

NOTES AND CORRESPONDENCE

Doppler Radar Wind and Reflectivity Signatures with Overrunning and Freezing-Rain Episodes: Preliminary Results

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ABSTRACT

Freezing rain is commonly caused by overrunning. The typical atmospheric structure and precipitation patterns associated with overrunning and freezing rain suggest a general association between 1) a bright band and 2) a wind-shear layer between the colder air mass near the surface and an overrunning warmer air mass above the frontal boundary. These features were easily detected by a Doppler radar, and their associated thermodynamic structure was documented by an instrumented aircraft in two freezing-rain events near Kansas City, Missouri, in February 1990. The two cases suggest that perhaps freezing rain caused by overrunning has recognizable and easily parameterized Doppler radar signatures that could be incorporated into a freezing-rain detection algorithm. A preliminary algorithm is discussed.

1. Introduction

Freezing rain is hazardous to aviation because it coats all exposed portions of aircraft with a hard, clear layer of ice, which is extremely difficult to remove and seriously affects aircraft performance. Thus, any procedure that could help aircraft avoid or minimize exposure to freezing rain would greatly benefit the aviation community.

Freezing rain is often caused by overrunning. According to Huschke (1959), overrunning is a condition existing when an air mass is in motion above another air mass of greater density at the surface. In the southern plains, overrunning is typically characterized by warm, moist south-southwesterly flow at lower- or midtropospheric levels (e.g., 850–500 mb) that ascends a shallow, slowly moving surface cold front or stationary front. Winds in the cold air behind the front range from a north to southeast direction in individual cases (Byrd 1989).

The typical precipitation pattern associated with overrunning is well known (e.g., Byers 1944). Moist air overruns a shallow cold air mass near the surface. Snowflakes form at higher altitudes and melt in a layer of above-freezing air above the frontal zone. The resulting liquid droplets fall through a colder air mass near the surface. If this mass is shallow, and surface

temperatures are below freezing, the droplets freeze upon contact with the surface.

The typical atmospheric structure and precipitation patterns associated with overrunning and freezing rain suggest a general association between the following features:

- 1) a bright band produced by melting snowflakes;
- 2) a wind-shear layer between the colder air mass near the surface and the overrunning warmer air mass above the frontal boundary.

Rawinsonde observations at 0000 and 1200 UTC are commonly used to determine the heights of freezing levels and frontal shear layers associated with overrunning. These observations, however, are valid only at 0000 and 1200 UTC and near the immediate location of the rawinsonde launch site. A Doppler radar could continuously monitor any bright band and shear layers that are present within a limited range of the radar and supply data to a suitable freezing-rain detection algorithm. This algorithm would be useful in a nowcasting environment within the Next Generation Weather Radar (NEXRAD) program. It could also provide assistance to air traffic controllers when using Terminal Doppler Weather Radar (TDWR) for air traffic management.

There have been numerous articles on applications of Doppler radar to summertime convection. There has been, however, relatively little work, to date, on applications to wintertime events. The potential to develop algorithms based on pattern recognition of radar data in wintertime events maybe as promising as those developed for summertime convection, microbursts,

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gust fronts, and tornado vortex signatures, to name a few.

As part of a Federal Aviation Administration research contract, personnel from the University of North Dakota (UND) documented freezing-rain episodes near Kansas City, Missouri (MKC), in the winter of 1989/90. This paper 1) describes two freezing-rain episodes at MKC caused by overrunning north of shallow surface fronts, and 2) relates features observed in these episodes to a preliminary freezing-rain detection algorithm for overrunning situations. Doppler radar and aircraft data sources will be briefly described, followed by the case studies of the freezing-rain episodes and a preliminary freezing-rain detection algorithm.

2. Data sources

The UND radar is a 5.4-cm Doppler that utilizes a 3.7-m antenna to obtain a 1° beamwidth. Peak power of the system was 250 kW, which provided a minimal detectable signal of -8 dBZ at 50 km. The radar was equipped with a pulse-pair processor that processed a maximum of 1024 range gates per radial, with range-gate spacing possible at any multiple of 25 m. The radar was located 9 km north of MKC at an elevation of 320 m MSL. Radial-velocity and reflectivity profiles were obtained by routine conical scans (PPIs) at constant elevation angles from 0.4° to 16.0° and cross-sectional views through regions of interest at fixed azimuths (RHIs).

The radar operated at a pulse repetition frequency (PRF) of 1100 Hz. These parameters gave a maximum unambiguous velocity (V_{\max}) of 14.85 m s^{-1} . Velocities greater than the maximum unambiguous velocities were considered "folded" and assigned values less than the maximum unambiguous velocity (e.g., Doviak and Zrnić 1984).

Heights of features (e.g., bright bands) were obtained by using a trackball with the PPI and RHI displays. The trackball program used the four-thirds-earth-radius model (Battan 1973), which assumes refraction in a standard atmosphere and includes the effects of earth's curvature. Heights were converted to mean sea level to facilitate comparison with aircraft data.

The UND Cessna Citation research aircraft measured microphysical, kinematic, and thermodynamic variables including air temperature, wind direction, and wind speed. Air-temperature measurements were made by a reverse-flow thermometer (Rodi and Spyers-Duran 1972). Winds were calculated from gust-probe and inertial navigation data using the procedure described by Lenschow (1971).

3. Case 1: 1–2 February 1990

a. Synopsis

A cold front that marked the leading edge of a polar air mass passed MKC at 1230 UTC 1 February. The

front slowed as it moved southward, and by 1800 UTC, stretched from northern Illinois to the Texas Panhandle. Stations in Kansas and Missouri, including MKC, reported rain and a change in the surface winds to a north or northeast direction after frontal passage. Surface temperatures across Kansas and Missouri decreased throughout the day behind the front, and rain changed to freezing rain across northeastern Kansas and northern Missouri by 0000 UTC 2 February 212 (Fig. 1).

Isobaric charts for 0000 UTC 2 February (not included) showed southwesterly winds at the 500- and 700-mb levels, and southerly winds with warm-air and moisture advection at the 850-mb level over MKC. Given that surface winds behind the front were northerly (Fig. 1), it appeared that freezing rain was caused by overrunning. This was substantiated by a cross section of equivalent potential temperature θ_e , humidity, and front-relative winds perpendicular to the front (Fig. 2). The front-relative winds were calculated by subtracting the velocity of the front from winds observed by rawinsondes. Based on the time of frontal passage at various observing stations near MKC, the mean frontal motion was from 308° at 7 m s^{-1} . Figure 2 shows that winds ahead of the front had a southeasterly (positive) component, while winds immediately behind the front had a northwesterly (negative) component. This implied that moist air was flowing over, or over-

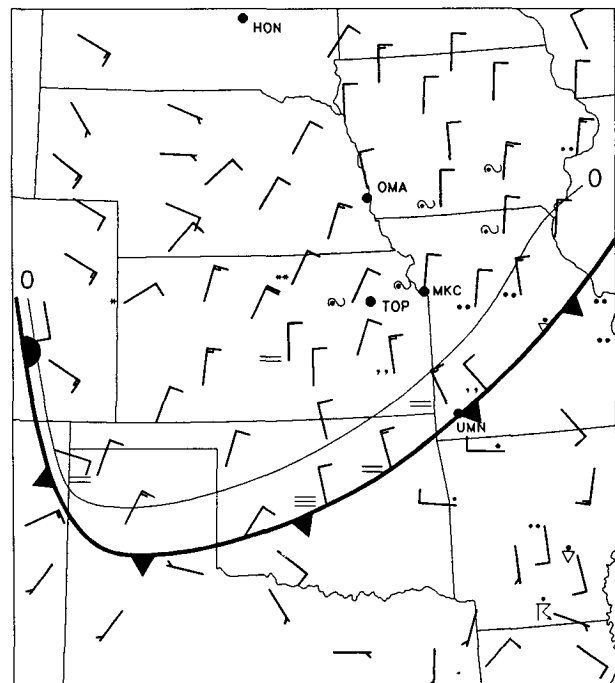


FIG. 1. Surface analysis, 0000 UTC 2 February 1990. One full wind barb is 5 m s^{-1} . The thin, solid line is the 0°C isotherm. HON is Huron, South Dakota, OMA is Omaha, Nebraska, TOP is Topeka, Kansas, and UMN is Monett, Missouri.

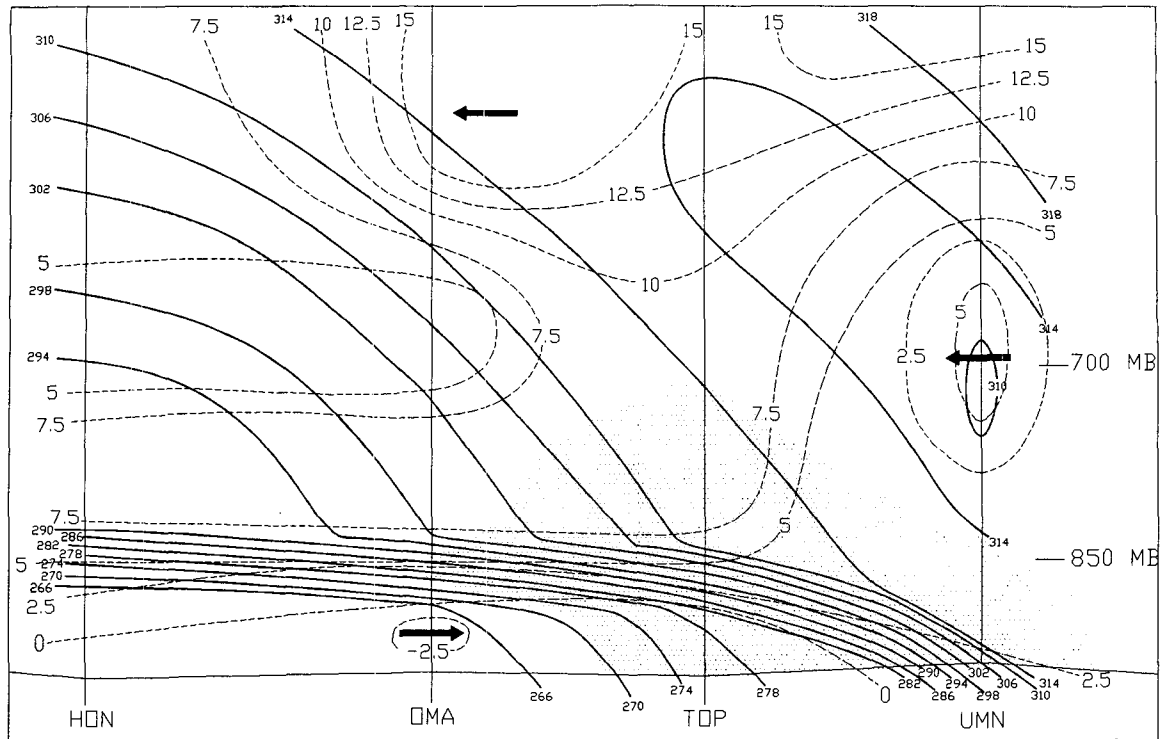


FIG. 2. 0000 UTC 2 February cross section of θ_e , relative humidity, and the component of the front-relative winds (m s^{-1}) in the plane of the cross section. Isentropes are thick, solid lines, and isotachs are thin, dashed lines. The arrows represent relative wind maxima and minima. Areas where the relative humidity equals or exceeds 90% are shaded. The stations are shown in Fig. 1.

running, the shallow cold front; subfreezing air below the front resulted in freezing rain at the surface.

Freezing rain changed to freezing drizzle in MKC at 0430 UTC 2 February as the mid- to lower-level moisture field moved to the northeast of Kansas City. A precipitation total was not available for MKC, but by the time precipitation ended in the Kansas City area around 0900 UTC 2 February, a liquid equivalent of 9 mm had been recorded 22 km north-northwest of MKC at the Kansas City International Airport (MCI). The freezing rain formed a 7–12-mm layer of clear ice on all exposed surfaces in the metropolitan Kansas City area and caused numerous reports of severe aircraft icing in the vicinity of MKC.

b. Doppler radar observations

A PPI scan taken at 5.4° on 1 February at 2300 UTC indicated a prominent melting-layer bright band within the reflectivity pattern and a veering wind profile at low levels beneath the frontal zone on the radial-velocity display (Fig. 3a). The bright band was identified on the PPI by a ring of higher reflectivities at a range of approximately 18.5 km. At 5.4° elevation, the center of the bright band was at 1760 m AGL (2080 MSL). It has long been known that bright bands are caused by water films that form on melting snowflakes

(e.g., Austin and Bemis 1950). In this case, the snowflakes melted as they fell through a layer of air with above-freezing temperatures above the frontal zone. Since the thermal-wind equation (e.g., Holton 1979) implies that a frontal zone is also a shear layer, there should have been a shear layer below the bright band in this case.

The lower freezing level should occur within the frontal inversion, and by the thermal-wind equation, it should occur within the shear layer as well. However, it is not usually known which part of the shear layer would correspond to the lower freezing level. The altitude where veering ceases (the altitude where the zonal-wind component switched from an easterly to a westerly component) was chosen as the level within the shear layer that might approximate the lower freezing level. The level where veering ceases should be easily seen on a Doppler radar. At a slant range of 9.8 km and elevation angle of 5.4° , the level where veering ceased was 930 m AGL (1250 m MSL) (Fig. 3a).

RHI scans taken at 2306 UTC ranged from 280° to 340° azimuth. Since the level where veering ceased was placed at the altitude where the zonal-wind component switched from an easterly to westerly component, an RHI closest to 270° or 090° radials was analyzed. In this case an RHI along the 280° radial (Fig. 3b) was used to compare the level where veering ceased

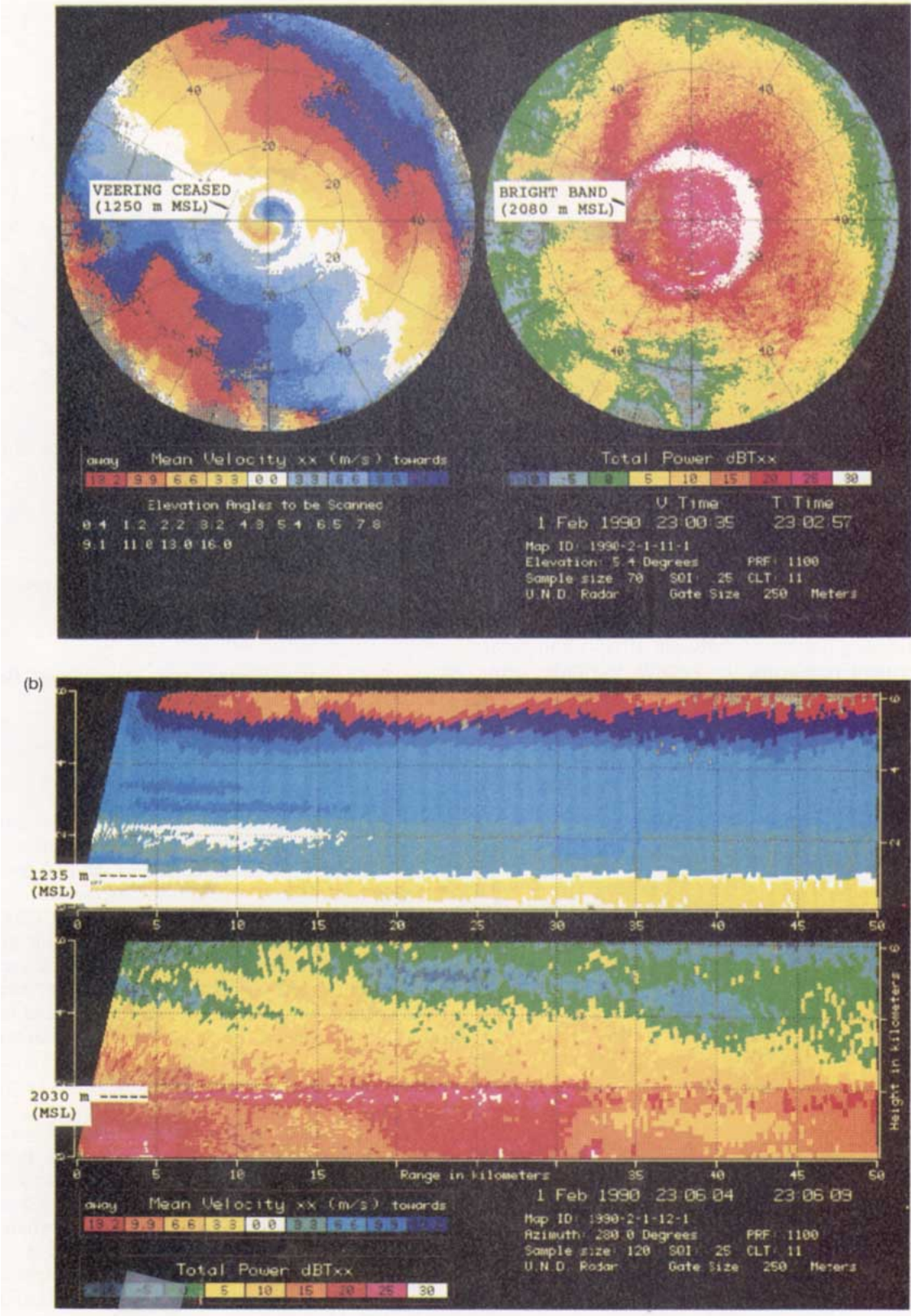


FIG. 3. (a) PPI scan from UND Doppler, 5.4° elevation, 2300 UTC 1 February.
 (b) RHI scan from UND Doppler, 280.0° azimuth, 2306 UTC 1 February.

and the height of the bright band against results found by using PPI data. The bright band was identified by a narrow horizontal line of higher reflectivities aloft. Analysis of the RHI placed the center of the bright band at 1710 m AGL (2030 m MSL), and the level where veering ceased at 915 m AGL (1235 m MSL). These heights were in good agreement with those found with the PPI scan at 5.4° (Fig. 3a).

c. Instrumented aircraft observations and comparison with Doppler radar observations

The Citation made an ascent step sounding from the surface to 6100 m MSL while in transit from MKC to a region 40 km northwest of the UND radar site from 2256 to 2341 UTC. A portion of this sounding is shown in Figs. 4a,b. The Citation encountered freezing rain on takeoff, which changed to rain during ascent through the lower of two freezing levels (1040 m MSL). The aircraft continued to ascend through the pronounced inversion and shear layer associated with the frontal zone. Temperatures through the inversion increased from -5.9°C at 935 m to +5.4°C at 1240 m MSL. Over this same distance, winds veered from 040° at 13 m s⁻¹ to 180° at 4 m s⁻¹, placing the level where veering ceased, as measured by aircraft, at 1240 m MSL.

Considering differences between aircraft and radar measurement platforms, the aircraft and radar measurements of the level where veering ceased (1250 m from the PPI, 1235 m from the RHI, and 1240 m MSL from the Citation) were identical. These measurements placed the level where veering ceased approximately 200 m above the height of the lower freezing level (1040 m).

As the Citation continued to ascend, the crew observed rain, which became mixed with melting snow immediately below the upper freezing level (2250 m MSL) (Fig. 4a), and snow thereafter. This placed the upper freezing level 170 m above the center of the bright band located at 2080 m MSL. The distance between the upper freezing level and the center of the

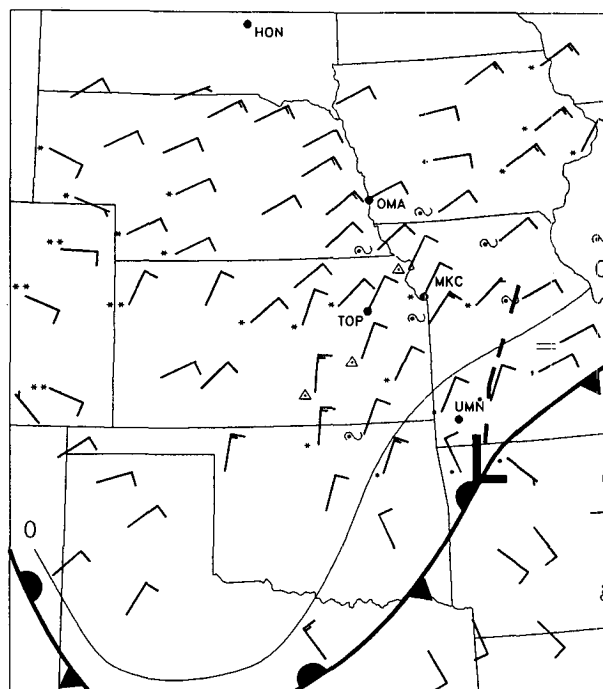


FIG. 5. Surface analysis, 2000 UTC 14 February 1990. Same conventions as Fig. 1.

bright band was consistent with Austin and Bemis (1950) and Hooper and Kippax (1950).

4. Case 2: 14 February 1990

a. Synopsis

A winter storm moved across the United States during 14–16 February 1990. The storm produced hazardous weather across a large part of the country (Martner et al. 1992). A cold front associated with the storm passed MKC at approximately 1000 UTC 13 February, and became stationary 325–400 km southeast of MKC by 1200 UTC 14 February. Surface winds were from the north or northeast at 5–7 m s⁻¹ behind the front, and southeasterly at 3–5 m s⁻¹ ahead of the front. No stations in northeastern Kansas reported precipitation at 1200 UTC, but many stations reported sleet, snow, or freezing rain by 2000 UTC 14 February (Fig. 5).

Freezing rain began in MKC at 1330 UTC 14 February and ended at 0500 UTC 15 February. Precipitation types through the period were freezing rain, freezing drizzle, ice pellets, and light snow. Surface temperatures ranged from -3.9° to -1.6°C when precipitation fell. A precipitation total was not available for MKC, but MCI reported a liquid equivalent of 15 mm for the 24-h period ending at 1200 UTC 15 February. A 7–12-mm coating of clear ice was present on all exposed surfaces at the UND radar facility, and nu-

CITATION SOUNDING
2256–2329 UTC
1 FEBRUARY 1990

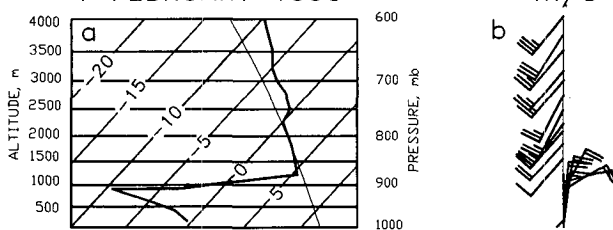


FIG. 4. (a) Temperature and (b) wind sounding from the UND Citation. Full barb = 5 m s⁻¹, one flag = 25 m s⁻¹.

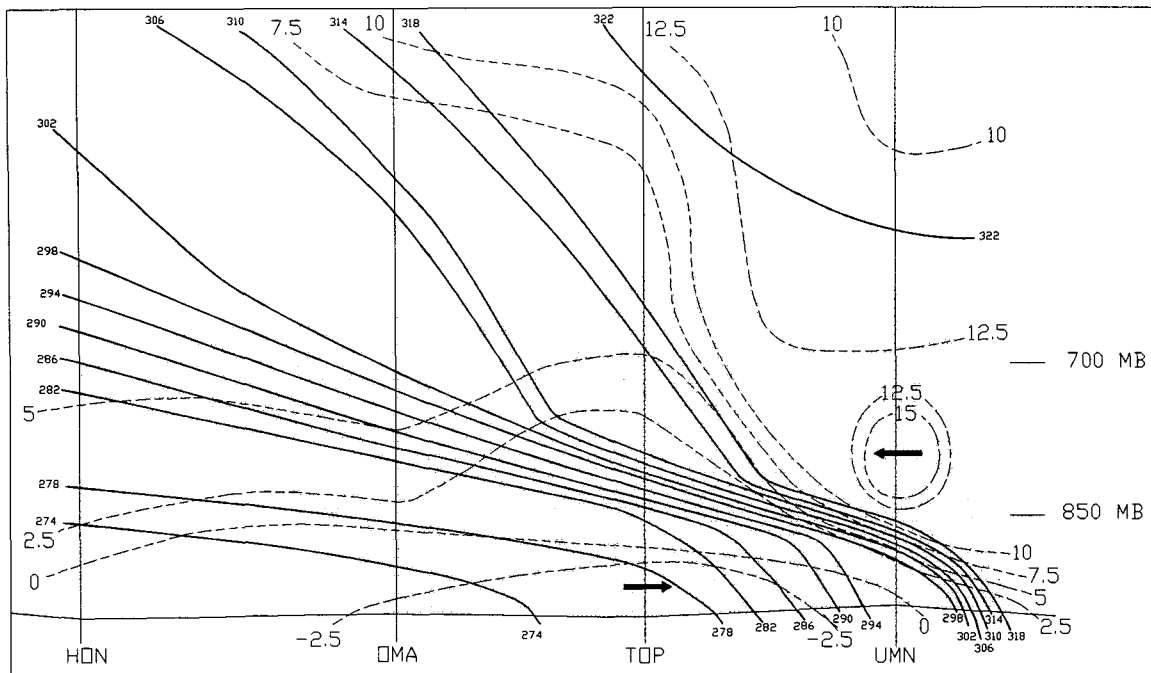


FIG. 6. 0000 UTC 15 February cross section of θ_e , front-relative winds and relative humidity. Same contour and shading conventions as Fig. 2.

merous pilot reports of moderate icing below 1800 m were received during the period.

As in the 1–2 February case, isobaric charts suggested that freezing rain was caused by overrunning: there was southwesterly flow at the 500- and 700-mb levels, southerly flow and warm-air and moisture advection over MKC at the 850-mb level, and northeasterly winds with subfreezing temperatures at the surface (Fig. 5). Overrunning was further substantiated by a cross section of θ_e , wind components parallel to the cross section, and relative humidity constructed perpendicular to the front at 0000 UTC 15 February (Fig. 6). As in the 1–2 February case, the flow relative to the front suggested that freezing rain fell as warm, moist air overran the shallow surface cold front.

b. Doppler radar observations

PPI and RHI scans from 2001 UTC most closely coincided with a sounding taken by the Citation from 2000 to 2041 UTC 14 February. Both the level where veering ceased and the melting-layer bright band were well defined on the PPI scan at an elevation angle of 5.4° (Fig. 7a). Analysis of PPI data placed the level where veering ceased at 1090 m AGL (1410 m MSL) and the center of the bright band at 2180 m AGL (2500 m MSL).

RHI scans at this time ranged from 300° to 350° azimuth. In this case the 300° radial (Fig. 7b) was used to compare the height of the bright band and the level

where veering ceased against results found by using PPI data. Calculations from the RHI scan placed the level where veering ceased at 1070 m AGL (1390 m MSL) and the center of the bright band at 2160 m AGL (2480 m MSL). This agreed well with measurements from the PPI scan (Fig. 7a).

c. Instrumented aircraft observations and comparison with Doppler radar observations

The Citation made an ascent sounding from the surface to 7930 m MSL in a region 50 km north of the UND radar. A portion of this sounding is shown in Figs. 8a,b. The Citation encountered freezing rain and occasional ice pellets that became rain as the aircraft ascended through the lower freezing level (1500 m MSL), frontal inversion, and shear layer. Temperatures through the frontal inversion increased from -7.9°C at 970 m to $+3.9^{\circ}\text{C}$ at 1810 m MSL. The strongest shear occurred between 1210 and 1470 m MSL where winds veered sharply from 110° at 13 m s^{-1} to 280° at 6 m s^{-1} . Citation measurements placed the level where veering ceased at 1470 m MSL. This was within 60 m of the height as measured by the RHI (1410 m MSL) and within 80 m of the height as measured by the PPI (1390 m MSL).

Considering the distance between the aircraft and radar ($\sim 50\text{ km}$), and the uncertainty in radar measurements at those distances, aircraft and radar mea-

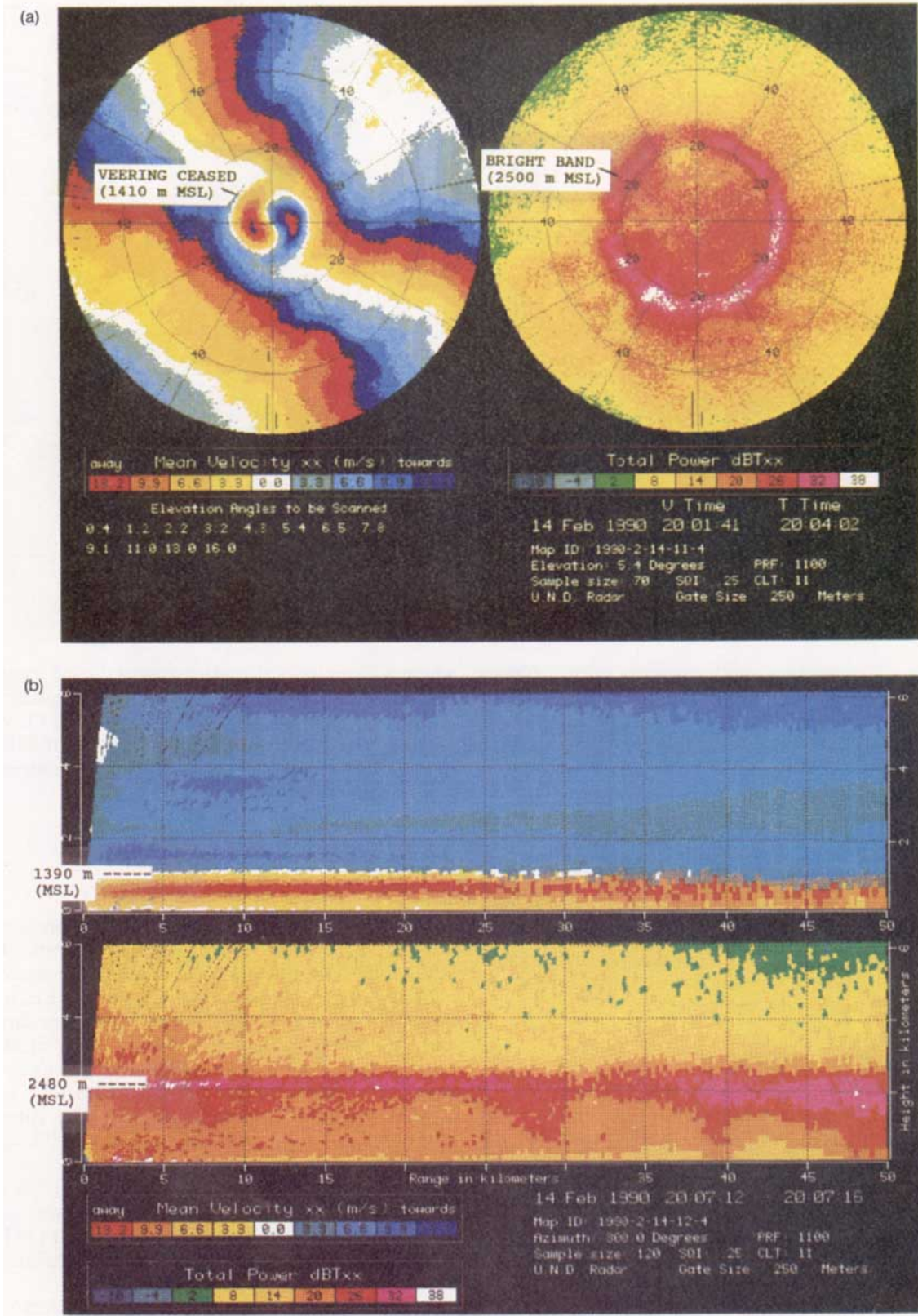


FIG. 7. (a) PPI scan from UND Doppler radar, 5.4° elevation, 2001 UTC 14 February.
 (b) RHI scan from UND Doppler radar, 300.0° azimuth, 2007 UTC 14 February.

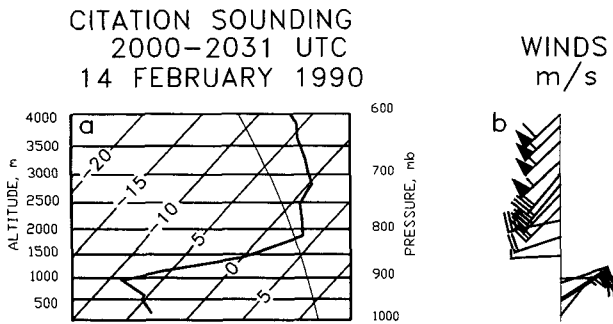


FIG. 8. Wind and (a) temperature and (b) wind sounding from the UND Citation. Wind-barb convention same as Fig. 4.

measurements of the altitude where veering ceased were identical. These measurements also placed the level where veering ceased within approximately 100 m of the lower freezing level (1495 m MSL). Thus, as in the 1 February episode, the level where veering ceased approximated the lower freezing level.

The Citation continued to ascend, and it intersected the upper freezing level at 2830 m MSL, 330 m above the center of the bright band. This distance between the upper freezing level and bright band was consistent with Austin and Bemis (1950).

5. A preliminary freezing-rain detection algorithm for overrunning situations

In both cases, Doppler radar and instrumented aircraft data from overrunning and freezing-rain events showed two distinctive radar signatures: 1) a bright band, and 2) a well-defined shear layer associated with a frontal zone some distance below the bright band. The level in the shear layer where the veering ceased was within 200 m of the lower freezing level in both cases.

The presence of the bright band and shear layer is consistent with the typical atmospheric structure and precipitation patterns associated with overrunning and freezing rain discussed in the Introduction. Similarities between the two freezing-rain episodes suggest that perhaps freezing rain caused by overrunning has recognizable and easily parameterized Doppler radar signatures that could be incorporated into a freezing-rain detection algorithm. A block diagram of a preliminary algorithm is given in Fig. 9. This algorithm first checks the surface temperature to determine the potential for freezing rain, and then looks for the occurrence of a melting-layer bright band and a shear layer some distance below the bright band. Assuming that the level where veering ceases in the shear layer approximates the lower freezing level, and that hydrometeors have completely melted before reaching this level, a freezing-rain hazard would exist from the surface to the level

where veering ceases when the surface temperature is below 0°C. The algorithm would issue a freezing-rain warning for the appropriate altitudes.

In some instances, the subfreezing layer next to the surface is sufficiently thick so that liquid hydrometeors become ice pellets at the surface. This occurred in the 14 February episode when the subfreezing layer next to the surface was approximately 460 m thicker than it was in the 1–2 February case. The freezing-rain detection algorithm would still issue warnings in these instances, except the icing hazard would exist at altitudes closer to the level where veering ceases.

Severe clear icing can occur when an aircraft encounters freezing rain. This hazard affects the general aviation fleet more so than commercial aircraft, especially on final approach for landing. With the help of a freezing-rain algorithm, air traffic controllers would know the extent of the icing hazard and, when necessary, would be able to direct aircraft out of danger.

6. Suggestions for further research

In order to obtain statistically significant results, testing of the freezing-rain detection algorithm will need a larger database than the two case studies presented in this paper. Therefore, investigators interested in extending this work should document more freezing-rain events. Those investigators may also want to address the following issues:

- 1) Does the level where veering ceases in the shear layer normally approximate the lower freezing level, as it did in the two freezing-rain episodes presented in this paper? If this is unusual, then the altitude of the lower freezing level could be supplied to the algorithm

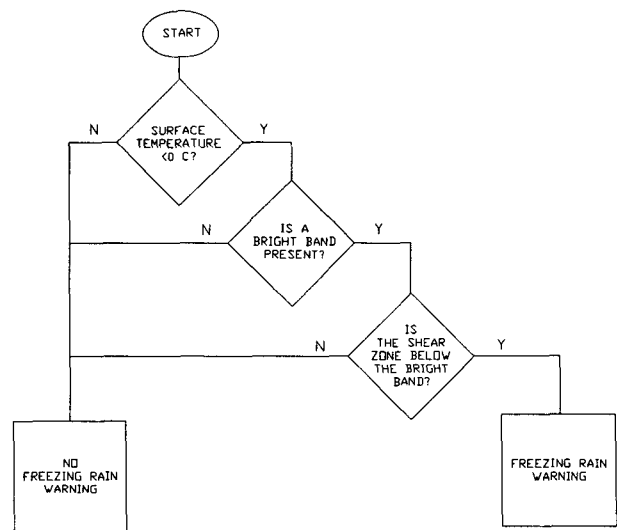


FIG. 9. A preliminary block diagram for an algorithm that detects freezing rain caused by overrunning.

from another source. One possible source is the thermodynamic profiler (Hogg et al. 1983), provided that precipitation is not falling heavily enough to attenuate microwave emissions from oxygen (Westwater and Decker 1977). Other possible sources are radiosondes and pilot reports, provided that they are representative.

2) What is the threshold cloud thickness necessary above the bright band for freezing rain versus freezing drizzle?

3) What is the minimum thickness of the above-freezing layer from the top of the bright band to the lower freezing level required to completely melt snow?

4) Should the algorithm have both speed and directional-shear thresholds? If so, what are the necessary threshold values?

5) Algorithms currently running or scheduled to run on the NEXRAD and TDWR systems utilize only PPI scans. Therefore, the height of the bright band and the level where veering ceases should be derived from PPI scans only.

Future algorithm development could take advantage of data available from NEXRAD in the southern plains region (i.e., Kansas, Oklahoma, Texas). As suggested by a reviewer, NEXRAD could probably produce PPI diagrams of vertical wind shear in real time, which would make algorithms for detecting overrunning freezing-rain events relatively easy to develop. Efforts in the southern plains might be particularly successful, since overrunning patterns can account for as much as 95% of cool-season precipitation in these areas (Byrd 1989).

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