering current, and this process will not be described here.

3. THE RESULTANT STEERING CURRENT

The mean wind charts for the layers used in determination of the steering current are shown in figures 2-14. The effective steering current for each layer was evaluated for 2-degree rings extending 2° out to 8° from the center. The contributions of the separate rings were then combined to obtain the effective steering current of the 2° - 6° and 2° - 8° rings. The data inside the 2-degree circle were not used because the accuracy of the means is subject to question.

The steering current was evaluated by obtaining the vector mean for each ring. This implies that the wind within each square is of equal importance in determining the motion of the storm. This is not necessarily so, but present knowledge does not permit any other assumption. The values presented in table 1 represent the vector mean for the rings and layers specified. Speeds are in meters per second and the directions indicate the mean directions from which the steering current is coming. These directions, however, bear no true relation to the actual azimuth indicated. The mean motion of the storms was from a bearing of 90° but this does not mean that the storms were moving westward; this was merely a convenient plane of reference. The differences between 90° and the directions shown in table 1 do, however, represent the deviation of the mean motion from the steering indicated. The mean speed of the storms was 5.6 meters per second.

The results in table 1 show that the hurricane moves faster than the computed steering current for all layers and rings except for the 2° - 4° ring through the 6-12.5, 10-12.5, and 12.5-16 km. layers and the 2° - 6° ring for the 10-12.5 km. layer. The motion of the cyclone is also consistently to the right of the computed steering current, except through the upper layers (6-12.5 km., 10-12.5 km., and 12.5-16 km.) where the motion is to the left of the indicated steering. The motion to the right of the steering current is consistent with the classical concept of hurricane steering [1] in which it was assumed "...it [the hurricane] will cut across this [steering] current at an angle of 10° to 20° toward higher pressure." That the motion of the hurricane is to the left of the steering indicated by the upper layers is probably a reflection of the predominantly anticyclonic circulation around the upper portions of the storm.

Figure 15 shows the average wind components (for the 2° - 6° ring) parallel and perpendicular to the direction of motion. There is a component directed to the left of the motion of the storm from the surface to about 8.5 km., and above that elevation the component is to the right of the motion. It is probably of no significance, but the level at which the direction of the perpendicular component changes is identical with the level at which net inflow

Table 1. - Mean steering current (m.p.s.) for various rings and layers. Average motion of storms used in preparing the data from which the computations were made was 090/5.6 m.p.s.

Layer	2°-4° ring		4°-6° ring		6°-8° ring		2°-8° ring		2°-6° ring	
	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed
0-1 km.	057	3.5	062	3.9	065	4.2	063	4.0	061	3.7
0-3 km.	057	3.5	066	3.8	071	4.0	068	3.8	065	3.6
0-6 km.	074	3.1	070	3.8	076	3.9	074	3.6	071	3.6
0-10 km.	078	3.8	076	3.8	079	3.7	079	3.7	077	3.8
1-3 km.	064	3.3	067	3.7	074	4.0	069	3.7	066	3.6
1-6 km.	067	3.4	074	3.8	078	3.9	075	3.8	073	3.9
1-10 km.	083	4.0	075	3.8	080	3.9	080	3.9	078	3.9
3-6 km.	067	3.6	076	3.7	082	3.6	078	3.6	074	3.7
3-10 km.	080	3.9	080	4.0	083	3.6	081	3.8	080	4.0
6-10 km.	085	4.4	085	4.1	083	3.6	084	4.0	085	4.2
6-12.5 km.	089	6.4	099	3.7	093	3.3	091	4.1	095	4.6
10-12.5 km.	103	7.1	108	5.2	119	3.0	110	4.7	106	5.9
12.5-16 km.	116	6.1	115	3.6	093	1.2	142	3.0	115	4.3

changes to net outflow [3] across a circle with a radius of 3°. The component parallel to the direction of motion is consistently less than the mean motion of the storms except near the middle of the 10-12.5 km. layer, where the motion of the storm and the parallel component have about the same value. The parallel component increases from the surface up to about 11 km., and above that level decreases.

There are two possible explanations for the apparent motion of the storm at a speed greater than that of the steering current. First, the data may be biased in favor of weaker storms on the right, since it is easier to release a sounding balloon on the left, or weaker side, than it is on the right, or stronger side. This could produce a false lack of symmetry within the mean wind field which would result in the mean steering current being computed as too slow. Second, this difference may be real, and a reflection of the contribution of the internal forces of the hurricane to the motion of the storm. The motion to the right of the indicated steering may also be due to forces within the storm itself. The mean motion of the storms used in the preparation of the composite charts was about northwestward. Consequently if the internal forces, presumably due to the variation of the Coriolis force across the width of the storm (Rossby forces), actually tend to increase the northward component of motion [6], a northwestward moving hurricane would move across the steering current toward the right at a faster rate than the steering current would indicate. Conversely a northeastward moving storm would move to the left of the indicated steering and also at a faster rate.

The data of table 1 indicate that the best steering layer is the 6-12.5 km. layer computed over a ring extending 2° - 6° from the center of the storm. This is approximately the 500-200-mb. layer. The indicated motion for this layer is from 095/4.6 m.p.s. which is 1.0 m.p.s. too slow. This is a higher and a wider layer than E. Jordan [2] defined as the steering current. This, however, may not be inconsistent. Only storms of moderate to great intensity were used in tabulating the data used in this report; the central pressures varied from 985 mb. down to 914 mb. The mean, determined by weighting the individual central pressures according to the number of wind observations synoptic with the central pressure measurement, was 966 mb. The average intensity of the storms used by E. Jordan in compiling her data is not known but if the central pressure were greater than 966 mb., a lower steering layer as well as one of less width might be expected.

4. HIGH-LEVEL STEERING

The high-level steering concept [1] has had wide acceptance for many years in hurricane forecasting, and its usage has apparently been relatively successful. Briefly, this concept states that the hurricane will move about 10° to 20° to the right of the current that flows across the top of the warm core. This method requires the selection of a level where the winds over the surface position of the hurricane are not a part of the vortex circulation. In actual practice this presents a difficult problem, since winds aloft are seldom available directly over the hurricane, and most forecasters who use high-level steering lean toward the selection of winds 200 to 300 miles ahead of the projected path of the storm as an indication of the steering current. The hurricane is forecast to move at a rate equal to 60 to 80 percent of the steering current.

The composite charts of figures 13 and 14 afford a method of estimating the probability of success, on the average, of the high-level steering concept. Figure 13 represents the mean wind field through the 10-12.5 km. layer. The rectangle ahead of the surface position of the hurricane encompasses the area from which winds aloft are normally selected for use in high-level steering. The rectangle covers a width of 4° and a length of 6° of latitude. The vector mean of the winds enclosed by this rectangle is from 082/7.7 m.p.s. The mean motion of the storms was from 090/5.6 m.p.s. Thus the storms moved with a speed of 73 percent of the steering current, and the motion was on the average 8° to the right. This would suggest that the rule based on the high-level steering concept is valid. Applying the same procedure to the next higher layer (12.5-16 km.), however, does not meet with the same success. The indicated steering is from 127/8.8 m.p.s. The storms moved with a speed equal to 64 percent of the indicated current, but the direction of motion of the storms was 37 degrees to the left. This would suggest that for this group of storms the 12.5-16 km. layer is too high and that taking the steering current at that level introduces a portion of the anticyclonic circulation evident at that level.

5. REPRESENTATION OF THE MEAN LAYER WINDS BY CONSTANT PRESSURE SURFACES

It would appear that the best approach to forecasting hurricane motion should be based on a detailed analysis of the mean tropospheric flow sur-

rounding the storm, although the depth through which the mean flow should be integrated may vary with the intensity of the hurricane. Realizing the difficulties involved, Riehl et al. [6] have substituted the 500-mb. chart, arguing that this level approximates the mean wind flow within the troposphere. Using this chart they have developed a system for forecasting the 24-hour motion by computing the mean geostrophic components over a grid extending 7.5° of longitude east and west of the storm and from 5° latitude south of the center to 5° to 10° north of the center. This method has shown considerable promise, although other users of the system have not been able to achieve consistently the same success from it as have the developers of the method. This is apparently due to differences in the analyses of the 500-mb. charts, to which the method is extremely sensitive.

However, it has not been established that the 500-mb. chart actually represents the mean tropospheric flow. Realizing this, the National Hurricane Research Project [4] has experimented with the use of a graphically determined mean of the 850- and 300-mb. charts to represent the mean flow between these two levels. Again, however, it has not been shown that this combination of constant pressure surfaces is truly representative of the mean flow for the layer, although it is logical to believe that it might be a better approximation than the use of a single level; e.g., 500-mb.

Testing of the hypotheses involved in both the Riehl-Haggard and National Hurricane Research Project systems appears desirable. Accordingly an experiment has been designed to attempt to test the relationships between the mean winds for various layers and the geostrophic components computed from the average constant pressure heights through the layer. This is not an easy task, simple as it may sound, for the following reasons:

1. The measurement of the constant pressure surfaces is subject to errors, primarily errors in measuring the temperatures, the probable error being of the order of 0.5° to 1.0°C . As the sounding balloon ascends, these errors accumulate, and at 200 mb. the probable error in the heights is of the order of 75-150 feet. This makes the computation of the geostrophic components very difficult.
2. The gradient may not be constant so that the geostrophic component varies considerably between two upper-air stations. This makes it difficult to compare an actual wind with the geostrophic component.
3. The actual wind measurement is subject to errors, although to a lesser degree than the height measurement.
4. Curvature of the flow pattern introduces a non-geostrophic component.

Curvature of the flow pattern is one of the most pronounced features of hurricane circulation. However, the radius of curvature is seldom known, and if a constant pressure chart is to be used to compute hurricane movement it would seem that practical difficulties make it necessary to restrict the computations to the geostrophic components, as Riehl [6] and others have done. Several attempts were made to surmount these difficulties, and the following

procedure was finally evolved:

1. The constant pressure height gradient was measured between two stations and it was assumed that this gradient was constant between the two stations. The geostrophic component normal to a line connecting the two stations was computed.
2. This geostrophic component was compared with the component of the actual wind perpendicular to a line connecting the two stations, the actual wind being measured as nearly as possible at the mid-point of the line. Three different sets of stations were selected which approximately fulfilled these requirements. These were Havana-Tampa, with the actual wind being measured at Miami; Hatteras-Washington, wind at Norfolk; and Washington-Nantucket, wind at Hempstead Air Force Base.
3. The 500-mb. charts were examined and cases were selected in which it appeared that geostrophic flow was approximated. The geostrophic component was then compared with the actual component of the wind at 500 mb. As it turned out, not all the cases selected were good ones; i.e., the computed component deviated considerably from the actual wind component. This was presumably due to the four reasons listed above. Therefore, the 62 best cases (out of about 100) were selected for the test; i.e., the two components were approximately equal. This apparently eliminated the four difficulties listed above, or it indicated that the individual errors may have cancelled each other, which is possible but not highly probable. This selection obviously biased the data, and the actual correlation between the geostrophic components and the actual wind components must normally be poorer than that indicated by the coefficients to be calculated later. However, the object of the experiment was to test the hypotheses that the geostrophic component obtained from various combinations of the constant pressure surfaces represents the mean flow through a layer. The results obtained from the 500-mb. chart were used as a standard with which to compare the data for the various layers. The goodness of the fit for the layer, compared to the fit for a level, should indicate the relative success that might be expected from using the various constant pressure surfaces to represent the mean flow for a layer as compared to the success obtained in using the geostrophic component for a level to represent the actual wind for that level.

The mean wind for three layers was determined from the three individual stations listed above. Three layers were used since it was considered possible that different layers might contribute to the steering, depending upon the intensity of the storm. These were the 1-6 km., the 1-10 km., and the 6-12.5 km. layers. These were considered to represent approximately the 850-500-mb., 850-300-mb., and 500-200-mb. layers. The 1-km. level instead of 1500 m. was used to represent the 850-mb. level since the data for the 1-km. level had already been tabulated, and the small difference involved did not appear to justify the extra work of tabulating an additional level.

The 62 cases selected for the goodness of the fit for the 500-mb. level were used in all the following correlations. In every case the geostrophic component normal to a line between the two stations was correlated with the component of the actual wind perpendicular to that same line. The 1-6 km.

mean wind component was correlated with the geostrophic component computed from the mean of the 850-, 700-, and 500-mb. charts. Similarly the 1-10 km. mean wind component was correlated with the geostrophic component computed from the mean of the 850-, 700-, 500-, and 300-mb. charts and also with the components computed from the means of the 850- and 300-mb. heights. The 6-12.5 -km. mean wind component was correlated with components computed from the 500-, 300-, and 200-mb. heights. The plots of the actual wind components versus the computed geostrophic wind components are shown in figures 16-19, and the actual linear correlation coefficients are shown in table 2.

The mean of the 850-, 700- and 500-mb. charts represents the mean flow for the 1-6 km. layer (correlation 0.97) as well as the 500-mb. chart represents the flow for that level (correlation also 0.97). The 850-300 mb. charts do not represent the flow through the 1-10 km. layer quite as well (correlation 0.89), but the addition of the two intermediate levels (700 and 500 mb.) raises the correlation to 0.95. The 500-300-200-mb. charts represent the mean wind for the 6-12.5 km. layer reasonably well (correlation 0.91), and the failure to secure a better fit may reflect the less accurate measurements of the constant pressure heights at the higher elevations.

These figures seem to indicate that the mean wind through a layer can be represented successfully by a constant pressure chart obtained from the means of the standard constant pressure surfaces enclosed by that layer. This would seem to justify the use of the mean chart devised by the National Hurricane Research Project. However, the hypothesis that the mean flow is also approximated by a level near the middle of the layer should also be investigated. Accordingly the wind components for the various layers were also compared with the geostrophic components obtained from the constant pressure chart near the middle of each layer, using the same data and technique used in the previous computations. The results are shown in table 2.

For the 1-6 km. layer the correlation of the layer wind with the 700-mb. component is 0.97, which is identical with that obtained by use of the 850-, 700-, and 500-mb. data. Through the 1-10 km. layer the correlation of the mean with the 500-mb. component is 0.97, while with the use of the 850- and 300-mb. charts it was 0.89 and with the use of the data from 850, 700, 500, and 300 mb. it was 0.95. The 300-mb. component compared to the mean wind of the 6-12.5 km. layer yields a correlation of 0.85, as against 0.91 when the three heights (500, 300 and 200 mb.) were used to determine the geostrophic components.

This would seem to suggest that the standard constant pressure surface near the middle of a layer is as good a representation of the mean flow within that layer as can be obtained by using the mean of the two surfaces at the top and bottom of the layer. There is some indication that some improvement is obtained by adding in intermediate layers before the mean is taken, but this improvement is not significant and apparently not worth the extra work involved.

It will obviously be suggested that the data used were biased and that this bias invalidates these results, inasmuch as the cases were selected for the goodness of the fit for the 500-mb. level. Accordingly a second set of

Table 2. - Correlation coefficients between actual wind and geostrophic components for various layers.

Geostrophic components computed from height of -	Observed wind component for layers			
	1-6 km.	1-10 km.	6-12.5 km.	500 mb.
(mb.)	<u>Selected-Random</u>		<u>Selected-Random</u>	
850, 700, 500	0.97	0.89		
700	0.97	0.89		
850, 300		0.89	0.86	
850, 700, 500, 300		0.95	0.85	
500		0.97	0.83	
500, 300, 200			0.91	0.78
300			0.85	0.83
500				0.97 0.73

correlations were worked out, using only randomly selected cases; i.e., the constant pressure charts were not examined at all before the data were tabulated. In this group there were 55 cases, all data being taken from the Hatteras-Washington-Norfolk stations.

These correlations are shown in table 2, under the tabulation of random cases. These also indicate there is no significant difference between the use of the level near the middle of the layer and the means of the constant pressure heights through the layer as a means of representing the mean flow. This would seem to suggest that the use of the 500-mb. surface as a representation of the mean flow [6] through a deep layer is, on the average, justified.

The question will undoubtedly arise as to whether or not the correlation coefficient is a good measure of the relation of the mean wind to the computed geostrophic component. There could be a large difference between the two, and the correlation might still be high if the difference was constant or if the ratio between the two was constant. That this is not true, however, may be determined by inspection of figures 16-19, which show that the plots of the two variables fall very close to a 45° line.

Obviously because of the limited number of cases used, this experiment cannot be considered as final and it is not meant to discourage the experimental use of mean charts as a representation of the mean flow for a layer. There are obviously cases in which the mean chart will give better results, and further research into their usefulness should be continued. It is suggested, however, that the use of a three-level model based on the 700-, 500-, and 300-mb. charts (to represent the 850-500, 850-300, and 500-200 mb. mean flow) might be a more profitable line of investigation. This line of research would be aimed at the use of a different steering level for storms of different intensities; the individual contributions of the different levels to the motion of the hurricane could be determined by multiple correlation.

6. CONCLUSIONS

It would appear that the best hurricane steering layer extends from 500 to 200 mb., if this flow is averaged over a ring extending from 2° to 6° of latitude from the center. Only moderate to intense storms, however, were used in this study, and a different steering layer may well apply to weaker storms. Through the 10-12.5 km. layer (about 300-200 mb.) the mean wind flow over a rectangle 4° wide and 6° long, centered 4° ahead of the projected path of the storm, indicates that the mean motion is about 10° to the right of the flow at a speed about 70 percent of the mean speed. Thus some validity is attached to the rule based on the high-level steering concept.

The mean flow through a layer can be approximated by using the mean of the standard constant pressure heights at the base and the top of the layer. This representation is improved, however, by including the intermediate heights. This improvement is not significant, however, and it appears that the middle of the layer represents the mean flow as well as any combination of the individual constant pressure surfaces.

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CASES 5 91% ₁	5 79 2	13 93 3	7 90 4	14 85 5	13 90 6	2 56 7	7 99 8	4 95 9	3 99 10	4 86 11	CASES 5 80% ₁₂
10 70 13	6 79 14	7 99 15	10 97 16	12 99 17	13 99 18	11 98 19	7 97 20	8 97 21	6 90 22	4 88 23	2 94 24
7 82 25	10 80 26	14 92 27	14 86 28	15 98 29	10 95 30	7 93 31	4 98 32	4 96 33	3 72 34	2 75 35	8 62 36
13 90 37	10 83 38	11 95 39	21 93 40	16 97 41	8 96 42	7 93 43	9 96 44	3 98 45	7 88 46	9 77 47	8 73 48
19 85 49	12 97 50	14 89 51	30 96 52	43 95 53	24 91 54	8 88 55	9 99 56	8 81 57	11 92 58	7 98 59	2 95 60
10 74 61	15 83 62	15 74 63	18 98 64	14 90 65	22 92 66	11 90 67	9 92 68	13 95 69	10 97 70	4 91 71	8 64 72
15 90 73	16 89 74	17 79 75	26 73 76	22 86 77	18 89 78	22 98 79	21 92 80	11 89 81	6 97 82	6 75 83	1 100 84
3 97% 85	8 99 86	7 85 87	18 69 88	19 76 89	19 79 90	14 69 91	15 59 92	13 76 93	11 79 94	4 84 95	1 100% 96

←2° LAT→

Figure 1. - Grid used in data tabulation, number of observations at 6 km., and persistence of the data (in percent). Arrows indicate the direction of storm motion.

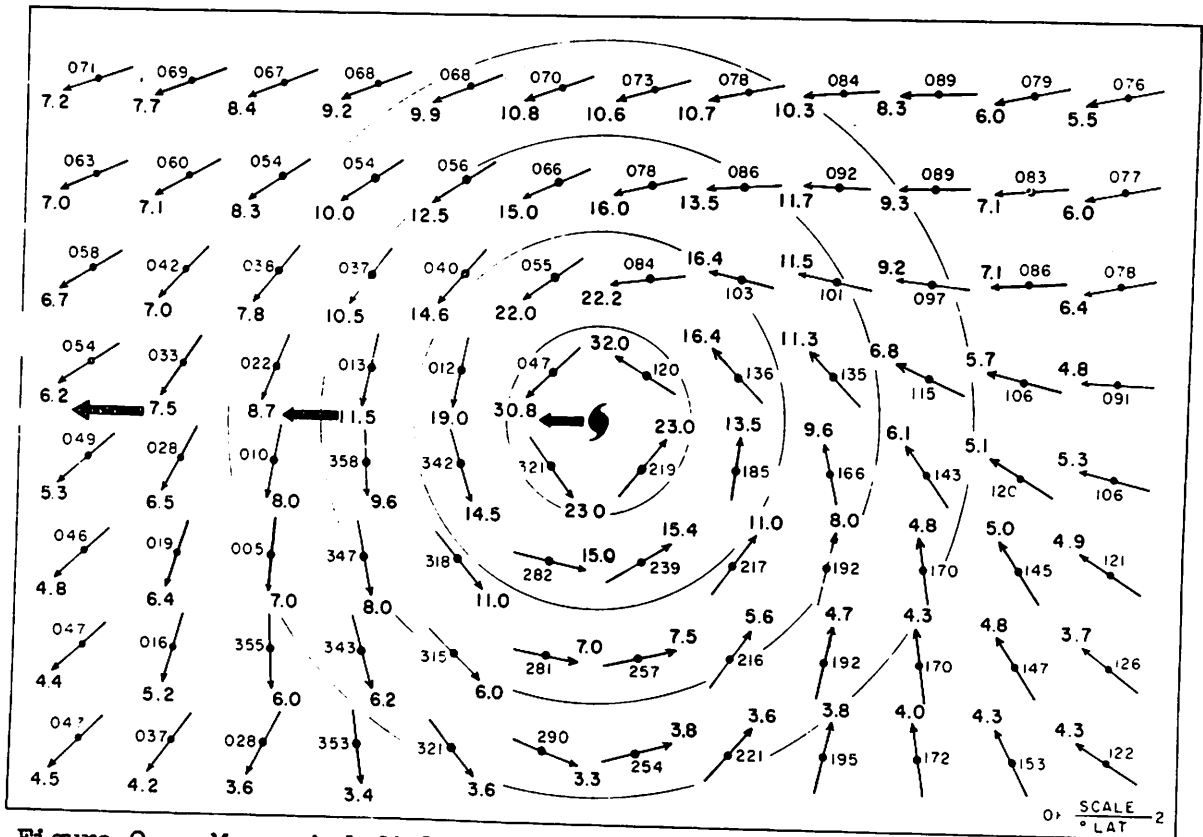


Figure 2. - Mean wind field 0-1 km. layer. Speeds in meters per second.

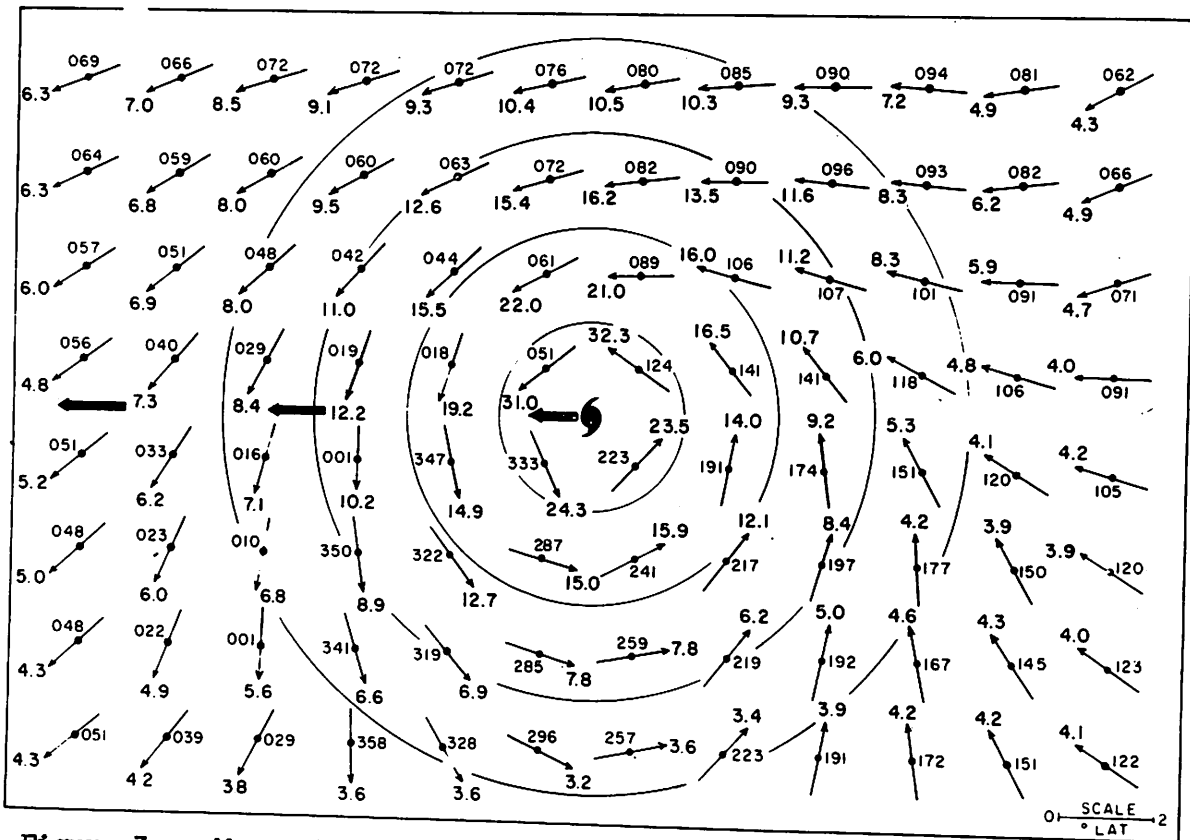


Figure 3. - Mean wind field 0-3 km. layer. Speeds in meters per second.

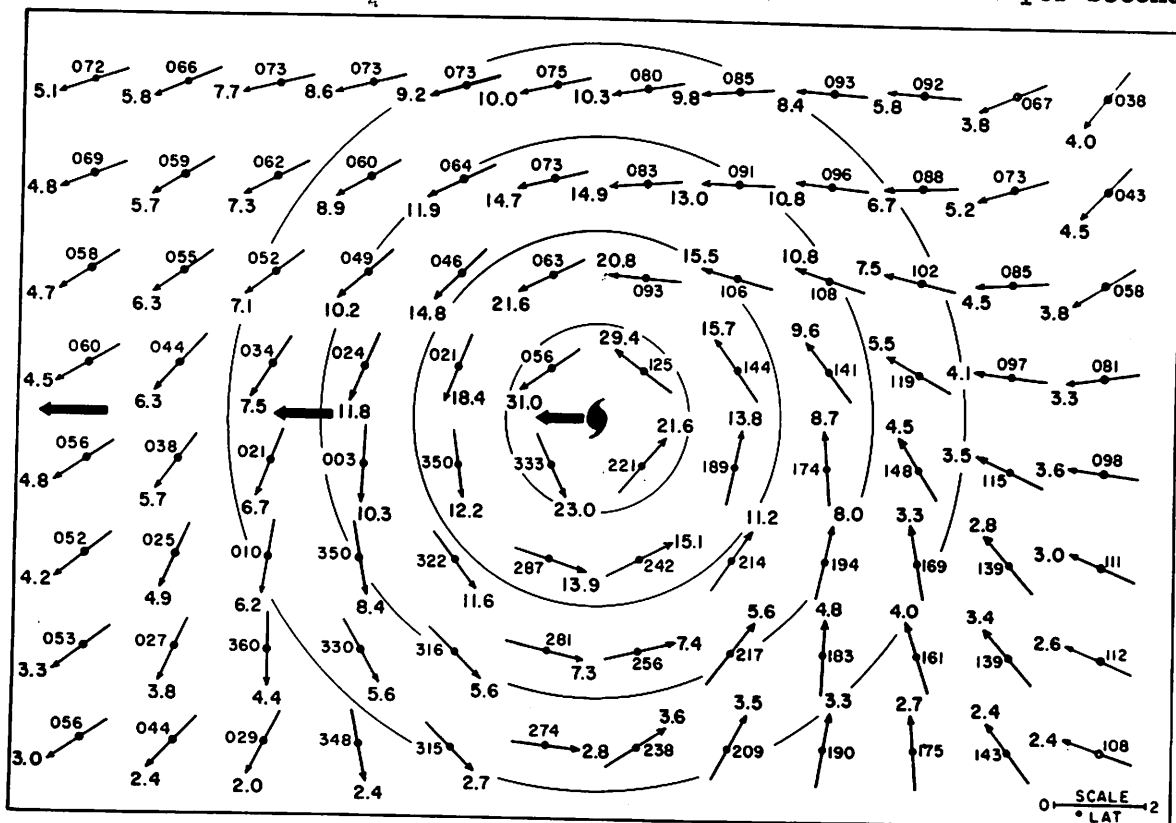


Figure 4. - Mean wind field 0-6 km. layer. Speeds in meters per second.

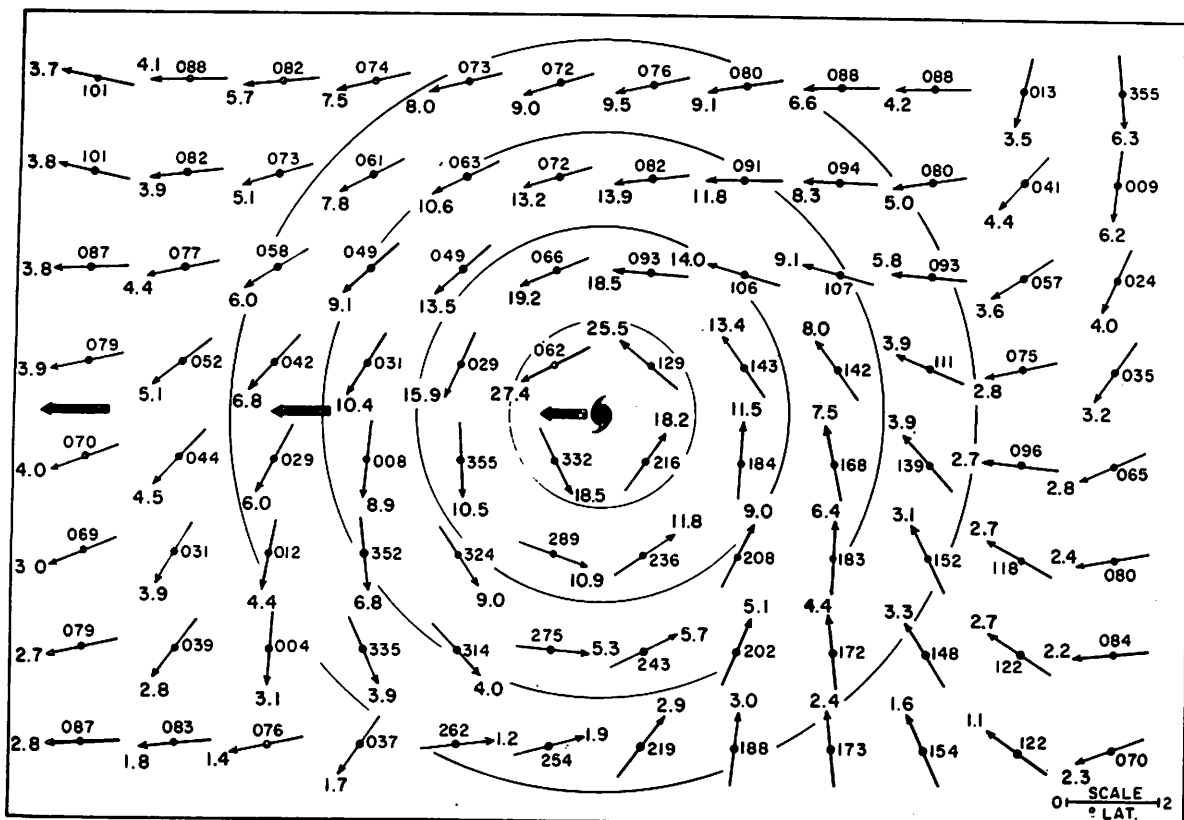


Figure 5. - Mean wind field 0-10 km. layer. Speeds in meters per second.

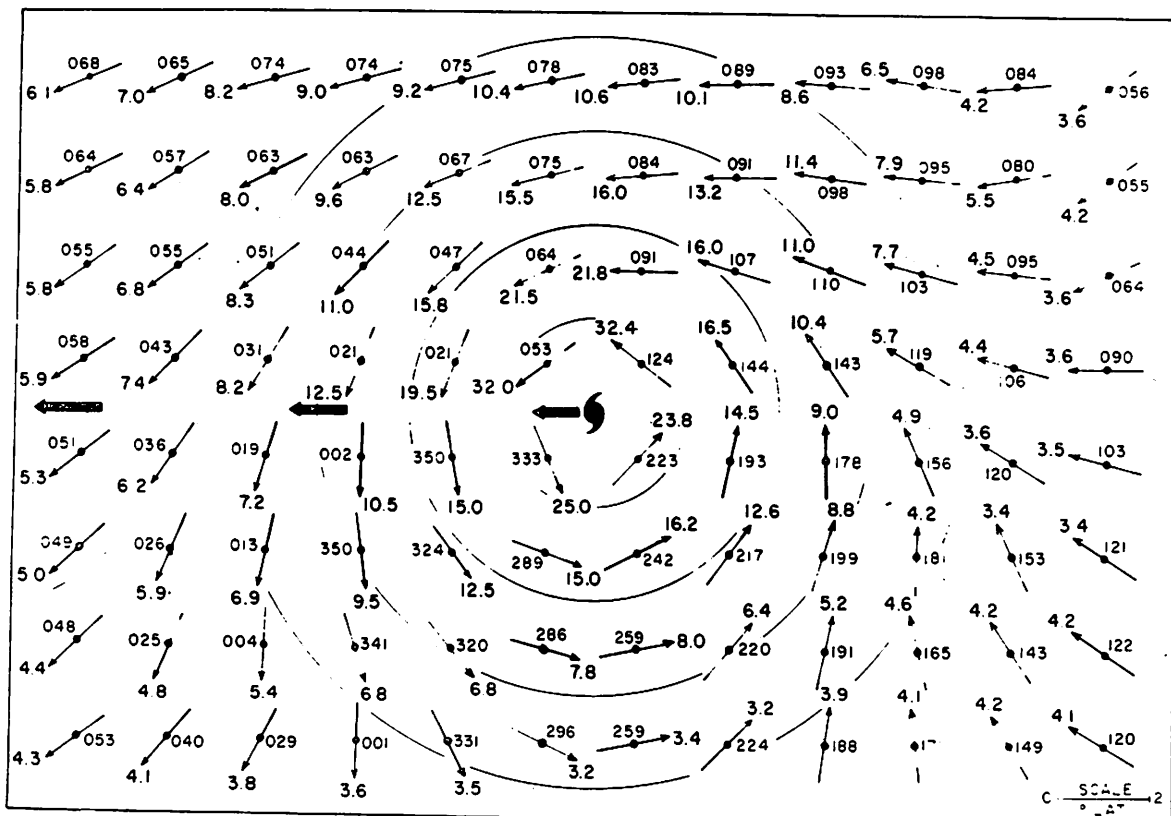


Figure 6. - Mean wind field 1-3 km. layer. Speeds in meters per second.

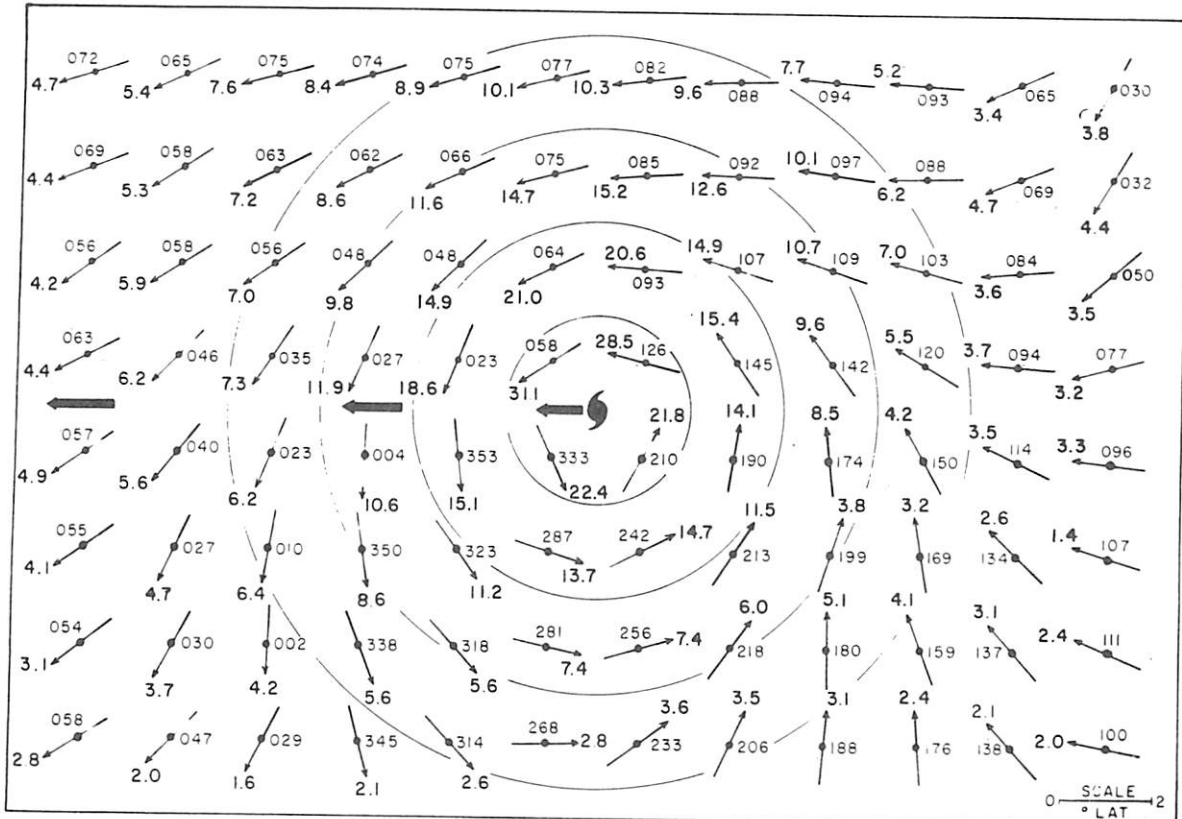


Figure 7. - Mean wind field 1-6 km. layer. Speeds in meters per second.

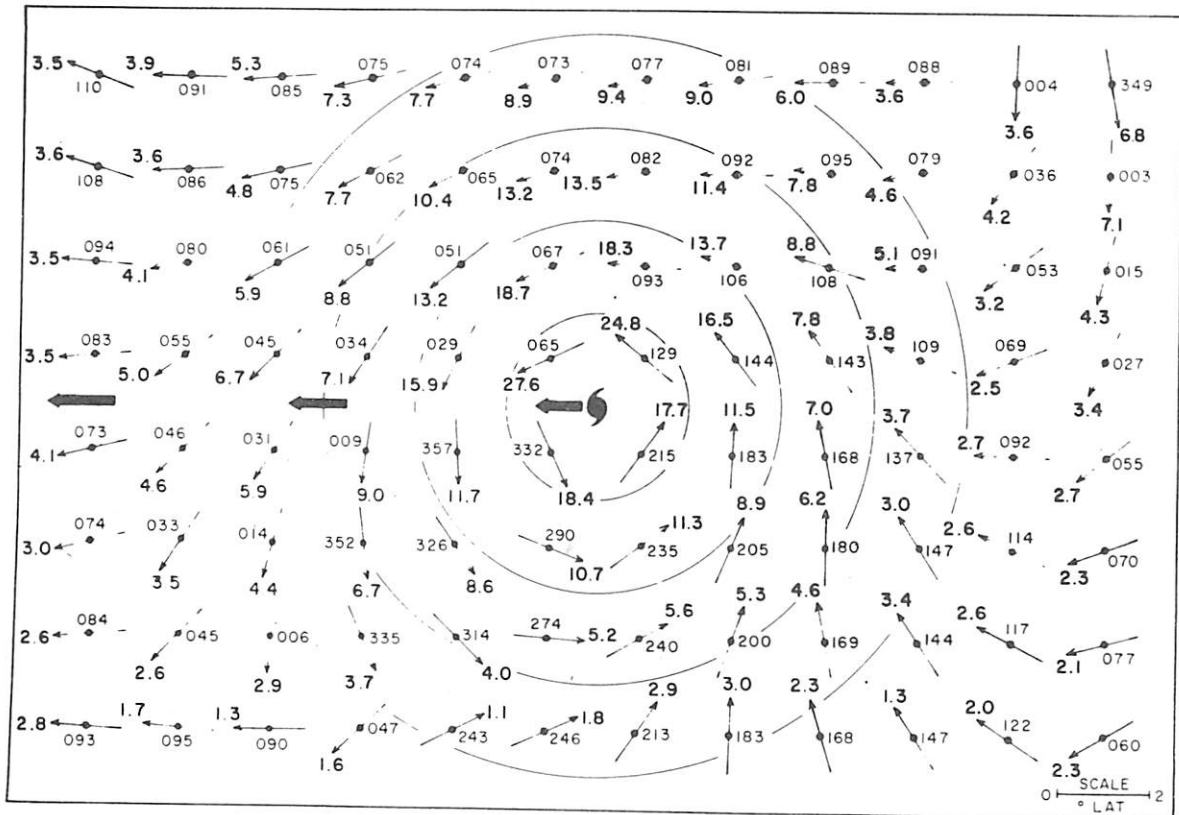


Figure 8. - Mean wind field 1-10 km. layer. Speeds in meters per second.

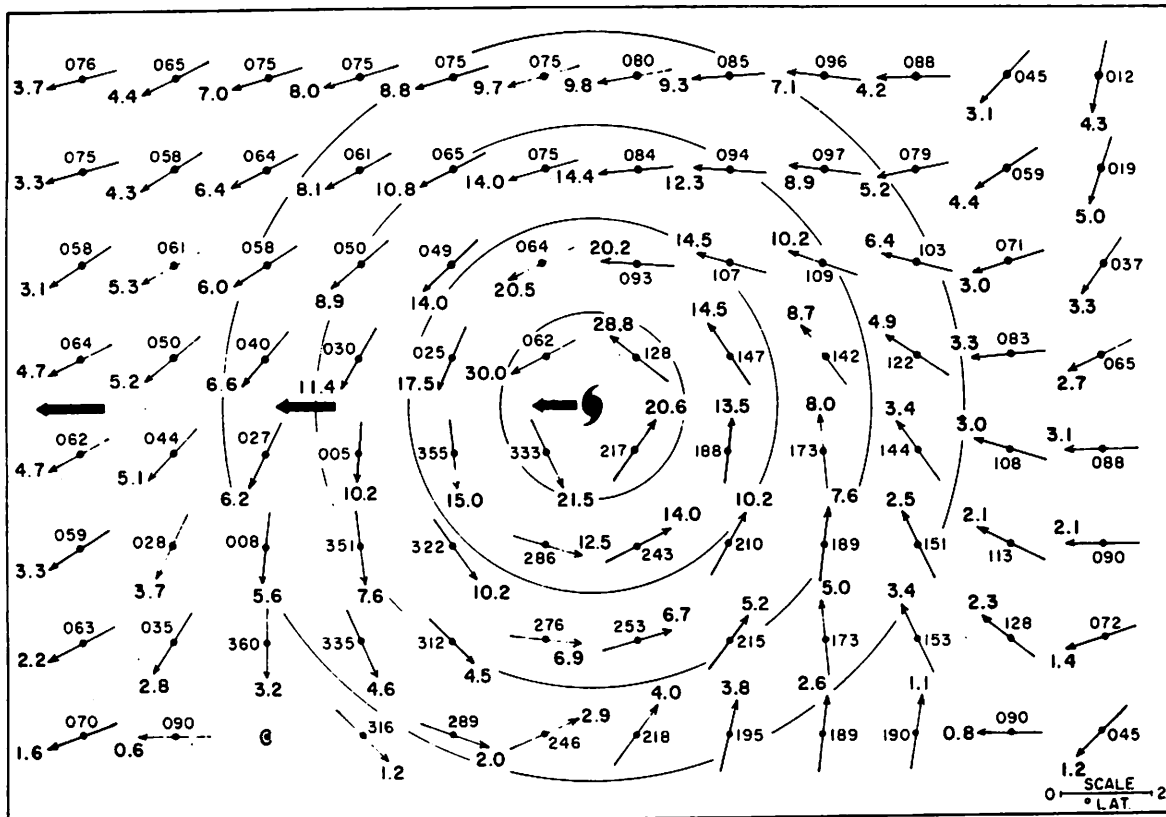


Figure 9. - Mean wind field 3-6 km. layer. Speeds in meters per second.

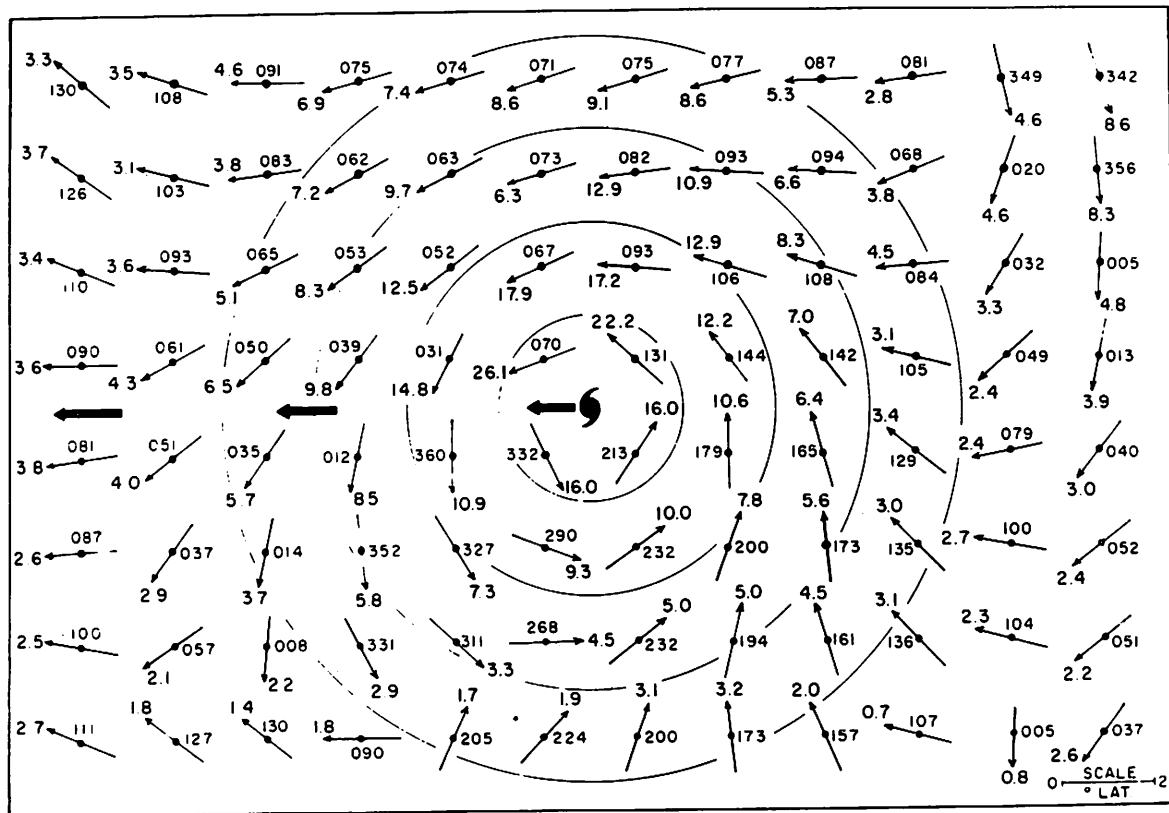


Figure 10. - Mean wind field 3-10 km. layer. Speeds in meters per second.

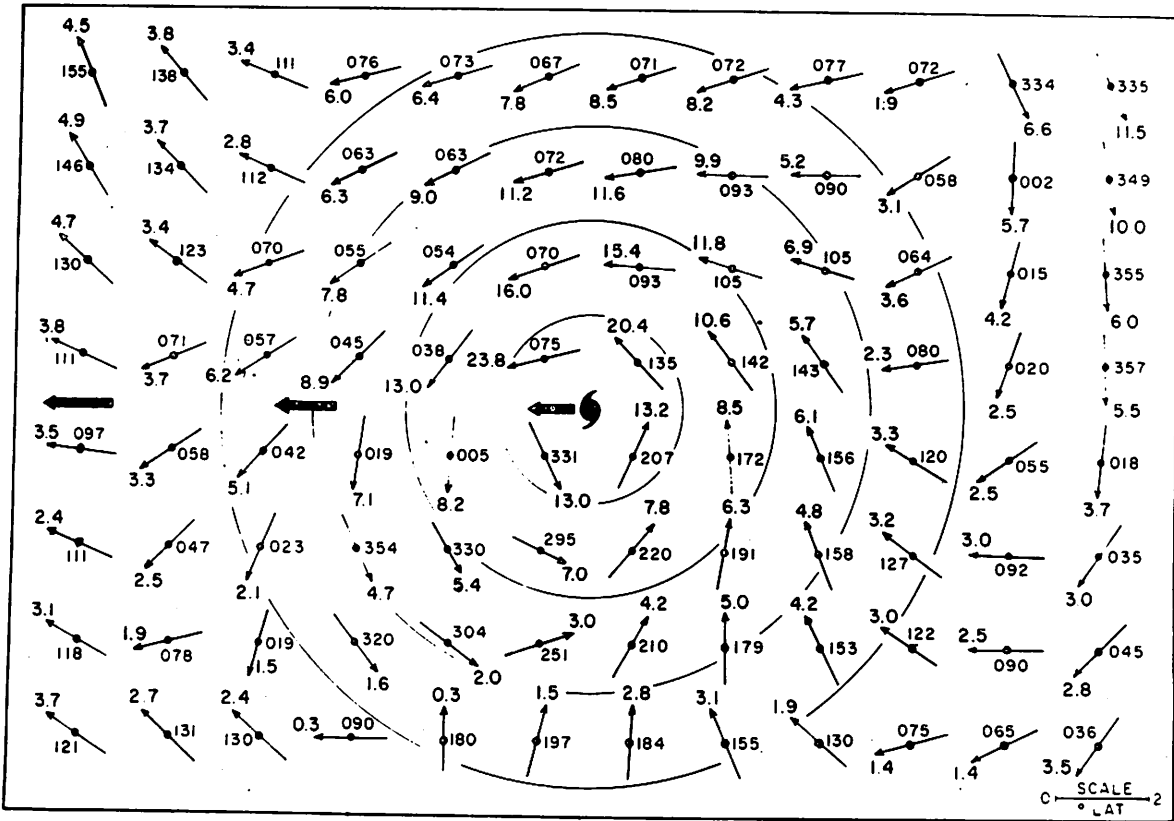


Figure 11. - Mean wind field 6-10 km. layer. Speeds in meters per second.

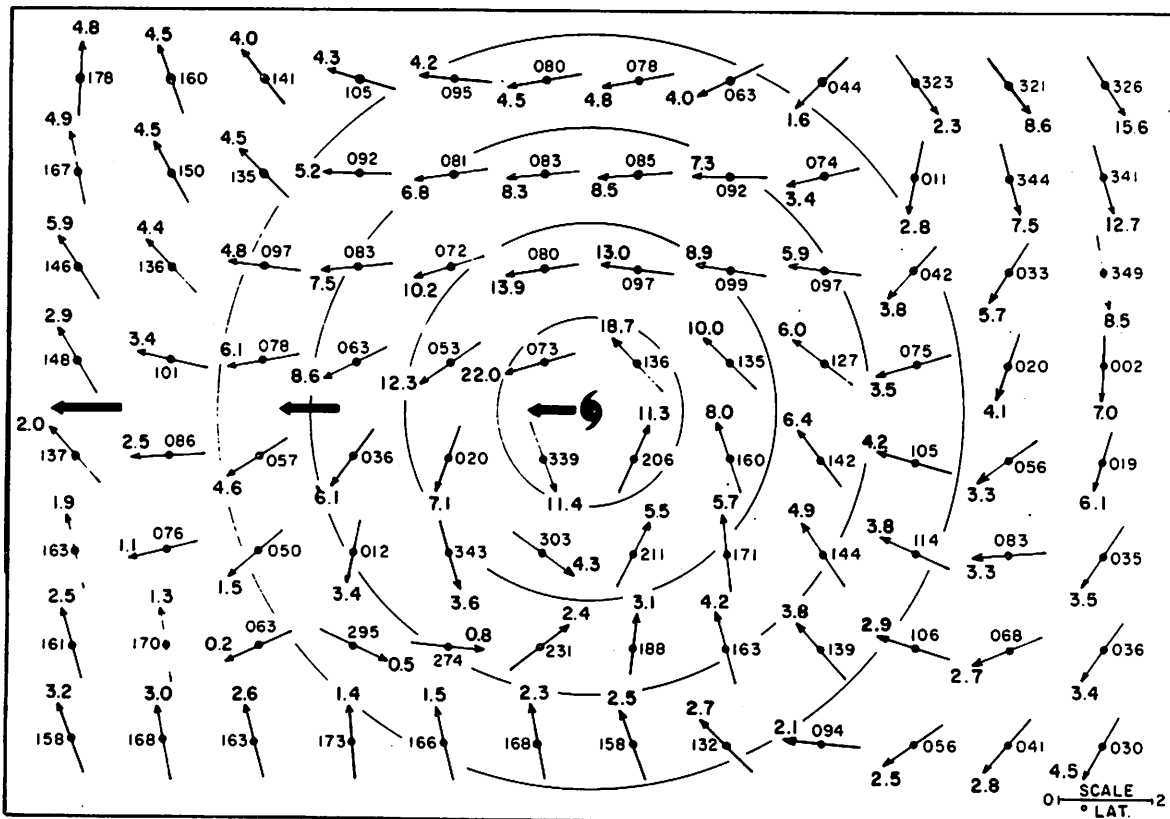


Figure 12. - Mean wind field 6-12.5 km. layer. Speeds in meters per second.

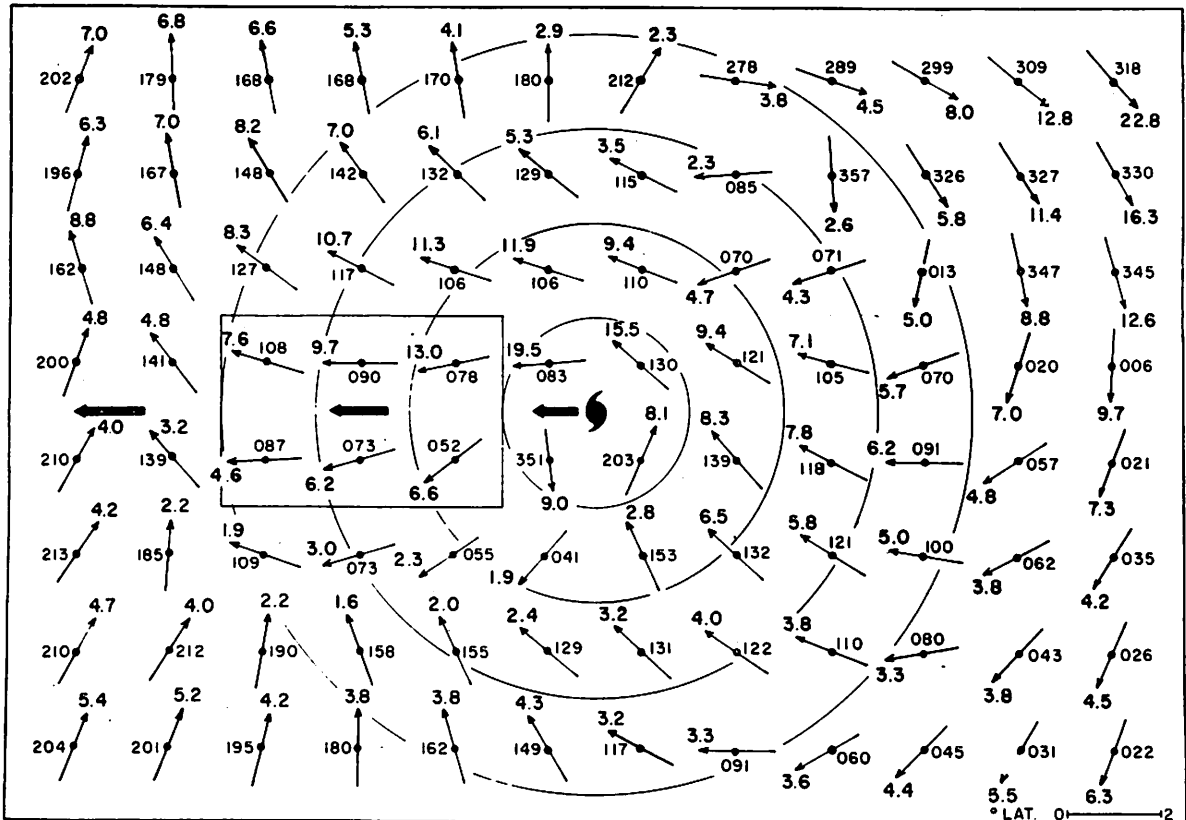


Figure 13. - Mean wind field 10-12.5 km. layer. Speeds in meters per second.

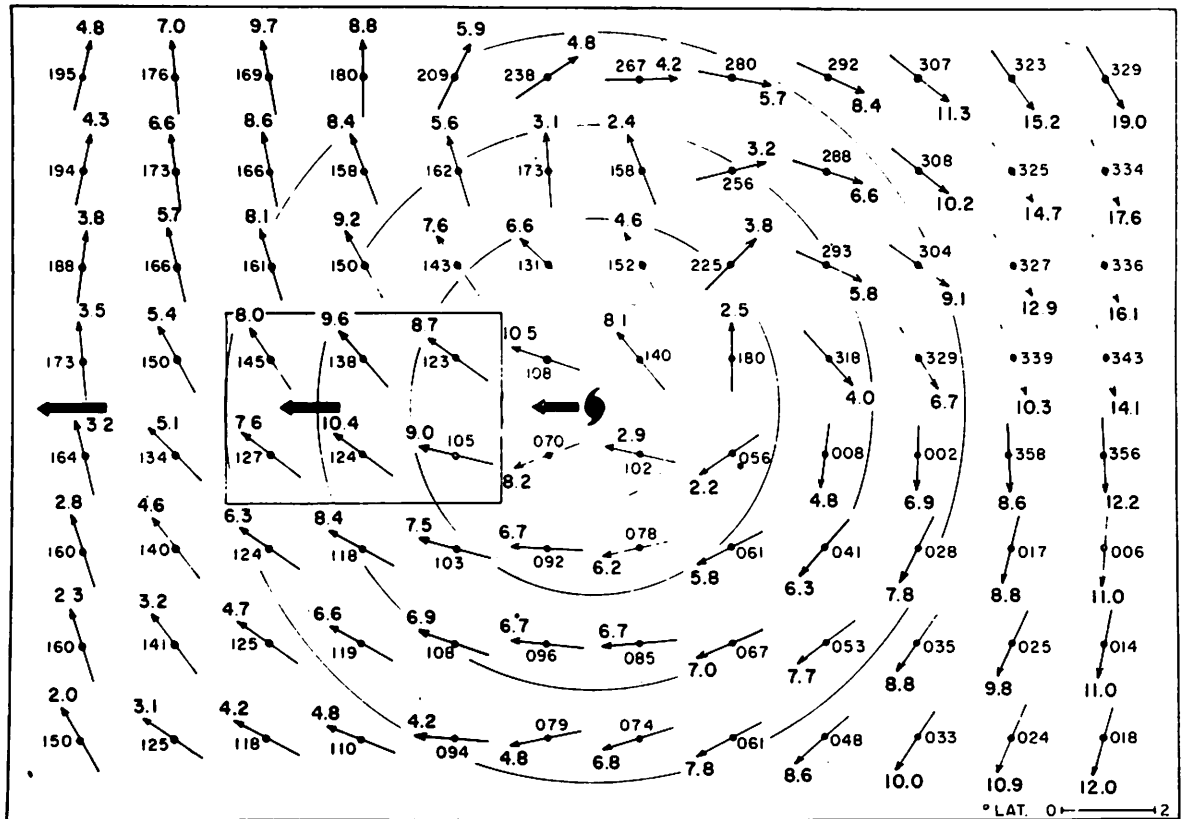


Figure 14. - Mean wind field 12.5-16 km. layer. Speeds in meters per second.

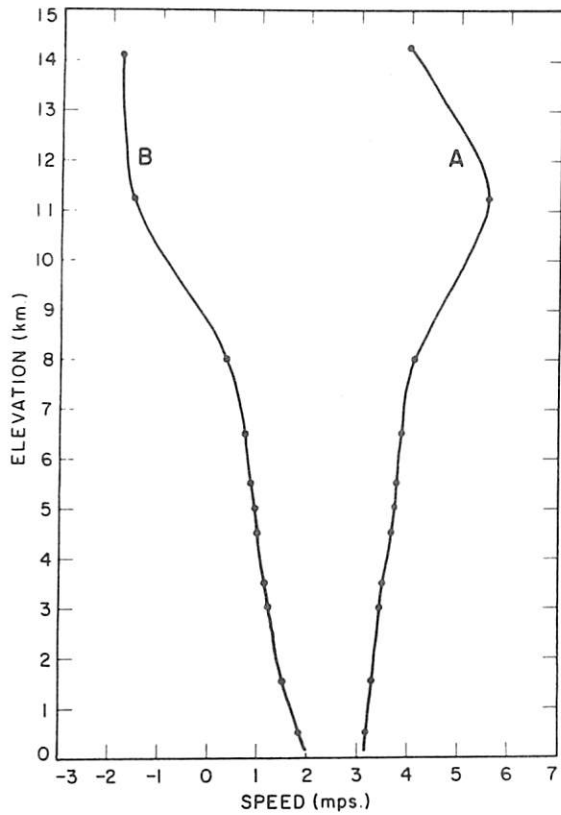


Figure 15. - Average wind component parallel to the motion of the storm, Curve "A", and perpendicular to the motion of the storm, Curve "B". Positive values for "B" indicate component to the left of the motion. Averages evaluated over a ring extending from 2° of latitude out to 6° from the center.

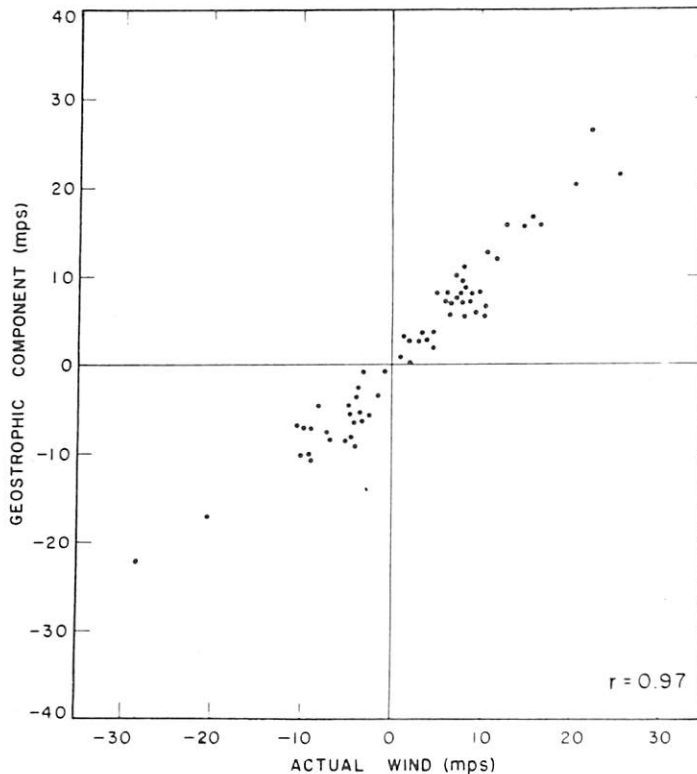


Figure 16. - 500-mb. wind vs. 500-mb. geostrophic component.

Figure 17a. - 1-6 km. wind vs. geostrophic component computed from the mean of 850-, 700-, and 500-mb. heights.

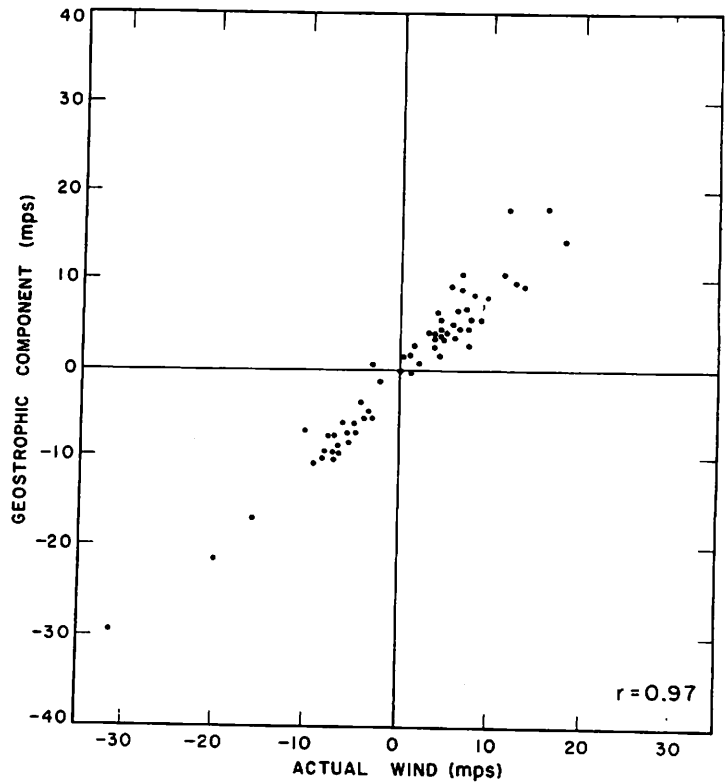
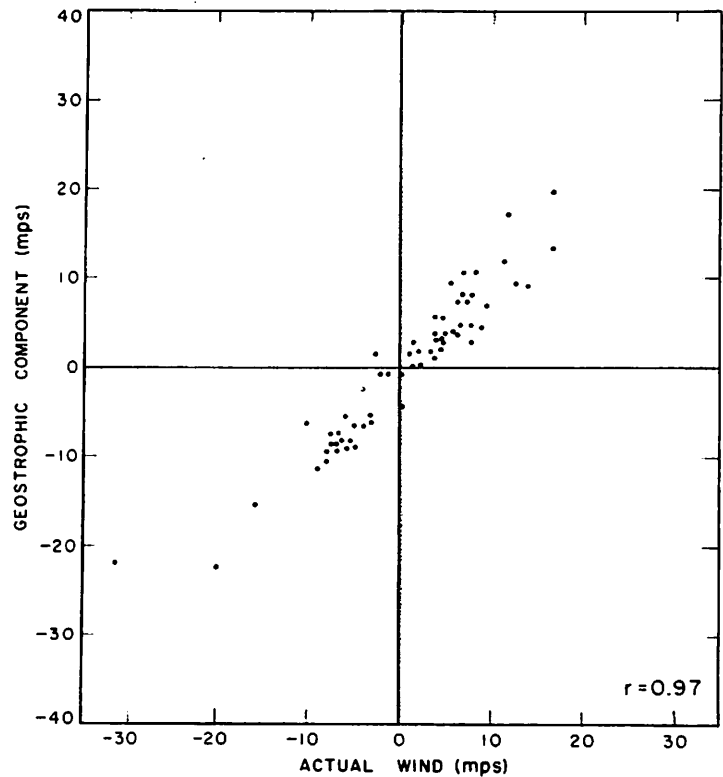


Figure 17b. - 1-6 km. wind vs. geostrophic component computed from the 700-mb. chart.



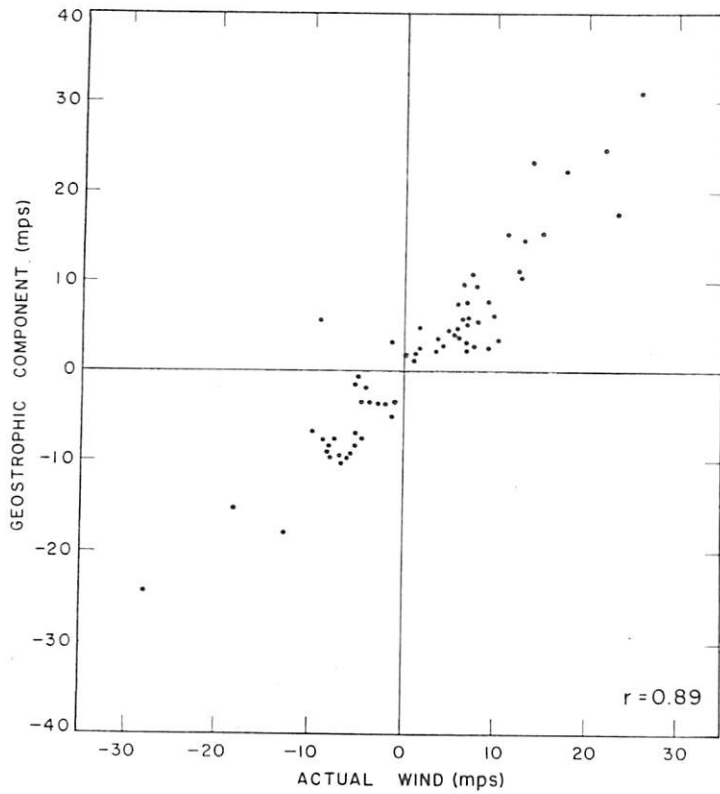


Figure 18a. - 1-10 km. wind vs. geostrophic component computed from the mean of the 850- and 300-mb. heights.

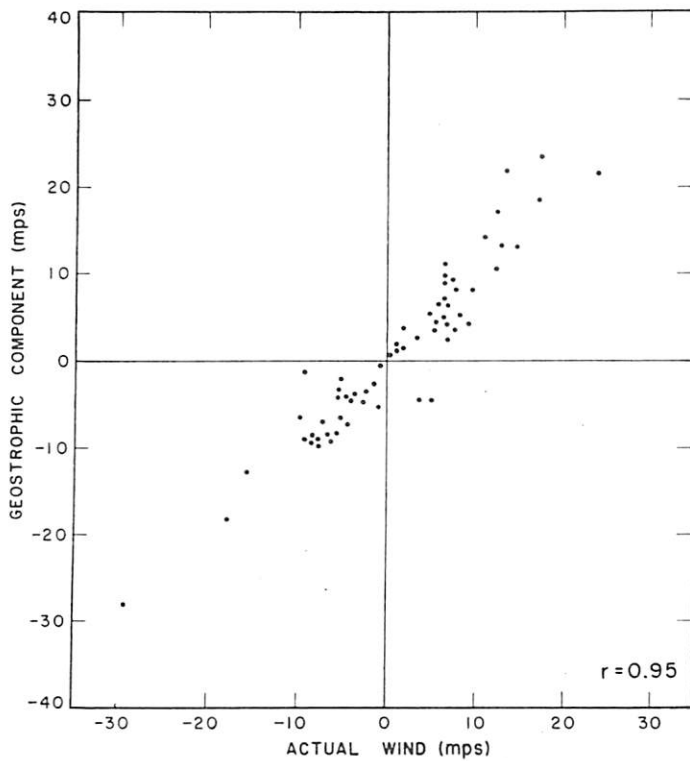
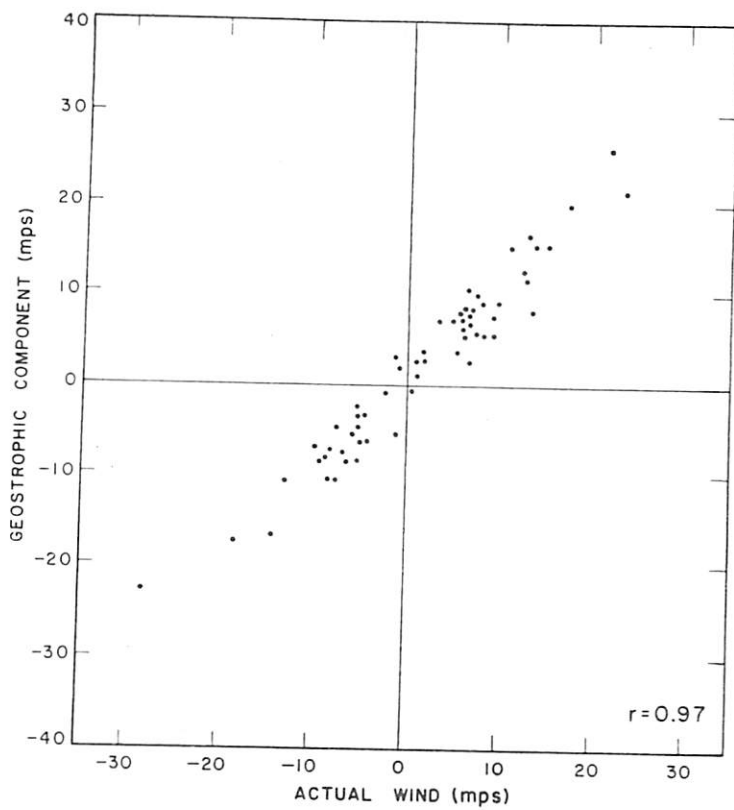


Figure 18b. - 1-10 km. wind vs. geostrophic components computed from mean of 850-, 700-, 500-, and 300-mb. heights.

Figure 18c. - 1-10 km. wind vs.
500-mb. geostrophic component.



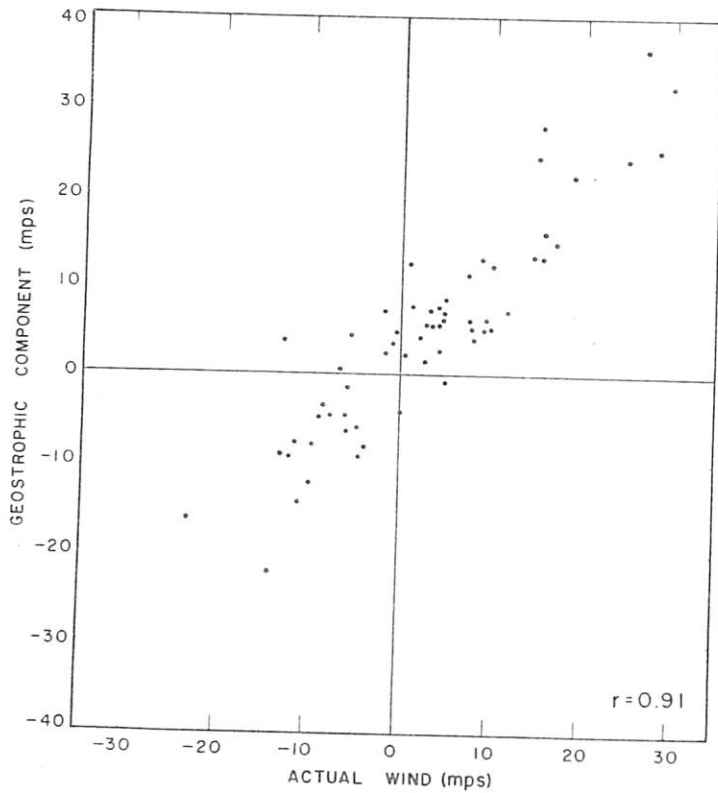


Figure 19a. - 6-12.5 km. wind vs. geostrophic component computed from the mean of 500-, 300-, and 200-mb. heights.

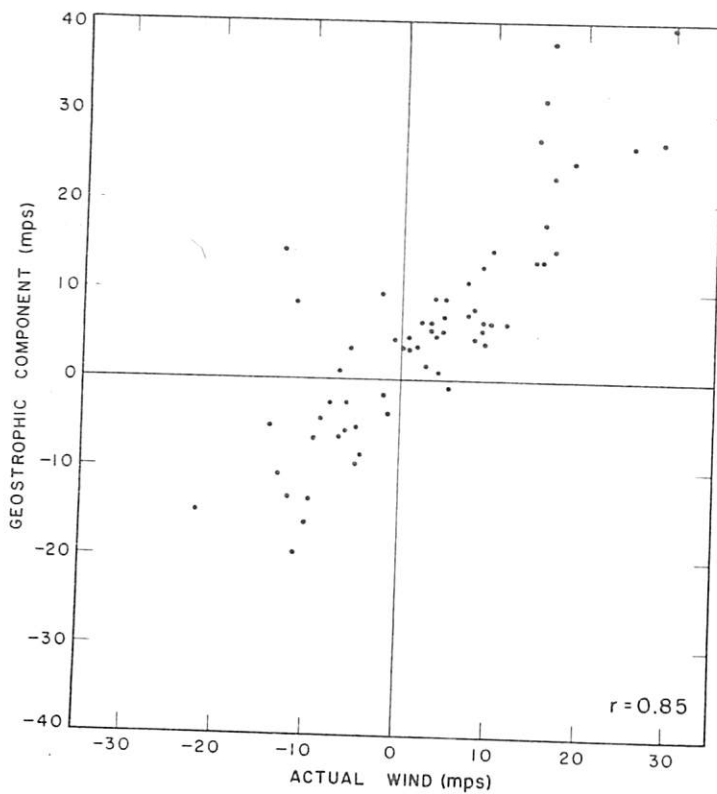


Figure 19b. - 6-12.5 km. wind vs. geostrophic component computed from the 300-mb. chart.