EYE REGION OF HURRICANE EDNA, 1954

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(Original manuscript received 4 November 1957; revised manuscript received 3 February 1958)

ABSTRACT

The eye region of Hurricane Edna (1954) is studied with the principal aid of radar and dropsonde data. Vertical sections show that over the eye there was a thick layer derived from the wall cloud which bounded the eye on the northeast. Precipitation fell from this upper layer into drier air beneath. A reasonable mechanism is thereby suggested by which large moisture values can become associated with air in the eye without producing the wet bulb potential temperatures or high winds characteristic of the rain-filled masses outside the eye.

Radar data giving the height of the "bright band" or melting level show that the warm core structure of Edna was most pronounced within the radius of maximum surface winds. This result is qualitatively confirmed by soundings and by comparison of surface winds and the speeds of radar weather elements in various portions of the storm. The radar photographs also show that heavy precipitation near the eye of Edna was bounded sharply in the western semicircle along an east-west line through the center of the storm. This boundary must be associated with a rather large change of vertical air speeds and therefore has special dynamic significance.

1. Introduction

The center of a hurricane is marked by light winds and the absence of rain, and is called the eye. The eye has been studied for many years, but detailed records at upper levels have only been available for about the last decade. A recent account of its significance for hurricane thermodynamics is given by Riehl [14]. Plan-position indicator (PPI) radar records of many different hurricanes have shown the eye to be at or very near the center of spiralling of rain bands. However, until the eye of Hurricane Edna, 1954, passed directly over Cape Cod, Massachusetts on 11 September, no vertical radar sections (RHI displays) through a hurricane eye were available for study.

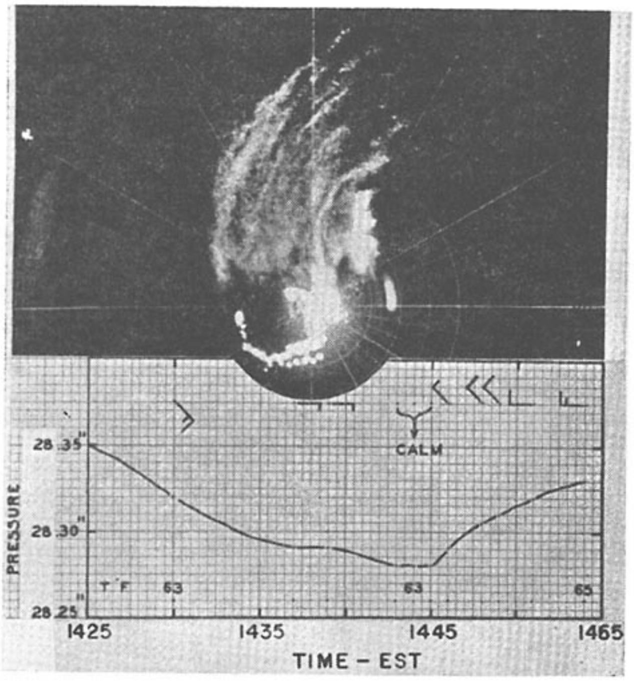

FIG. 1. Photograph of the plan-position indicator of the 23 cm FPS-3 radar, South Truro, Mass., 1504 EST, 11 September 1954, and record of surface pressure, temperature, and wind at the same place some minutes earlier. Circular range marks on the photograph are at intervals of ten nautical miles from the radar, north is to the top, and the outline of Cape Cod, Mass. appears at the center of the illustration. The eye of Edna is believed to be located on the photograph at 60 deg, 15 n mi.

Edna was observed by several radar instruments of the M.I.T. Lincoln Laboratory site at South Truro, Massachusetts (location is illustrated by fig. 5) and by aircraft reconnaissance. Subsequently, many of the data were analyzed and the results published [9; 11; 17]. The present note is intended to describe some interesting and unique observations of the eye region of this storm. This description may help us to a better understanding of hurricane dynamics and is also intended to demonstrate how radar can be used as an important analysis tool.

2. General description of eye area

Fig. 1 shows the PPI of the 23 cm FPS-3[1] radar at South Truro at 1604 EST, just 20 min after the occurrence of calm and partly cloudy skies at South Truro. The outline of Cape Cod shows clearly at the center of the picture which is marked by range rings at intervals of 10 n mi. This PPI picture also shows the

[1] The notation, FPS, refers to radar equipment which is Fixed in location (*i.e.*, not readily portable), of the Pulsed type (as opposed to continuous-wave equipment), and used for Searching.

banded structure characteristic of the precipitation of this storm. The band which extends southward from the main mass to a point 10 mi east of the radar site was reported by Captain Wallace Taylor, observer on the reconnaissance B-29, to be a line of heavy cumulus, decreasing in vertical extent toward the south. This line is believed to bound the western portion of the eye. The eastern side of the eye is bounded by the southern portion of the intense echo band 20 to 40 mi northeast of the radar site. This PPI picture was taken at reduced receiver gain in order to display the prominent features in the vicinity of the eye. The precipitation actually extends out to much greater ranges to the north-northeast and northwest. Also, the areas between the more intense bands are filled in at higher gain.

Fig. 2 displays the vertical radar cross sections recorded by the 3 cm FPS-4 radar, just five minutes after fig. 1. The scale of these pictures is given by fig. 3. These RHI cross sections show that the intense echo or wall cloud, twenty to forty miles northeast of the radar site, has an associated dense anvil which at 35,000 ft trails the main cloud mass and overlies part of the volume not containing low-level precipitation masses. The orientation of this veil probably indicates that in its vicinity the component of the wind in the direction of motion of the storm eye decreases with height. Its form is also indicative of rising motion and high level divergence above the wall cloud since the anvil has a much greater area at 35,000 ft and above than at lower levels, such as 25,000 ft. Note especially that the anvil is connected to the wall cloud only at 40 deg azimuth (fig. 2). Toward 220 deg, upper layers are found at progressively lower altitudes with increasing range and may represent descending and evaporating remnants of earlier anvil clouds. R. H. Simpson has told the author that this anvil is not the same as the spiralling cirrus reported by him over Edna's eye [17]. It may, however, have had an origin similar to that of the cirrus-stratus over the eye of Dolly, 1951 [16].

Another very interesting feature of the vertical sections is a "V" or inverted cone of rain-free air 10 mi southwest of the sloping vertical axis of the wall cloud (see especially pictures at azimuths 40 deg and 50 deg). The position of this feature at the time of the photographs corresponds within the limits set by various uncertainties to that expected for the center of calm, on the basis of its observation over South Truro and the average motion of the hurricane as a whole. The presence of precipitation echo at the surface in the center of the eye is undoubtedly due to the detection of light drizzle by the sensitive FPS-4 radar. Scattered tiny droplets were observed at South Truro during the calm.

Fig. 4 depicts horizontal sections through the eye at 12,000 ft height intervals. South of the radar site, only a few high-level precipitation layers are seen. Fig. 2 shows these to be more or less connected, and suggests that they are associated with the anvil or veil over the eye. To the north and northwest, where heavy precipitation continues, the low-level echoes extend to the maximum range of the radar display. The RHI's show some evidence of attenuation of the distant signals in these directions by the intervening rain. To the west of the radar site, echoes at the lowest levels extend farthest south. This is probably due in part to the northerly, low-level winds west of the eye which carry the descending precipitation southward from the region of active updraft and precipitation deformation.

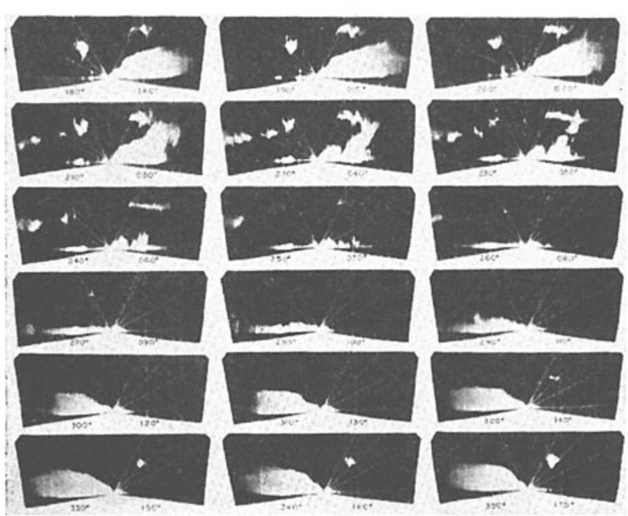

Fig. 2. Photographs of the Range-Height Indicator of the 3 cm FPS-4 radar, South Truro, Mass., 1508, 1512 EST, 11 September 1954. Each block in this figure is a vertical cross section through the radar site, at the azimuths indicated, and is prepared by matching two RHI photographs at supplementary azimuthal angles, one of the prints being prepared from a reversed negative. The center of the eye of Edna is believed represented in the radar echoes by the open "V" which appears at azimuths 040 deg through 070 deg. The deep echo at 020 deg through 050 deg is thought to be the wall cloud northeast of the eye. The echo above the "V" apparently has its origin in the wall cloud and may represent an important means whereby moisture is added to the dry air often present at various levels in the eye.

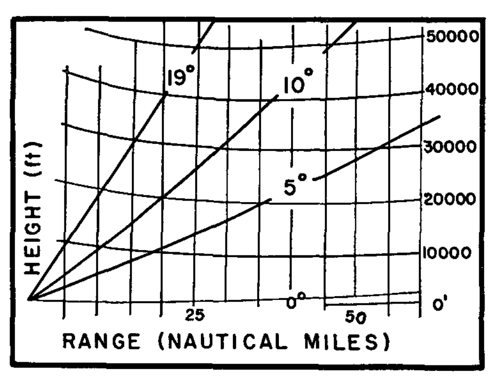

Fig. 3. Key to photographs of fig. 2. The angle marks refer to the elevation angle of the radar beam. The sector above 20 deg is not scanned in this case and in fig. 2 appears as a blind inverted cone centered at the radar.

The southern boundary of 2000 ft echoes of fig. 4 effectively marks the line along which precipitation ends at the ground; this line is also well defined in the PPI photograph which is fig. 1. This striking demarcation must separate updrafts in the forward semicircle of the storm and downdrafts to the rear, as is usual with northward moving hurricanes in middle latitudes [6]. The complete explanation of this phenomenon would doubtless have important implications for the whole storm system. Although insufficient data preclude our studying this in detail, some further information is given by the RHI sections. For example, it is interesting that the vertical sections, fig. 2, show weather echoes just north of the demarcation line to have very sharply defined tops. These sharp tops suggest a close correspondence between limits of upward vertical air velocities and the observed echoes. (Diffuse limits of radar weather echoes imply gradual thinning of precipitation with a strong probability that undetected light snow or rain masses and accompanying ascending air currents fill large spaces.) To the extent that this interpretation is valid, the boundary separating rising currents in the forward left quadrant and subsidence in the rear is not vertical along the line where precipitation ends at the ground, but slopes northward with increasing height, about 15,000 ft in 15 mi. A similar, though less pronounced distribution of vertical velocities may be usual in connection with winter storms of New England, where low level snow flurry or shower activity often persists in connection with a definite clearing aloft after passage of a trough or low center [2; 3; 10].

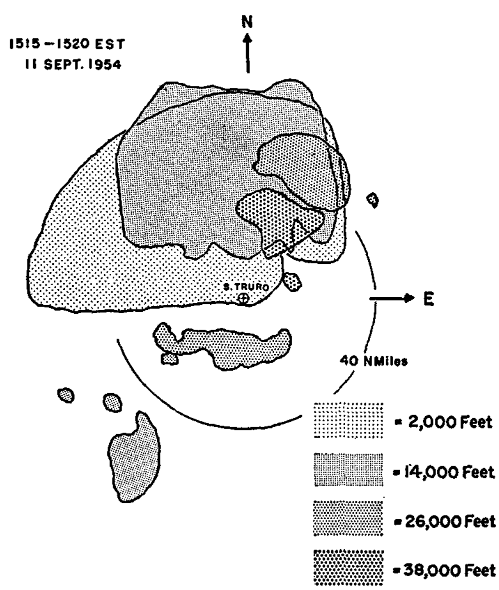

FIG. 4. Superimposed constant level charts of radar echoes as derived from an RHI series made a few minutes after that shown in fig. 2. The eye of Hurricane Edna is marked by notches in the 2000 ft and 14,000 ft layers 20 to 25 mi northeast of the radar site. The northeastward slope of the eye shown here and in fig. 2 is as reported by aircraft reconnaissance four hours earlier.

Fig. 5 shows the weather map at 1500 EST, about ten minutes prior to the time of the radar picture shown. This map has been prepared by reference to copies of original station records, interpolation between reports at earlier and later times, and use of data from Nova Scotia and other places not shown on the illustration. Comparison of the map with the radar pictures shows that the radar center, as nearly as can be judged, is located about ten miles southeast of the center of the last closed isobar on the map. For further details regarding the radar identification of the hurricane eye, the reader is referred to [11].

3. Thermal structure of the eye area

Fig. 6 shows a sounding in the eye of Edna which to 700 mb is based on aircraft dropsonde information gathered four and one half hours before the RHI and PPI illustrations shown here. The aircraft dropsonde has been extrapolated to 500 mb from consideration of the radar "bright band," and it is important to note that the portions of the sounding which are above and below 700 mb are not part of the same vertical column. That below 700 mb was measured by dropsonde in mostly clear air, while the 500-mb values refer to the adjacent rain area. The bright band which has furnished the 500-mb data is a layer of enhanced

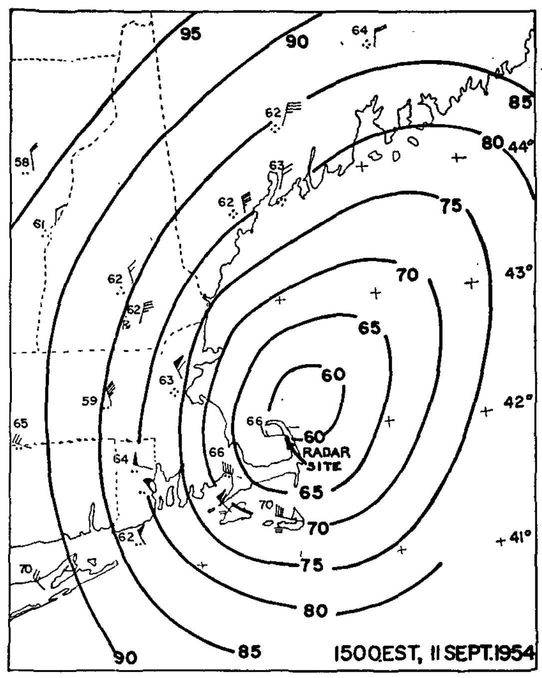

FIG. 5. Simplified surface weather chart, 1500 EST, 11 September 1954. Wind speeds are indicated in miles per hour with a flag indicating 50 mph, and isobars are labeled in millibars with initial "9" omitted. South Truro, the site of the radar on Cape Cod, experienced calm wind and partly cloudy skies fifteen minutes before map time. Note heavy rain in Maine more than 200 mi north of the hurricane center, but only light rain or less everywhere over land south of an east-west line through the hurricane center.

radar return marking the stratum in which snowflakes melt. In the RHI's reproduced here, the bright band shows fuzzily at great range at 340 deg and as the flat echo top at 300 deg and 310 deg. The flat-topped echo appears in these photographs where snow is not present directly above the bright band, the melting snow giving rise to the bright band being advected into the beam from the north, or where snow is not intense enough to be detected by radar. The reader is referred to the literature, for example [1; 18], for more complete quantitative discussions of the bright band phenomenon.

Careful study of the original photographs reproduced here as fig. 2 shows the bright band between 17,000 and 18,000 ft in the rain immediately surrounding the radar eye. As shown in fig. 6, a 500-mb temperature of 0C is associated with a height of about 17,700 ft, and the mid-point of the bright band should be somewhat below that level.

Probably the most interesting aspect of the bright band datum is that it shows conditions at 500 mb in the rain area adjacent to the eye which must have arisen from lifting of air from the surface to that level. A state of moisture saturation at 0C and 500 mb would be achieved by lifted saturated air from the surface if the initial wet bulb temperature were 77F and pressure 1000 mb or 75F and 960 mb. These figures correspond closely to surface conditions reported by ships at 1330 EST. On the other hand, the mean West Indian sounding of fig. 6 indicates that wet bulb potential temperatures (θ_w) in the middle troposphere of the hurricane environment are considerably lower than that of the 500-mb rain area about the eye. While the 500-mb precipitation bearing air surrounding the eye is thus shown to have a surface origin, the 700-mb rain-free air measured by aircraft may not, since the surface temperatures consistent with the 700-mb conditions are some 3F higher than the highest observed. The possible stratospheric origin of this 700-mb air is discussed below.

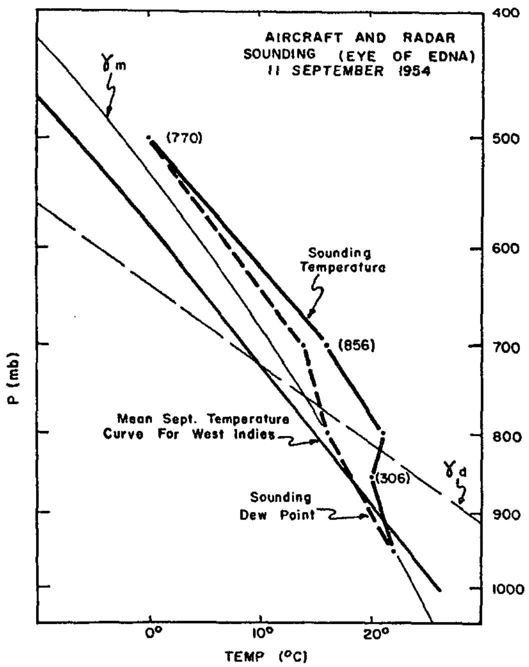

FIG. 6. Upper-air data in the eye region of Hurricane Edna and mean temperature curve for the West Indies in September. The Edna sounding to 700 mb is based on dropsonde observations made at 1030 EST, 11 September 1954. Data at the 500-mb level have been entered on the basis of radar observations made at about 1500 EST, and described in the text. The 500-mb conditions shown refer to the rain area near the eye, while those at 700 mb and below apply to rain-free air. The West Indian sounding is from (7) and is based on records gathered at Swan Island, Miami, and San Juan.

4. Dynamics consistent with the eye observations

The wet bulb potential temperature at 700 mb is reported by aircraft dropsonde to be about 300K, 3F higher than the highest temperatures reported by ships in Edna and about 5F higher than those given in the surface layers by the average sounding illustrated in fig. 6. The complete average September sounding for the West Indies shows θ_w = 300K near 125 mb, so one might imagine the air at 700 mb in the hurricane eye to have descended from this upper level. However, an immediate difficulty is presented by the reported specific humidity at 700 mb which far exceeds the values associated with saturated stratospheric air. We note further that the uncertainties inherent in humidity and temperature measurements by aircraft dropsondes and surface ships are such that one cannot definitely link the 700-mb air in the eye to a high-level origin. No definite conclusion on this point is reached here, but it is interesting to note that the radar photographs illustrate a mechanism whereby moisture can be transferred from the precipitation area about the eye to the air within the eye without at the same time carrying along the momentum and θ_w characteristic of the rain area, as occurs with mixing. This mechanism is simply the gravitational separation of precipitation from the air mass that bears it. The process is illustrated by the RHI photographs which show material from the layer at 35,000 ft actively descending and evaporating in drier air beneath. The stalactite-like appendages which appear at the base of the upper layer are the direct evidence of this [5; 10, pp. 147–156].

The distribution and origins of air within the hurricane eye are given by the three dimensional fields of large-scale motion and by mixing processes of smaller scale. Malkus [12] has shed much light on this problem through her consideration of the moisture and momentum balance following mixing processes between the eye air and its environs, but it is likely that more accurate measurements of hygro-thermal and dynamic properties of the air within the eye at several levels will also be a prerequisite to a really satisfactory formulation of the general field of motion. As an illustration of the importance of such observations, we note an interesting relationship between the speed with which an air parcel must come to a given observed level in the eye and its horizontal motion relative to the eye. Assume, for example, that the air at 700 mb in the eye of Edna came from 125 mb and had no systematic velocity component in the direction of the eye's motion. With an eye diameter of 20 mi, an average downdraft of about 10 mps or more is required to carry the air from the upper level at the edge of the eye to the lower level at the eye center, while the eye speeds along at about 35 mph. A vertical current of this magnitude should be observed by the crew of a weather reconnaissance aircraft which remains in the eye for any appreciable time [4], but no reports of such a phenomenon were made by the aircraft observer in this case. If the air at upper levels within the eye has an average velocity equal to that of the eye itself, the air within would remain there except for the effects of mixing with that of the rain area outside. In this case, no sustained downdrafts are required by this relation, and only that necessary to maintain the eye properties in the presence of mixing with the environment need occur. This problem has also been discussed by Malkus [12] in considerable detail. Unfortunately, reports are not available concerning the detailed relationships between wind and pressure at upper levels in the eye of Edna, although calm horizontal winds are reported at the ground at the same time that the pressure there attains its minimum value (see fig. 1). This problem is apparent in other cases, too, such as Typhoon Marge, reported by Simpson [15], who suggests that air in the eye at about 17,000 ft descended to there from 47,000 ft. If this occurs with symmetrical temperature field aloft and calm horizontal wind, vertical drafts of at least 2 mps are required, on the basis of Simpson's figures. While this is a large figure compared to those usually encountered in synoptic practice, the magnitude is too small to be readily measured by an ordinary airplane [4]. However, a carefully calibrated aircraft could add much to our knowledge by measurements of both vertical and horizontal winds in hurricane eyes.

It is clear that better observations in the eye are required in order to obtain a clear picture of the way in which the hurricane air flows in order to satisfy the hydrostatic requirement of a warm core. The present study points to no definite conclusion regarding the origin of the 700-mb air reported by dropsonde in the eye of Edna. However, the author is inclined to reject the possibility of a 10 mps downdraft in the eye of this storm and to believe that the air at upper levels tends to move with that feature while subsiding at a substantially slower rate, or that the dropsonde humidity report suggesting a very high-level origin for this air is erroneous. This study does suggest an important means by which moisture can be added to air in the eye without addition of other properties of the environmental air, and thereby explains reports of high humidity and θ_w which are incomprehensible on any other basis excepting instrumental error.

The high temperature and relative humidity of only 70 per cent reported at 800 mb by the aircraft sounding are direct indications of subsidence at low levels in the eye. However, it can be shown that θ_w at 800 mb is about the same as at the surface. Therefore, this air probably first ascended from the surface in the rain area near the eye and, after attaining some intermediate level, was caught in a sinking branch of the circulation and descended again.

The RHI photographs of fig. 2 and the horizontal sections derived therefrom indicate a very asymmetrical structure. Similar configurations have been reported elsewhere on occasion, for example by Potter [13] and Simpson [16]. However, in the present case, the pattern shown is probably not a steady form since PPI radar pictures and reconnaissance observations indicate that the eye area is constantly changing. Further evidence of a transient or intermittent wall cloud is offered by the weather events at South Truro immediately preceding arrival of the eye. Only light rain was reported and the heavy precipitation, such as expected with the wall cloud shown in radar photographs, ended an hour before.

5. Winds and temperature within 200 mi of the eye

Finally, we should show how radar measurements serve to augment our knowledge of the three-dimensional fields of wind and pressure. Fig. 7, taken from

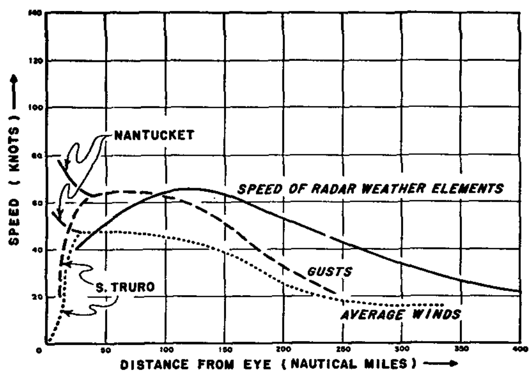

FIG. 7. Comparison of speeds of radar weather echoes and surface winds in Hurricane Edna. Wind speeds at South Truro and Nantucket are nearly the same when compared at the same distance from the eye of Edna except within 40 mi of the eye, and the curves for the two stations are mostly combined in this figure. The wind is indicated to increase with height outside the radius of maximum surface wind speed, and decreases with height within 50 or 75 mi of the eye.

[11], shows the mean winds and gusts recorded at the surface at Nantucket and South Truro, Massachusetts, during Edna. The distances of the storm eye from the stations at different times have been used to change the measurements at fixed points into horizontal profiles of the wind. The same has been done with the radar weather elements tracked on time-lapse film, and this record also appears in fig. 7.

As discussed in [11], the radar weather elements are believed to move with the winds between 5000 and 10,000 ft. Fig. 7 indicates that the winds of Hurricane Edna increase with height at greater distances from the eye than those corresponding to the maximum surface winds. Rawins reproduced in [11] show that much or all of this change occurs in a rather thin surface layer. Within about 50 or 75 mi of the eye the radar and surface winds show decreasing speeds with increasing height, but no rawins are available in this area.

The horizontal temperature gradient, which can be determined at the melting level from the slope of the bright band, may be related to the vertical gradient of wind through the thermal wind equation. A warm core structure is thereby associated with decreasing cyclonic circulation with increasing height, and conversely. When the lapse rate, $\partial T/\partial Z$, is known, the horizontal temperature gradient is given by $\partial T/\partial x = -(\partial T/\partial z)(\partial z/\partial x)$, where $\partial z/\partial x$ is the slope of the isotherm or of the bright band. Table 1 lists measurements of bright-band height made at different distances from the eye of the storm. Radiosonde data taken during Edna show an average value of the lapse rate near − 1.6C per thousand feet at a height of about 15,000 ft. This is in agreement with Jordan's average [7]. The difference shown in the table of some 4800 ft between the bright-band height 170 mi ahead of the eye and in the eye region is thus indicative of a difference of temperature of 7 or 8C at about 15,000 ft over the same horizontal distance. Soundings reproduced in [11] indicate a 6C temperature change over the same range at the 10,000-ft level, while beyond 170 mi from the eye the soundings indicate small, irregular temperature changes. The bright-band heights and the soundings both show the strongest temperature gradients to be concentrated near the eye, and this is similar to the structure shown in numerous reports, most strikingly in [15]. The deduced thermal structure is thus in qualitative agreement with the distribution of wind with height as given by radar weather elements and surface winds, and with the data of other investigators. In the case of Edna, it is concluded, on the basis of the data given above, that the pronounced warm core structure is confined to the space within the radius of maximum surface winds.

Table 1. Height of bright band in Edna.

Distance NNE of eye (nautical miles)*	Ht. of center of bright band (feet)	Radar used
325–170	12,700	FPS-4 and FPS-6**
160	13,500	FPS-6
125	14,000	FPS-6
20	16,000–16,500	FPS-4
Eye boundary	17,000–18,000	FPS-4

* No bright-band data are available between 125 and 20 n mi of the eye.
** The FPS-6 is a 10 cm radar of very high power.

6. Summary

Radar data demonstrate that the central eye of Hurricane Edna was marked by a singularity in the three-dimensional distribution of precipitation. The singularity was nearly coincident with the pressure minimum. Most prominent in the radar records is a towering precipitation mass and associated anvil which swept southwestward at 35,000 ft and overlay the clear area which was probably identified as the eye by ground observers. The combination of radar and conventional synoptic data shows that the air at 500 mb in the rain area near the eye was derived from the surface layers. A dropsonde report from the rainless eye at 700 mb indicates a high-level origin for this air, but is not in itself a conclusive indication. The air at 800 mb in the eye had a wet bulb potential temperature very close to known surface conditions, although the relative humidity was only 70 per cent. These observations suggest that the air at this level first rose from the surface and then descended again. Moisture came to the eye by virtue of the origin in the moist environment of some (if not all) of the air in the eye, and by the fall of dense rain or snow masses present at times over the eye at upper levels, as represented by the anvil in the RHI photographs. One of the most interesting features of this study is the radar observation of a dense precipitation mass over the eye. This provides a possible basis for interpreting reports of temperature and humidity in this and other hurricane eyes which cannot be explained on the basis of lifting from the surface or mixing between stratospheric air and that surrounding the eye.

Rainfall of Edna was confined mainly to the northern semicircle of the storm, as is common to hurricanes in middle-latitudes. A well-defined boundary between rain-filled and rain-free air occurred at low levels along an east-west line through the storm center and is strikingly shown by the radar photographs. Radar winds and bright band heights and conventional radiosonde data demonstrate that the "warm core" structure common to hurricanes was most pronounced within the radius of maximum surface winds in Edna.

In conclusion, it is noted that as long as there is uncertainty in observations there will be a corresponding uncertainty with respect to the deductions

derived therefrom. It is not unlikely that two or more eye soundings or radar photographs following the eye would have shown somewhat different things and inspired different interpretations.

Acknowledgments.—The author is indebted to Project Lincoln personnel at South Truro who gave of their time and equipment, and to Dr. David Atlas who took the pictures. Drs. Atlas and Raymond Wexler and the late Professor Charles F. Brooks have aided the study greatly by their constructive suggestions and critical review of the manuscript. Mrs. Anastasia Cakste prepared some of the illustrations.

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