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DOPPLER VELOCITIES IN RAIN BANDS OF HURRICANE BELLE,(U)
MAR 78 R J DONALDSON, M J KRAUS, R BOUCHER

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Hurricane Belle skirted the east coast of the U.S. during the evening of 9 August 1976, crossed Long Island just east of New York city shortly after midnight, and dissipated in the mountainous country of western and northern New England. Several of the hurricane rain bands passed over the AFGL Doppler radar site at Sudbury, Mass., providing an excellent opportunity for monitoring local winds aloft in the hurricane circulation, using the VAD technique of Lhermitte and Atlas. In the outer and middle bands there was a low-level wind maximum from the northeast quadrant

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at heights well under 1 km, with strong directional shear up to 3-5 km where there was generally a wind maximum from the SSE. Generally the winds veered with height but during a brief period they backed. Winds at the cirrus level of 6-9 km were consistently from the south. Maximum wind speeds were 25 to 30 m/sec ~~$^{-1}$~~. Interesting velocity information was also acquired at low elevation angles in remote portions of bands. Velocity patterns in the innermost rain band indicated a period of intense deformation, pronounced curvature of the wind field, and speeds up to at least 35 m/sec ~~$^{-1}$~~, which is consistent with the proximity of the center of low pressure. Other prominent anomalies were noted in the Doppler velocity structure of the rain bands indicative of a non-homogeneous wind field. The interpretation of these observations is, of course, subject to the ambiguities inherent in measurement of a vector field by a single Doppler radar.

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DOPPLER VELOCITIES IN RAIN BANDS OF HURRICANE BELLE

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1. INTRODUCTION

Hurricane Belle skirted the east coast of the U.S. during the evening of 9 August 1976, crossed Long Island just east of New York City shortly after midnight (all times are noted in EST), and dissipated in the mountainous country of western and northern New England. Figure 1 shows an hourly track of surface pressure centers of Belle, analyzed from hourly reports of weather stations affected by the hurricane. After landfall at about 0030 on 10 August, the pressure center commenced filling, slowly at first and then more rapidly after 0400.

Radar observations from the AFGL weather radar facility at Sudbury, Mass. were started at about 1600, 9 August and continued until 0325 10 August, using the 5.5-cm, 0.9° beamwidth Porcupine Doppler with pulse pair processor, digital recording, and color display of velocity mean and variance estimates and power (Jagodnik et al., 1975). A pre-existing shallow northeasterly flow with light rain dominated the local scene during the afternoon and evening of 9 August. Figure 2 indicates that the surface winds at Sudbury increased markedly in gustiness and turned southeasterly after 0100, suggesting the influence of hurricane flow at the surface after this time. A rain band, probably associated with Hurricane Belle, was observed as early as 1810 and several others passed over our site during the evening. These were somewhat showery and ragged, and on this account were not the most desirable tracers of the wind field. However, the final innermost band, first observed remotely at 2230 and locally at 0150, provided an adequate supply of tracers. Accordingly, the wind field surrounding the radar was monitored during this period, using the technique first described by Lhermitte and Atlas (1961) with the refinements of Browning and Wexler (1968).

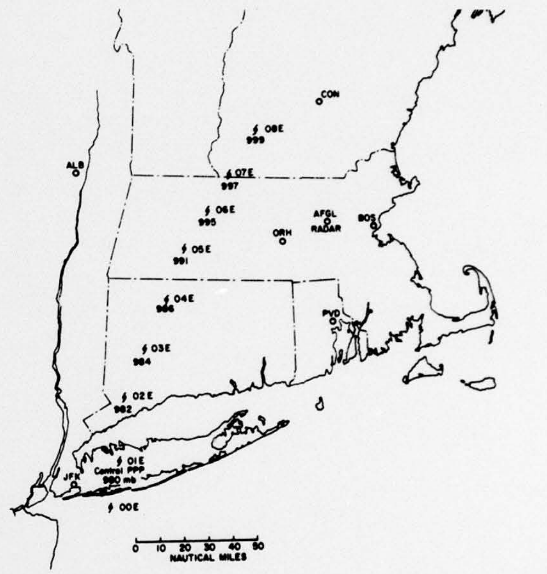


Fig. 1. Hourly track of Hurricane Belle's surface pressure center.

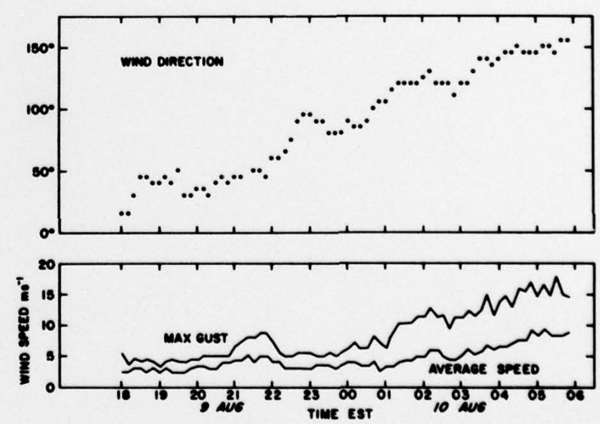


Fig. 2. Surface wind direction and speed, at Sudbury, as a function of time.

2. THE APPROACH OF BELLE

As Hurricane Belle moved toward New England, local winds aloft data were provided by a U.S. Army rawinsonde team. Unfortunately, their observations terminated at midnight, before the arrival of the final rain band. A hodograph of their last observation (2308 release time) is reproduced in Fig. 3, along with the lowest 3 km of the previous observation. Above 3 km the two observations were rather similar. In a little less than three hours, the light northeasterly flow which extended up to a height of 600 m at 2028 had

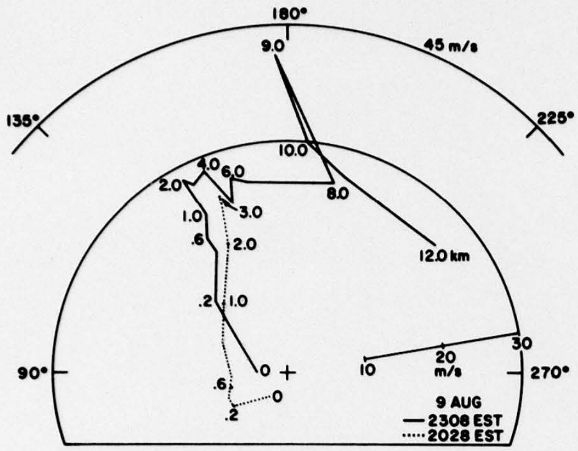


Fig. 3. Hodograph for local soundings. Both soundings were similar above 3 km.

veered to a stronger southeasterly slow. Wind speeds also increased markedly at 1 and 2 km. It appears as if the hurricane extended its influence downward with time. Rough estimates of wind by radar, using the color display, are consistent with this picture. For example, at 2050 the radar estimate of wind at a height of 0.6 km was 18 m s^{-1} from 150°; at 2100 the 5-km wind was estimated to be 26 m s^{-1} from 170°.

As the innermost band came within range at about 2230, the velocity contours at 1° elevation, corresponding to an altitude of 3 to 4 km, were tightly packed. At the tightest packing, the Doppler velocities in the approaching band changed from 0 to 21.6 m s^{-1} in just a 16° increment of azimuth. If the wind in the band had no curvature, its speed would have been nearly 80 m s^{-1}! More than likely, however, the wind field was curved around the pressure center, in which case speeds could have been much less with the same Doppler velocity pattern.

Meanwhile, at higher elevations, corresponding to roughly 4 to 7 km altitudes, the velocity pattern in the approaching band was highly disturbed. It could not be related to any conceivably simple wind field. This disturbance was noted continuously for an hour until severe antenna control problems interrupted data acquisition for another two hours. Steady data-taking resumed at 0135. At 0148 the northeastern edge of the innermost band reached the radar site, and observations were taken from the within-band vantage point until 0325 when we terminated operations.

3. VELOCITY STRUCTURE FROM WITHIN A HURRICANE RAIN BAND

At the time of this writing, a digital analysis of the wind field has been made at only three of the nearly one-hundred data sets taken within the inner rain band. Each data set consists of a 360°-azimuth circle at a fixed elevation angle. A variety of elevation angles was used, mostly at 6° and below but with a few at higher angles, in order to cover a wide range of heights. Unfortunately, the main action was far to the southwest. Only the eastern extremity of the band passed over Sudbury, and the maximum height of echoes overhead was only 2 km. However, the wind field that we could measure by VAD methodology displayed some interesting features which the approaching band telegraphed.

3.1 Curvature and Deceleration

One of the obvious differences between the wind field in the hurricane band and in other widespread storms was in curvature. On many color displays of velocity, there was a notable shift in maximum and minimum velocities at the same range (hence same height) from a straight-line configuration. The upper picture of the color plate, for example, indicates maximum inbound velocities at ranges in excess of 32 km (portrayed in yellow) from the south-southeast, while at the same ranges the maximum outbound velocities (portrayed in purple) are toward the northwest. We tried to estimate this shift by visual inspection of the color pattern in 26 cases, and calculated a median radius of curvature of 101 km, for winds ranging in height from 0.6 to 1.7 km. During this time period, 0150-0320, the pressure center of Belle was 160 to 210 km distant. Either these low-level winds were curved additionally with a radial as well as a tangential component, or we overestimated the curvature.

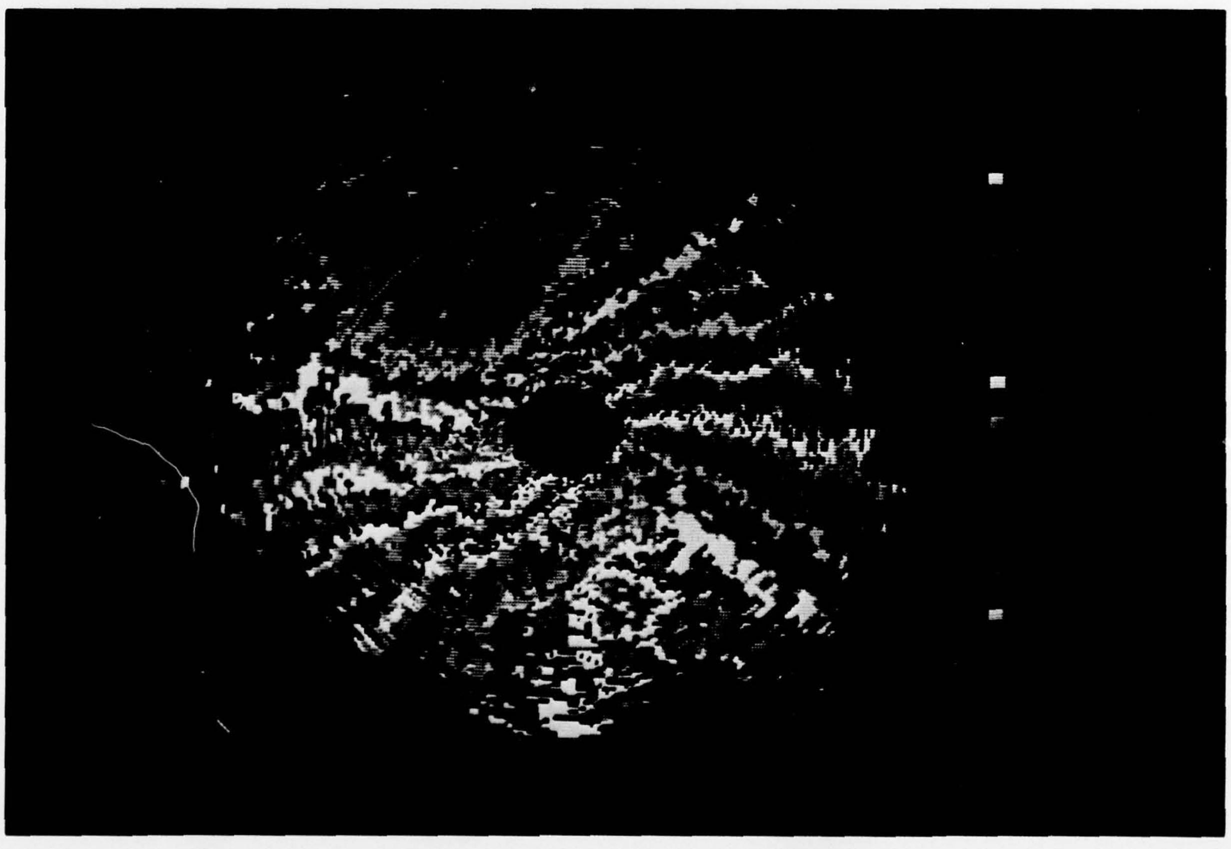
More detailed analysis revealed that probably both factors were responsible. Using data taken at 1° elevation (the upper color picture), we split the usual VAD analysis, using observed components every 10° of azimuth, into separate upwind and downwind velocities. This so-called HAVAD (half a VAD) procedure yielded excellent data at heights of 300, 400, and 500 m. Although the data for a height of 200 m were considered somewhat doubtful because of many interpolations necessitated by ground-clutter interference, they were included because they follow the trend of the high-quality measurements. Results are tabulated below:

Table 1: Comparison of downwind and upwind velocities by HAVAD Analysis for 0302 -1° elevation.

Ht. (m)	Downwind Velocity (m s^{-1})	Upwind Velocity (m s^{-1})	Radius of Curvature (km)	Deceleration (s^{-1} 10^3)
200	13.9 from 123°	16.6 from 133°	130	0.12
300	17.0 from 124°	18.6 from 138°	140	0.05
400	19.7 from 127°	22.1 from 145°	145	0.05
500	22.1 from 129°	24.4 from 150°	155	0.04

The analysis shows less curvature than the visual estimates. The eye can be fooled. But still, the hurricane was more distant (170 km at 0302) than any of the measured radii of curvature, so there was a small degree of inflow, which increased with decreasing height. Wind speed also decreased as the air circulating around Belle flowed over land.

Currently, a VAD taken at 6° elevation at 0303, one minute after the previous one, showed lower wind speeds at corresponding heights. This may be a measure of error in the analysis, or it may reveal irregularities in the wind field, since the 6° data



were taken at approximately one-sixth the radius of the 1° data for corresponding heights. The answer awaits further analysis.

The third VAD, taken at 0153 at an elevation of 5°, provided an idea of the change of winds with a time interval of 70 minutes, as the hurricane pressure center moved from a distance of 210 to 170 km. The best-quality data are in the three middle heights. Incidentally, the bearing of Belle with respect to our radar was 230° at 0153 and 238° at 0303. Normals to these bearings are 140° and 148°, in both cases indicated in Table 2 by the wind direction somewhere between a half and one kilometer in height.

Table 2: Velocity increase with approach of hurricane.

Height (m)	0153-5°	0303-6°
	Velocity ($m\ s^{-1}$)	
300	12.4 from 123°	15.9 from 125°
400	12.6 from 134°	18.5 from 131°
500	16.7 from 133°	21.7 from 137°
1000	28.1 from 150°	29.2 from 151°
1500	30.3 from 156°	32.4 from 159°

3.2 A Possible Wave Pattern

Between 0150 and about 0220 the color velocity patterns were anomalous and puzzling. A typical example is illustrated in the lower picture of the color plate. As the viewing angle changed from a cross-wind direction, indicated by the narrow black bands oriented WSW and ENE, toward a maximum or minimum Doppler velocity, the observed velocity magnitude suddenly decreased and then resumed its climb (or descent) toward maximum (or minimum). There were thus four extra bands of color. In addition, the region of approaching (but not receding) velocity maximum in the SSE was unusually heterogeneous. The variance of velocity was sharply peaked in these five regions.

The VAD of 0153, which displayed this anomaly well, was analyzed for deformation, using the scheme proposed by Browning and Wexler (1968). The resultant deformation for the three highest-quality measurements of 0153 ranged from 0.26 to $0.45 \times 10^{-3}\ s^{-1}$, in comparison with 0.17 to $0.23 \times 10^{-3}\ s^{-1}$ for the corresponding heights observed at 0303 when the phenomenon had ceased. That was really not very much difference, nor much magnitude of deformation in any case, considering the striking contrast in appearance on the color display. Evidently the 10°-VAD analysis steps skipped right over much of this pattern, but most important, the pattern did not have its peaks spaced 45° from its zeros, as a second harmonic would. Since the anomalous color stripes seemed to be spaced about 20° from zero Doppler velocity, the anomaly might show up with higher-order and more highly resolved harmonic analysis.

This peculiar pattern invites a lot of speculation. We considered whether it could be an effect of a fault in the radar or processing gear. However, several considerations suggest otherwise: (1) The phenomenon was not radially oriented, but curved with the zero Doppler contour in accordance with directional shear. (2) It was not a function of a particular velocity level, because a greater range of velocities was covered smoothly in the downwind region. (3) Besides, there were irregularities of detail in the occurrence (but not the general location) of the pattern. (4) Between 0218 and 0229, we were able to detect the pattern fading out from the south-southwest. Following this, the pattern affected only a small portion of the contours toward the northeast. (5) Recall the disturbed appearance of a part of the inner band when it was still distant. Also, a hint of the anomalous pattern was present as early as 0116 during a brief attempt to resume observations.

We conclude that the phenomenon was of atmospheric origin, but involved a mechanism that we cannot at present discern. Perhaps it was some rather high-intensity wave of undetermined configuration generated by the interaction of the hurricane and the frictional forces released by landfall. In any event, it is certainly an inspiration for both our imaginative and our analytical resources.

4. ACKNOWLEDGEMENTS

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