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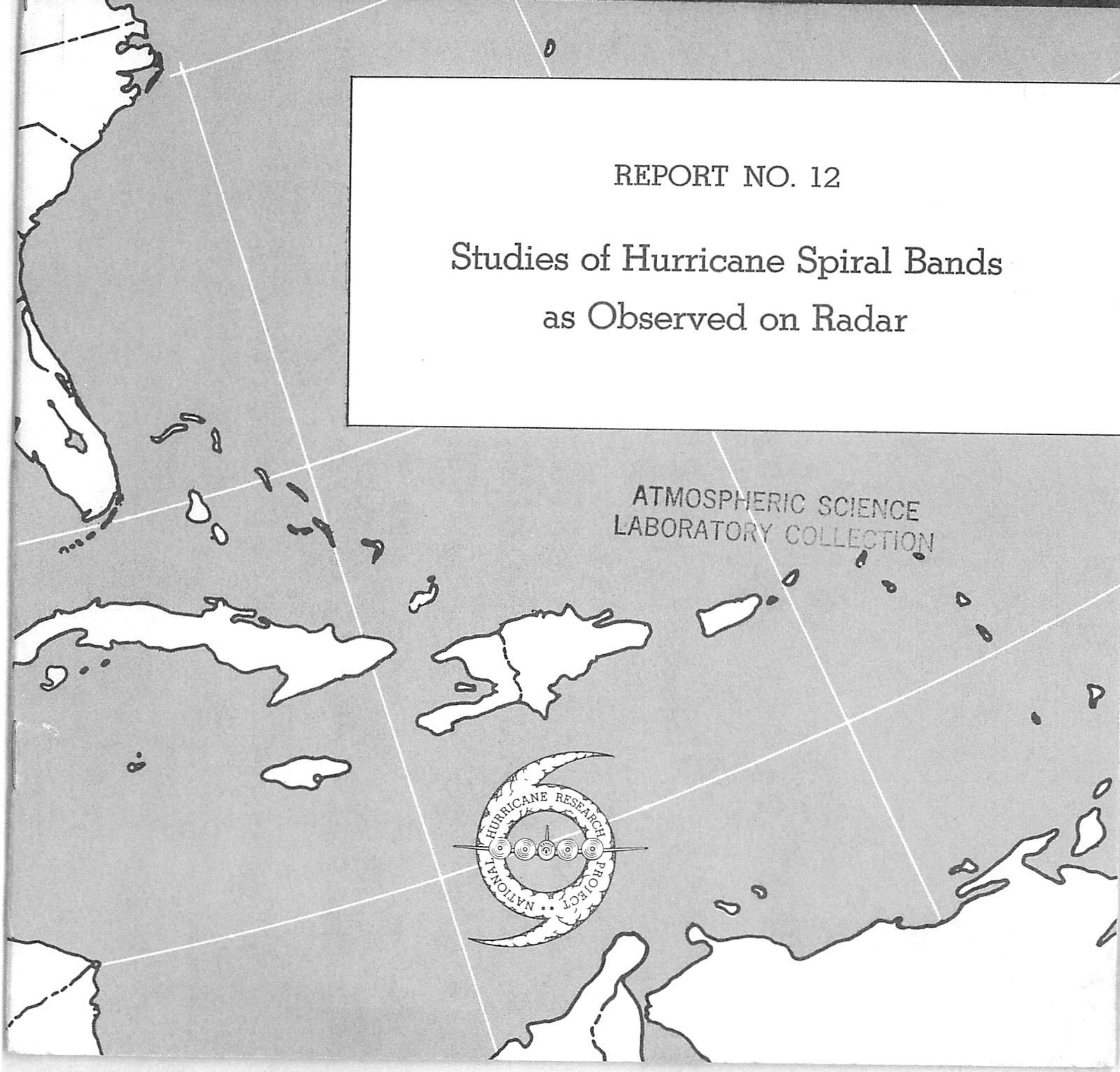

REPORT NO. 12

Studies of Hurricane Spiral Bands as Observed on Radar

NATIONAL HURRICANE RESEARCH PROJECT

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

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Studies of Hurricane Spiral Bands as Observed on Radar

by

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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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Commerce-Weather Bureau, Washington, D. C.

STUDIES OF HURRICANE SPIRAL BANDS AS OBSERVED BY RADAR[1]

[Manuscript received June 17, 1957]

ABSTRACT

A modified logarithmic spiral which provides for the limiting circle necessitated by the eye of a hurricane as well as theoretically circular storm construction is presented. This modified formula also accounts for varying crossing angles which may more truly represent the structure of hurricanes found at low latitudes than the original "fixed crossing angle" spirals. These various formulas are compared and the original simple spirals prove to be more practical for operational use.

Correlations between surface winds and the movements of radar spiral band elements for several storms show the relative unimportance of minor variations in surface terrain over which the storm passes and the comparatively low steering levels controlling the patterns these elements form. In addition, simple correlations between spiral band characteristics and other storm parameters are presented along with further evidence of pre-hurricane squall lines. A variety of arguments is presented to show that the radar rain band pattern reflects the wind flow in a layer centered near 2,500 feet.

INTRODUCTION

The purpose of this research, as stated in the Final Report on U. S. Weather Bureau Contract No. Cwb-8735 issued in October 1956 is: "...to make a comprehensive study of precipitation bands in hurricanes as observed on radar, including (1) their relationship to the center of the storm; (2) changes of their characteristics in relation to the translatory movement of the storm as well as to various internal parameters of the storm, such as pressure, wind, size and shape of eye, etc.; and (3) the evolution of the spiral bands. The ultimate goal is to develop techniques for tracking the hurricane and measuring some of its internal parameters by observing the rain bands on radar."

Several of the introductory sections of the previous report which presented preliminary work and some of the procedures used in the analysis of data have not been reproduced here. However, the work and methods explained in that report will be freely referred to in this paper.

[1] The original paper was identified as Final Report, January 1957, to U. S. Weather Bureau, Contract No. Cwb-9066, The Marine Laboratory, University of Miami, Coral Gables, Fla.

I. ANALYSIS OF DATA

A. MATHEMATICAL DESCRIPTION OF BANDS

Although the previous final report indicated that there was very good agreement between the storm center as represented by the simple logarithmic spiral

(1) $$\ln r = A + B\theta$$

and the best eye or center position as determined by other more conventional methods, several complications arose which seemed to point to a need for revision of the basic spiral formula. When over four hundred of the spirals were classified into "near" and "far" groups, the "near" group of bands had crossing angles which were slightly lower than those for the "far" bands, indicating that they were more circular. Furthermore, the logarithmic spirals seemed to fit rain bands best at intermediate distances. The logarithmic spiral crossed the innermost portions of the "near" bands which form the eye of the storm; and the outer portions of the "far" bands often diverged slightly from the spirals, becoming less circular than the computed spirals. Finally, a theoretical as well as observed inner limit to rain bands is indicated by the necessity for a closed, roughly circular wind system around the center of the storm to avoid excessive convergence in the eye which would result if the bands were allowed to continue to spiral inward toward the storm center indefinitely.

1. <u>The Modified Logarithmic Spiral</u>

The modified logarithmic spiral of the form:

(2) $$\ln (r - r_o) = A_1 + B_1\theta \quad ,$$

(where A_1 and B_1 are constants, r is the radial distance from an assumed storm center to a point on the spiral band, r_o is the radius of an inner limiting circle which is the origin of the spiral, and θ is the angle between the radius and an assumed axis of origin) was derived to answer the above objections to the original simple logarithmic spiral and to provide a more realistic fit to some of the radar rain bands.

In order to interpret this formula and the constants which appear in it, the following analysis is made:

Taking the antilog of (2) gives

(3) $$r - r_o = e^{A_1 + B_1\theta} \quad .$$

Then differentiation of both sides with respect to θ yields

(4) $$\frac{dr}{d\theta} = B_1 e^{A_1 + B_1\theta} \quad .$$

Then substituting for $e^{A_1 + B_1\theta}$ from (3) gives

(5) $$\frac{dr}{d\theta} = B_1 (r - r_o) \quad .$$

Division of (5) by r leaves

(6) $$\frac{1}{r}\frac{dr}{d\theta} = B_1 \left(1 - \frac{r_o}{r}\right) \quad .$$

A simple geometric construction shows that the left-hand side of (6) is the general expression for the tangent of the "crossing angle" with which a curve, expressed in the polar coordinates r and θ, crosses concentric circles of radius r. Making this substitution yields

(7) $$\tan \alpha = B_1 \left(1 - \frac{r_o}{r}\right) \quad .$$

Since the constant A_1 does not appear in (7), it has no bearing upon the crossing angle. It specifies only the angular origin or orientation of the curve. As r becomes very large (7) becomes

(8) $$\tan \alpha_L = B_1 \quad ,$$

where α_L is the limiting maximum crossing angle. Substituting this in (7) yields the desired formula

(9) $$\tan \alpha = \tan \alpha_L \left(1 - \frac{r_o}{r}\right) \quad ,$$

which includes both an inner limiting circle r_o and an outer maximum crossing angle α_L. When $r = r_o$ the tangent of α, and therefore α itself, becomes zero. This radius r_o is the radius of the inner limiting circle which the spiral approaches asymtotically. It represents the distance from the storm center at which the wind is wholly tangential.

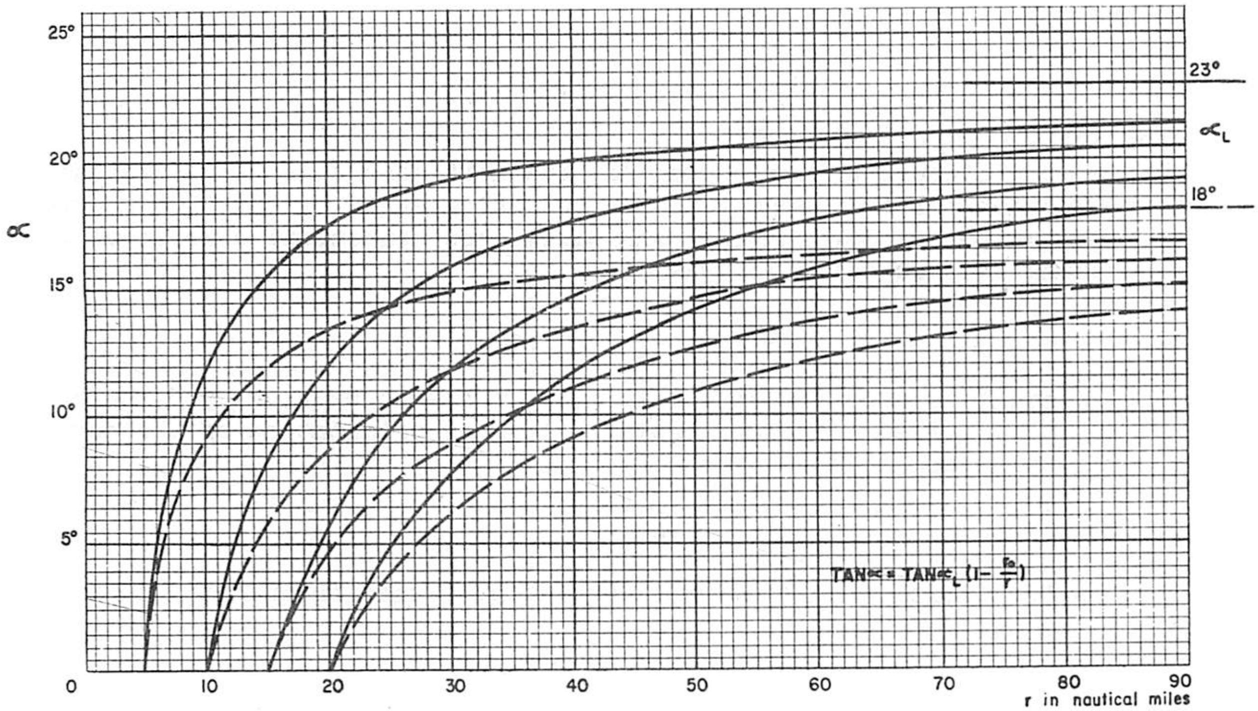
Since the crossing angle in this formulation changes with distance from the storm center, it is instructive to graph its dependence upon distance using several representative values of r_o and α_L. Figure 1 shows two families of curves. The dashed lines illustrate curves all having the maximum limiting crossing angle $\alpha_L = 18°$ but having four different r_o values. The solid lines illustrate four curves having $\alpha_L = 23°$ with the same four r_o values as the dashed curves.

It is evident that an infinite number of curves exist even within the rather narrow practical limits of observed inner limiting circle dimensions and crossing angles. It is also evident that most of the change in α takes place very near the limiting circle. The variation in α within a given family of curves is nearly equal to the subjective limitation of fitting curves to the radar data in the ranges at which most spiral bands are observed.

2. Utility of the Modified Spirals

Myers [1] has developed a curve from empirical data which shows the relationship between crossing angle for hurricane surface winds and distance from the storm center. Since this curve can be represented in the form

(10) $$\frac{1}{r}\frac{dr}{d\theta} = \tan \alpha \ (r) \quad ,$$



FAMILIES OF MODIFIED SPIRALS

HAVING VARIOUS r_0 (LIMITING INNER CIRCLES) AND α_L (LIMITING MAXIMUM ANGLES)

FIGURE 1

i.e., crossing angle as a given function of distance, a unique spiral streamline is implied and can be determined analytically by integrating this relation.

The basic similarity between Myers' empirical curve and the analytical relation chosen in this study is shown in figure 2, where our modified curve (dashed line) is given the same limiting radius r_o and limiting crossing angle α_L as Myers' curve (solid line). The dash-dot line at $\alpha = 37°$ represents the mean surface wind crossing angle observed below many of the spiral bands of Connie, Diane, and Ione 1955. This might be considered the crossing angle curve for a single logarithmic spiral. When these curves are compared, it seems evident that at any distance beyond 30 miles from the storm center the variations between the curves are less than those which probably existed in the original individual data from which the curves were drawn.

Both the simple and modified logarithmic spirals were developed from radar rain band level data, whereas Myers' curve represents surface wind data. The modified spiral in figure 2 has values designed only to show similarity of form to Myers' curve. The important question of rain band level winds is treated more extensively in a later section.

Several modified spirals were drawn with limiting circles from 10 to 40 miles in diameter and limiting crossing angles from 10° to 30°. Figure 3 shows an example of one of these modified spirals drawn for r_o = 15 miles and α_L = 20°. When r_o is varied and the resulting curves are drawn to the proper scale

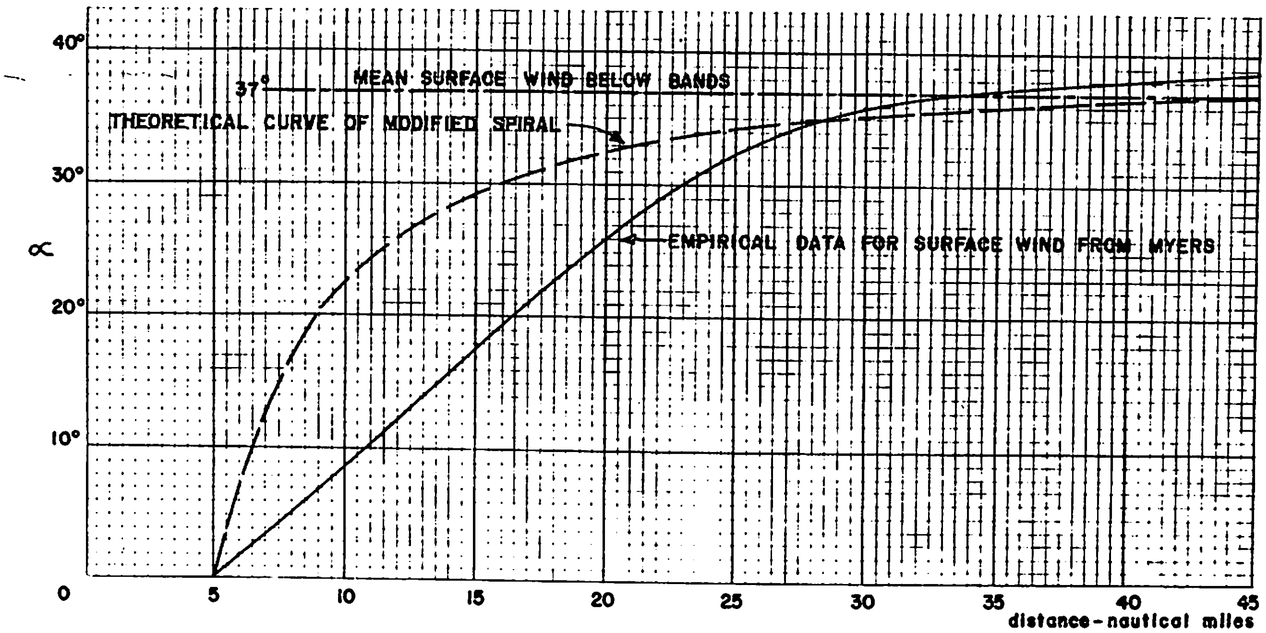


FIGURE 2

they provide a good fit to the near bands (the only ones available for testing), observed in the lower-latitude storms including Easy, 1948, and Betsy, 1956. It should be pointed out that modified spirals are not intended to fit storms found at middle or higher latitudes. These storms, which are usually in more mature or even decaying stages, have higher translation speeds and bands with greater crossing angles which approach the eye more rapidly than low-latitude storms. However, some of the rain bands observed while Ione, 1955 was stationary or looping near latitude 35°N. southwest of Hatteras were also fitted by the modified spirals with good results.

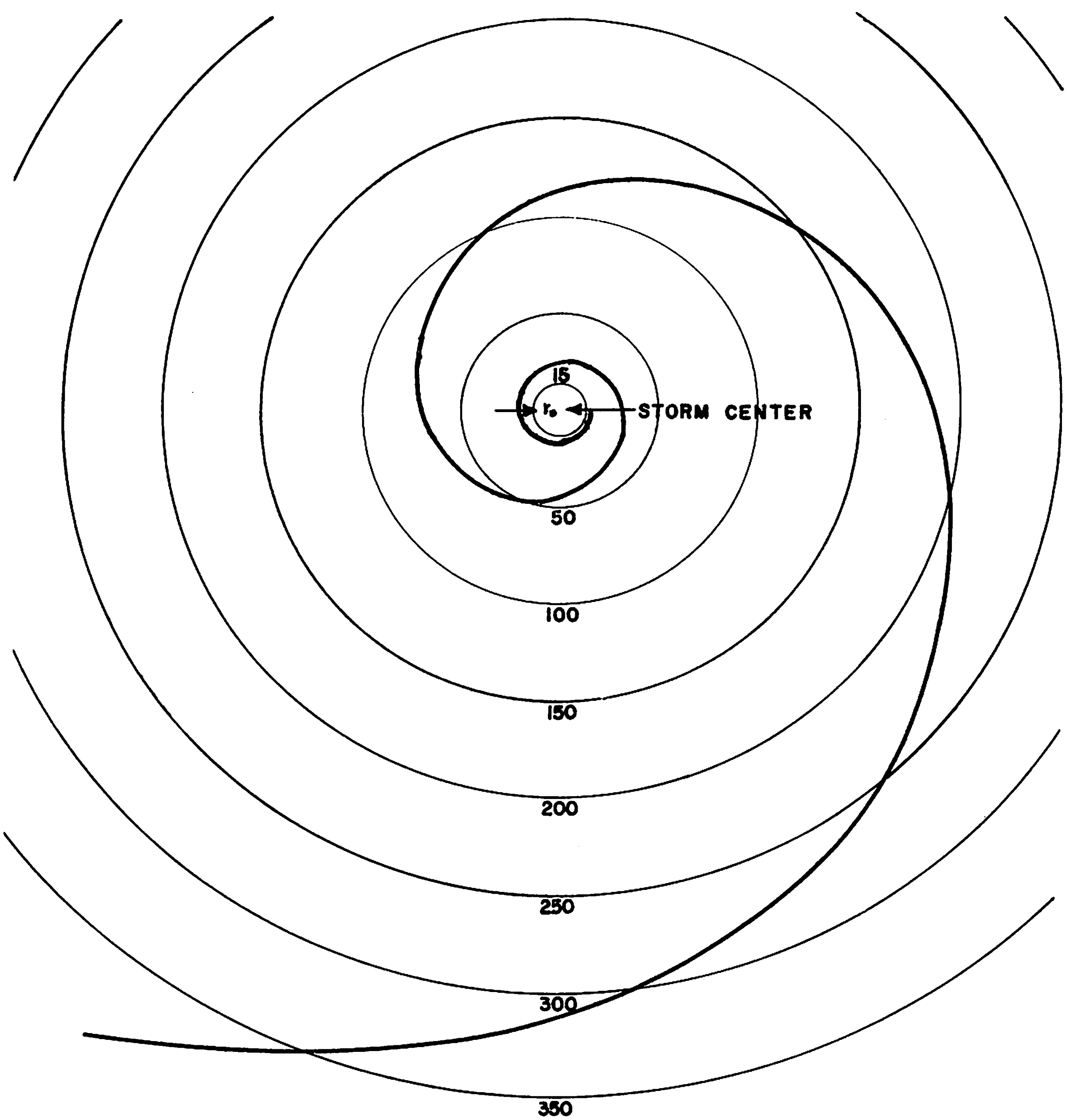
3. Comparison of Simple and Modified Logarithmic Spirals

Although the modified spirals fit some of the data slightly better than the simple spirals, they have several disadvantages which considerably lessen their usefulness.

(a) Only one set of three simple spirals is required in order to fit any size or range scale of radar scope, whereas separate sets of all possible α_L and r_o modified spirals are needed for each radar scope size or range scale.

(b) One simple spiral will give a reasonably good fit to at least one-half of the rain bands used in this study and the October final report pointed out that two of the computed spirals would fit over 83 percent of those data. However, because the crossing angles of modified spirals are dependent on r_o, the size of the eye or limiting circle, as well as α_L, the largest crossing angles they can assume, it would take a larger set of spirals to locate the center of the storm with the same degree of accuracy attained by only two of the simple spirals.

(c) Choice of which of the simple spirals to use in fitting a given rain



MODIFIED LOGARITHMIC SPIRAL

$\tan\alpha = \tan\alpha_L (1 - \frac{r_o}{r})$, $r_o = 15$ Mi., $\alpha_L = 20°$

FIGURE 3

band for the purpose of locating the center of the storm is dependent on only two factors: the latitude of the storm and the approximate mean radius of the rain band from the storm center. Using these two criteria, as well as a subjective appraisal regarding the curve which fits the rain band best, the storm center could be estimated very quickly and accurately in most cases. Only the latter subjective estimate of best fit can be used to determine which one of the larger set of modified spirals to use in locating the storm center. Since the spiral bands observed on radar are often of such a nature that small allowances have to be made for minor variations in order to fit them with any computed curve, several different modified curves might be chosen by various analysts. The variations in center positions obtained when fitting an observed rain band by rotating the computed curves of a family of modified spirals having a constant maximum crossing angle α_L are small, generally less than 20 miles. However, when computed curves having various final crossing angles α_L are rotated so as to give an equally good fit to an observed band, the resulting center positions vary by over 40 miles in some cases.

It is possible to derive more sophisticated spirals that have the near band circular attributes of the above modified spirals but provide an even better fit to the extreme outer ends of the rain bands, which often assume considerably greater crossing angles than the rest of the band. However, this would provide an even larger family of curves with little objective basis for choice among them under operational conditions. The simple logarithmic spirals probably describe the storm center position more accurately for a greater percentage of the data than any other single mathematical expression. Since they are also more convenient, the use of various modified forms has been discontinued.

B. DISCUSSION OF CROSSING ANGLES OF BANDS

It was recognized early in this study that there would probably be differences in the crossing angles determined by (a) a least squares line of best fit of the longitudinal axis of the band to formula (1), and (b) a subjective fitting of a spiral overlay to the longitudinal axis of a band. These differences may result from an inability to form subjective least squares approximations in terms of polar coordinates. However, minor variations are relatively unimportant for they result in differences in storm center determinations of the order of only 10 miles for bands with average radii of 100 miles when the error in crossing angle determination is 5°. The crossing angle error will usually not exceed 5° because errors in overlay selection greater than that are not likely even when only a 90° segment of a band is being fitted. These fitting errors and their effects have been fully discussed in the previous final report. Since differences in crossing angles are well within the lower limits of error, the second method (b) has been used to determine the mean crossing angles of rain bands not previously studied. This has also provided a very limited amount of testing with independent data.

The film of the Florida hurricane in September 1945, taken on a 10-cm. radar at Orlando, Fla., was studied and twenty rain bands were fitted by means of three plastic overlays having constant crossing angles of 10°, 15°, and 20°. Although the 10° overlay was absolutely necessary in two cases in order to give a reasonably accurate center position, use of both the 10° and 20° spirals was limited to only five rain bands. The 15° spiral was used in fitting all of the other fifteen spiral rain bands. A modified logarithmic spiral with r_o = 15 miles and α_I = 20°, was also used on many of the same twenty bands with approximately the same degree of success. As in most of the other storms previously studied, the radar data were not obtained with the primary purpose of identifying spiral bands and consequently only a very few bands were defined well enough to be of use.

One spiral band was fitted from an intense storm observed on Dow Chemical Company radar, Freeport, Tex. on July 10, 1956. This band was almost 350 miles long and 200 miles in diameter. Although the 15° overlay fitted it perfectly, the storm never developed a center but broke up as it reached the Texas coast so that the accuracy of the center position could not be verified.

Formula (1) was used to fit several bands in four radar scope photographs of two 1950 storms from data given by Bunting, et al. [2]. All of the bands had average radii less than 50 miles from the storm center and all required the use of the 10° spiral overlay to give accurate center positions. Although modified logarithmic spirals were not available for the various scales used in the photographs, it was evident that an inner limiting circle existed and that bands found farther from the storm center had greater crossing angles than the 10° overlay used to fit the "near" bands.

The data on Betsy, 1956, were not received in time to include in this report, but they should provide excellent independent information for future studies.

C. PRE-HURRICANE SQUALL LINES

Further evidence of pre-hurricane squall lines was found in the Florida hurricane of September 1945 as observed on radar at Orlando. The storm entered southeastern Florida as it began to recurve, and after traversing most of the peninsula and passing very near the radar site, it crossed the coast south of Jacksonville. This is another of the relatively rare cases where the radar was situated in a favorable position with respect to the storm path and where early and continuous records were obtained containing radar data on these distinctive squall lines.

Apparently, land-based radars either were not in good positions to obtain data on pre-hurricane squall lines during Betsy, August 1956, or else they had no facilities for recording them for future study. However, brief perusal of Navy reconnaissance flight radar data shows that squall lines were present, and they will be studied further when this film is available for more extended analysis.

D. PRELIMINARY CORRELATIONS OF BANDS WITH OTHER STORM PARAMETERS

1. Echo Speed Versus Distance from Storm Center

The speeds of over thirty radar echoes were determined from time-lapse photos of storm Diane during the period from 0800 to 0900 EST, August 17, 1955. These speeds were reduced to speeds relative to the moving storm by the vectorial subtraction of the motion of the storm. These corrected speeds were plotted against the distance from the storm center at which they occurred.

The resulting speed profile displayed a pronounced maximum at a distance of 80 nautical miles. At a distance of 240 miles, the wind speeds fall to zero according to this profile. These results show the utility of the radar determinations, but in this case, the profile itself must be qualified by the fact that all thirty echo movements were found in the right-rear quadrant of the storm. Simultaneous observations of a storm by several radars in favorable positions to view various quadrants, or good data from stationary storms, are necessary to do justice to a study of this nature.

2. Echo Direction versus Rain Band Orientation

Although cursory examination seems to show individual echo movements to be along the spiral rain bands in which they are imbedded, closer examination reveals that their motion is slightly more circular than the rain band shape. This distinction is difficult to determine because nearly all studies must be carried out on moving storms. The "bands within bands" phenomenon discussed in the previous final report is probably a result of the same factors which produce cross-band echo movement.

3. Rain Band Crossing Angle versus Surface Wind Crossing Angle

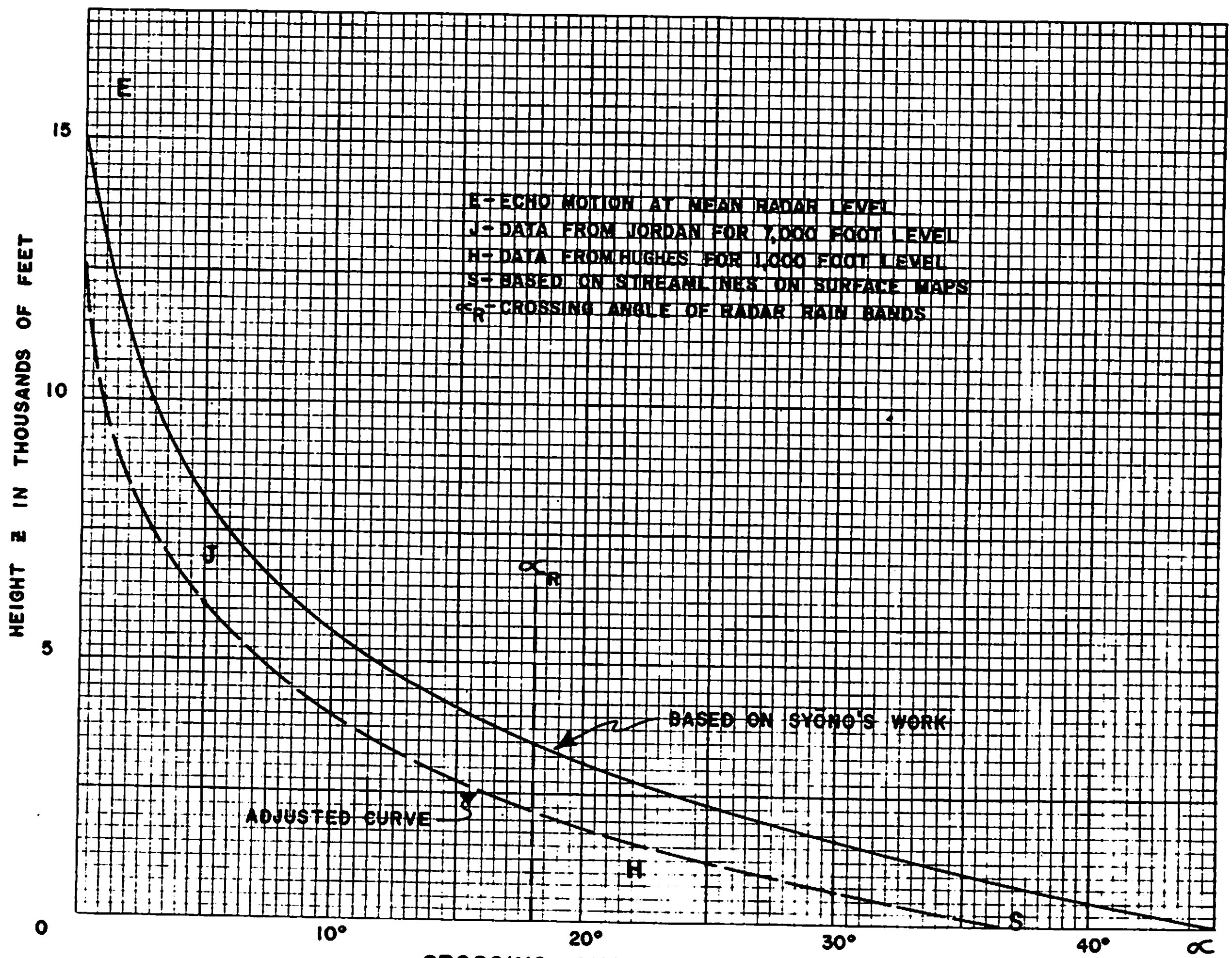
Surface maps and radar photos for six storms were used to obtain mean crossing angles of surface streamlines α_S and mean crossing angles of rain bands α_R. A plot of α_R versus α_S was then prepared which showed a moderate positive correlation between them. Perhaps the most noticeable feature is the relatively small spread in the values of α_R as compared to α_S. α_S has a total spread of 20° and is undoubtedly dependent on a mean surface roughness parameter for each storm. However, α_R is relatively independent of terrain and is, in fact, nearly the same for all of the storms studied. A crossing angle of $\alpha_R = 18°$ is within 3° of the mean for each of the six storms.

4. Rain Band Crossing Angle versus Mean Radius of Rain Bands

Scatter diagrams have been plotted for rain band crossing angles α_R versus mean distance from the storm center for five storms. These values represent the crossing angles α_R of the best simple logarithmic spiral fit to individual rain bands versus the mean distance $\bar{r}$ from the storm center of points separated by angular intervals of 30° along this spiral. This radial distance measure gives greater weight to the lower r values. It was used because it was the most readily available parameter for all of the storms and was not significantly different from various other measures which might have been employed. Although these diagrams show considerable individual scatter as well as variation from diagram to diagram, there is a fairly clear tendency for the crossing angle to increase with distance from the storm center. The points plotted tend strongly to fall within the family of curves shown in figure 1 illustrating the crossing angle versus distance relation used in constructing the modified spirals.

E. EVOLUTION OF SPIRAL BANDS

Measurements of crossing angles of surface streamlines were determined from about thirty surface maps for storms Ione, Connie, and Diane, 1955. These yielded a mean crossing angle of 37°. This value appears as the letter S on



CROSSING ANGLE VS HEIGHT

FIGURE 4

the graph in figure 4 and is also shown in figure 2.

According to Hughes' data [3] concerning radial and tangential wind speeds at the 1000-foot level in Pacific storms, a mean crossing angle of about 23° is implied for the range from 0-100 miles from the storm center. This appears in figure 4 as H.

The few determinations that were made of the angle at which small echoes crossed the spirals about 100 miles from the radar (as mentioned in paragraph 2, section D), indicate angles of less than 5°. This is a difficult parameter to ascertain since it is complicated by the storm motion. Assuming standard radar propagation, these echoes were observed in the broad layer between 7,000 feet and 26,000 feet. A point representing these data is tentatively entered near 16,000 feet and 4° in figure 4 as E.

Jordan [4] gives graphical data on radial and tangential wind speeds at 7,000 feet in the area surrounding a mean storm. With her data, mean radial and tangential wind speeds around a storm have been determined at a distance of 120 miles (the minimum distance toward the storm center which her data include). Taking the ratio of these two gives the tangent of a crossing angle of 5°. This result appears in figure 4 as J. Before attempting to draw a curve through the few and rather uncertain points E, J, H, and S, the theory of directional wind shear due to kinematic viscosity should be considered. The results of Syōno's investigation [5] have been used for this purpose. His calculations yield expressions for radial and tangential wind speeds as functions of height. When the radial is divided by the tangential wind speed the tangent of the crossing angle is obtained and is given by

$$\tan \alpha = \frac{\sin \beta z}{\cos \beta z - e^{\beta z}}, \quad \text{where } \beta = \sqrt{\frac{\lambda + \zeta}{2\nu}}, \tag{11}$$

z is the height in cm, λ is the Coriolis parameter at 35° N. Lat., ζ is the mean vorticity of the region of the storm under consideration and is taken from Riehl [6], and ν is the kinematic viscosity taken from Syōno. The values of these quantities are:

$$\lambda = 8.3 \times 10^{-5} \text{ sec}^{-1}$$
$$\zeta = +2 \times 10^{-5} \text{ sec}^{-1}$$
$$\nu = 5 \times 10^{5} \text{ cm}^{2} \text{ sec}^{-1}$$

The relation between α and z given by (11) is shown in figure 4 as the solid curve.

The broken curve beginning at S, the most reliably known point, is intended as a better approximation to the real state of affairs. This curve is then continued with the solid curve serving as a general guide as to shape. Point H, representing Hughes' typhoon data, is treated as being somewhat lower than average since it is based on storms over water where the effect of surface friction is at a minimum. Point J, representing Jordan's data, is treated as being unusually high since it is based on measurements at greater distances from the storm center than were used in the radar investigations. (As has been discussed in sections A2 and D5, the crossing angle increases with distance.)

Since inflow increases with crossing angle, the broken curve proposed is in accord with Riehl's statement [6] that most of the inflow is in the lowest 3000 feet and that there is little or no net inflow in the layer from 10,000 to 30,000 feet.

The broken vertical line labeled $\overline{\alpha}_R$ in figure 4 indicates the mean value computed for the crossing angles of the radar rain bands of all the storms studied. If the broken curve of figure 4 is accepted as the true profile of the crossing angle of the wind versus height, then it may be seen that the mean crossing angle of the radar rain bands is the same as that of the wind flow at about 2,500 feet. This rather unexpected result strongly suggests that it is the wind flow around the 2,500-foot level, with its associated intense convective activity, which is responsible for both the generation and the shape of the spiral rain bands. The section of the atmosphere integrated in the radar photographs displaying the bands normally ranged from about 5,000 to 25,000 feet, and rarely extended as low as 2,500 feet. Consequently, the shape of the radar-level rain bands which may be observed at relatively high levels provides a means of inferring the low-level wind flow pattern.

II. CONCLUSIONS

Despite the fact that more complicated spirals can be found which might fit a given band or group of bands slightly better than the original simple logarithmic spiral, the latter provides a better fit to the vast majority of bands studied. Furthermore, (a) only a very few are needed to fit all bands on any radar scope, (b) several slight clues are available to help in selecting an overlay to fit a given band, and (c) a slightly better storm center position is given in most cases by the use of the original simple logarithmic spiral.

Although data are still not available to provide conclusive evidence of the fact, low-latitude storms seem to have slightly lower crossing angles than storms at higher latitudes. Whether this is a result of lower translation speeds for the low-latitude storms is a question which also warrants further study.

Evidence seems to indicate that although a slight positive correlation exists between the surface wind crossing angle α_S and the rain band crossing angle α_R, the rain band spirals are relatively independent of minor terrain variations. However, echo movement is generally outward across the bands, indicating a lower crossing angle than that observed for the bands themselves. This and other observed and theoretical evidence indicates that convergence and convective activity near the 2,500-foot level produces the spiral rain band pattern normally observed by radar at considerably greater heights.

III. FUTURE PLANS

If this investigation is continued, work will be concentrated along the following lines:

1. The search will be continued to obtain all possible radar scope photographs and motion pictures of hurricanes, especially those occurring at lower latitudes. The authors will greatly appreciate receiving information regarding the location or availability of such data.

2. All available photographs of spiral bands will be enlarged, analyzed, and classified to determine: (a) changes of band characteristics with relation to the translatory movement of the hurricane; and (b) correlations between characteristics of bands with hurricane intensity, size, latitude, winds, etc.

3. Further studies will be made on the motion and evolution of individual storm cells as well as entire precipitation bands observed on radar.

4. "Pre-hurricane squall lines" and "internal squall lines" or "pressure jump lines", which are all distinctly different from normal spiral bands, will be further investigated.

5. Operational techniques including curves, nomograms, and other devices for the use of radar data will be developed wherever possible.

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