Gust Fronts in Doppler Radar Data

Diana L. Klingle and David R. Smith
Department of Geosciences
Purdue University
West Lafayette, Indiana 47907

Introduction

A gust front is the boundary between the horizontally propagating cold air outflow from a thunderstorm and the surrounding environmental air. The sharp changes in wind speed and direction across a gust front can produce turbulence and wind shear of sufficient magnitude to be hazardous to aircraft during takeoff and landing. Analyses of aircraft accident statistics published by the National Transportation Safety Board for the years 1976-78 indicate that one of the most significant hazards to aviation is low altitude wind shear (12). It is in response to such hazards that research projects such as JAWS (Joint Airport Weather Studies) have been conducted. Gust fronts, as well as downbursts and tornadic phenomena, constitute a hazard to aviation, but it is impossible to detect the low altitude wind shear they produce with the conventional radars currently in use. Doppler radars are capable of sensing air motions and, therefore, are useful tools in the detection of this aviation hazard. This paper examines the use of Doppler radar in the detection of thunderstorm gust fronts and their associated wind shear patterns.

Background on Gust Fronts

A. Gust Front Structure

A gust front is the leading edge of an outflow which is produced when the thunderstorm downdraft reaches the ground and spreads horizontally. The passage of the gust front is often accompanied by a sharp rise in pressure, a decrease in temperature, and abrupt changes in wind speed and direction (4). As the cooler, denser outflow intrudes into the warmer, less dense environmental air, the warm air is lifted up and over the outflow boundary (Figure 1). This intrusion of colder air into warmer has been likened to a gravity current (1, 6, 8, 16).

Studies of laboratory gravity currents have illustrated the presence of phenomena which have counterparts in thunderstorm outflows. Fluid within the outflow moves faster than the outflow boundary. Under the proper conditions, friction between the

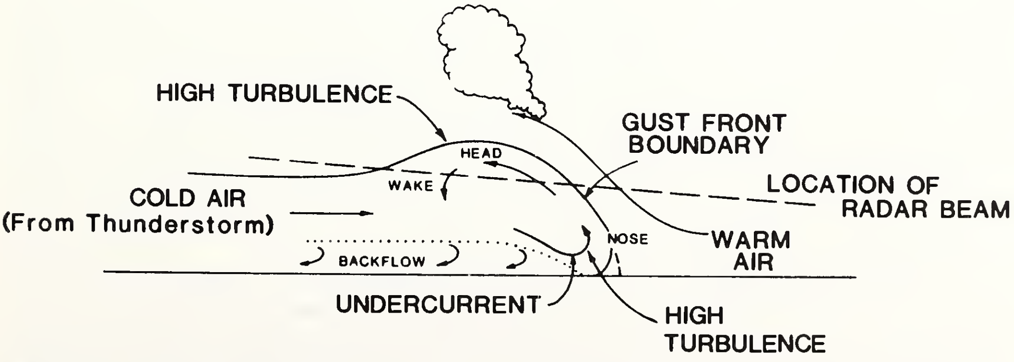

Figure 1. Schematic diagram of the vertical structure of a thunderstorm outflow and gust front. Motion is relative to the gust front. (Adapted from Goff, 1975)

fluid and the surface across which it propagates causes the lowest layers of the flow to be retarded. Some of the fluid is deflected downward, producing the "backflow." The fluid above this friction layer moves faster and protrudes ahead of the surface boundary. This protrusion is known as the "nose" of the gust front (Figure 1). The advancing fluid is deflected upward at the leading edge producing a bulge known as the "head." Studies have shown evidence that these features also exist in nature (5, 7). A turbulent "wake" region is located behind the head. The leading edge of the outflow is not an impermeable boundary. Along with lifting, mixing of the environmental and outflow air occurs at the outflow interface, which produces yet another turbulent region.

B. Doppler Radar Signatures of Gust Fronts

It has been shown that Doppler radar is capable of detecting thunderstorm outflows (2, 13, 17). The abrupt change in wind speed and direction mentioned previously can be sensed by Doppler radar and displayed such that regions of radial shear are apparent. Doppler radars sense the component of the wind along the radar beam; inbound (*i.e.*, toward the radar) is considered negative, outbound is positive.

There are some difficulties which may prevent gust front detection by radar (18). For example, the distance of the center of the radar beam above the surface increases with distance from the radar due to the curvature of the Earth. A shallow outflow at a large distance from the radar may be below the beam, and thus go undetected. Near the radar, ground clutter contaminates the signal. Range folding (targets beyond the unambiguous range appear to be located within the first trip) can mask the gust frontal signature. Despite these problems, gust fronts can generally be detected in the Doppler data at ranges up to 100 km.

1. Reflectivity

Gust fronts are often associated with "thin line" echoes in radar reflectivity fields. Strong gradients in the refractive index at the leading edge of the outflow have been cited as a possible explanation of this phenomena (3, 14, 15). Also, it is believed that the thin line is caused by insects which are picked up and carried along by the outflow and by birds that feed on these insects (9, 10). More recently it has been suggested that the thin line is produced by the "precipitation roll," that is, by precipitation particles which are swept along with the outflow winds as they move away from the parent storm (17). Others have suggested that this thin line is caused by the accumulation of dust and debris particles.

2. Doppler Velocity

Gust fronts can be identified in the Doppler wind field as linear patterns of radial shear. As an example, assume a gust front is approaching the radar from the west. A reasonable first approximation is that winds within the outflow are oriented perpendicular to the gust front and therefore have a strong radially inbound component in regions where the gust front is perpendicular to the beam (Figure 2). Environmental winds ahead of the gust front are typically from the southeast to southwest quadrant and display outbound (+) or weak inbound (−) velocities. Moving away from the radar toward the gust front along a radial, one finds the Doppler velocities changing from positive (or weak negative) to negative (or more strongly negative) as the gust front is encountered. This abrupt change in Doppler wind speed produces a linear radial shear signature at the leading edge of the outflow.

The gust front tends to curve (Figure 2) and portions of its length may become aligned along a radial. When this occurs, the flow is primarily across the beam and as such is sensed as zero velocity by the Doppler radar. Identifying the radially-oriented portions of the gust front in the radar velocity field can be difficult, yet important in the interpretation of the strength of the outflow.

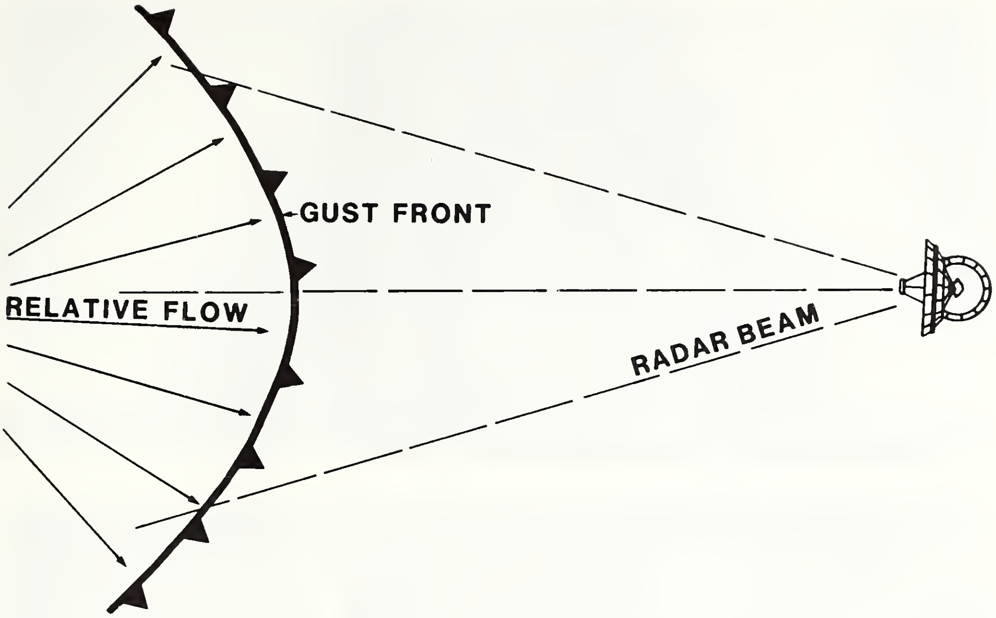

Figure 2. Schematic diagram of the horizontal structure of a thunderstorm outflow and gust front. Winds within the gust front tend to flow perpendicular to the gust front. The dashed lines indicate possible locations of a radar beam which scans the outflow.

Case Study

As an example of the ability (and difficulties) of Doppler radar to detect gust fronts, a case study is presented. This case involves two gust fronts which were produced at different locations along the same line of storms over Oklahoma on 26 April 1984. Photographs (Figures 3-6) of the reflectivity and Doppler velocity displays from the Doppler weather radar of the National Severe Storms Laboratory (NSSL) in Norman, OK show the major features of this storm and accompanying gust fronts.

The line of storms displayed in Figures 3a and b was initiated by a rapidly moving cold front, advancing toward the moist unstable air over central and eastern Oklahoma, producing severe thunderstorms and tornadoes. At 20:21:09 CST, the first outflow boundary produced by this line (cursor) had not separated from the parent storm to form the thin line reflectivity signature, but roughly paralleled the 16dBZ reflectivity contour at the leading edge of the parent line. (A value of 10 dBZ has been added to the displayed values in order to bring weak signals above the display threshhold.) This gust front was identified as such by the linear radial shear pattern in the velocity display (Figure 3b). Radial wind speeds within the outflow average 19 ms $^{-1}$ inbound. While this gust front was scanned, it never separated from the storm to form the thin line signature (Figure 3a). However, the radial shear line was present in all low elevation angle scans.

In Figure 3b, all of the velocities within the outflow (west of the shear line at the leading edge) are inbound (negative). This is no longer the case in Figure 4b. Except for a narrow band of negative velocities behind the leading edge at the north end of the gust front (label A), the velocities within the outflow are positive. It is believed that the radar beam is cutting through the head of the gust front and sensing environmental winds (roughly from the southwest at 27 ms $^{-1}$) on either side. The location of the radar beam illustrated in Figure 1 indicates a possible configuration for

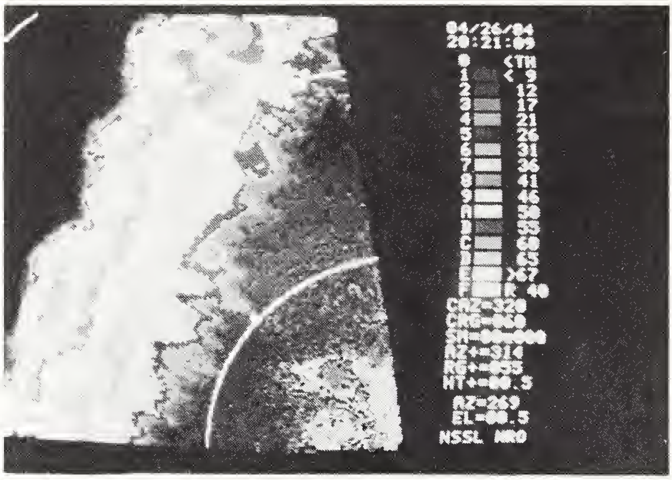

FIGURE 3(a)

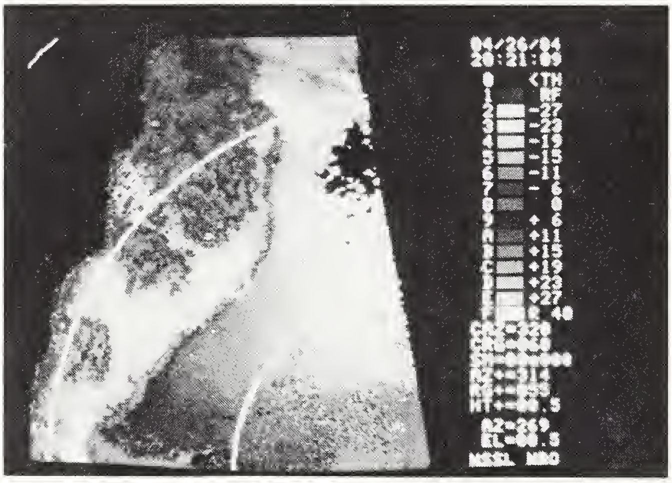

FIGURE 3(b)

FIGURE 3. Plan Position Indicator displays of (a) reflectivity and (b) mean Doppler velocity from the Norman, OK Doppler radar for 26 April 1984, 20:21:09 CST. Note information common to all radar display photographs: The legend at the right of the photographs indicates the date (4/26/84) and time (20:21:09 CST) of the PPI scan. Beneath these lines are the color categories (0 through E) and their associated reflectivity (in dBZ) or velocity (in ms $^{-1}$) values. Category F (white) is reserved for the cursor, navigation aids, and range rings (white arcs on the displays). "R40" shows that the range marks are separated by 40 km. The azimuth and range of the center of the display are given by CAZ (320°) and CRG (60 km). Storm motion (SM) is the speed and direction of the storm (00@000) that is subtracted from the velocity field so that the displayed velocities are storm-relative. The azimuth, range and height above the ground of the center of the cursor is shown by AZ+ (314°), RG+ (55 km) and HT+ (0.5 km). At the time of the photograph, the radar was pointed at azimuth AZ (269°) with an elevation angle EL (0.5°). All following radar display photographs are interpreted similarly.

that in Figure 4b. This situation illustrates how a change in the elevation angle of the radar can alter the appearance of the gust front on the radar displays.

The line of storms continued to propagate east-northeast and, at about 2040 CST, it became evident that a second gust front was being produced by the cell at the south

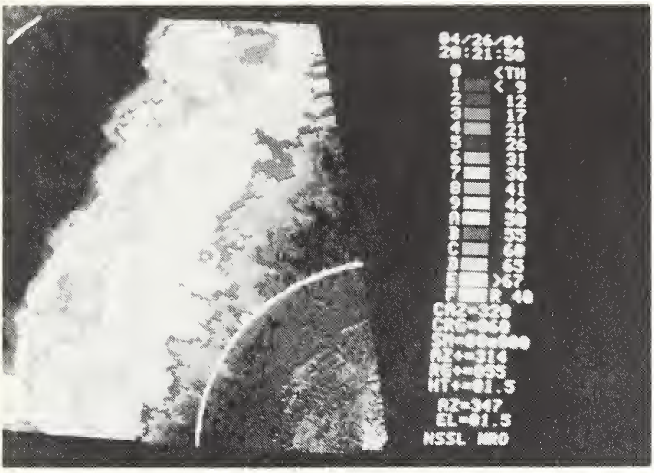

FIGURE 4(a)

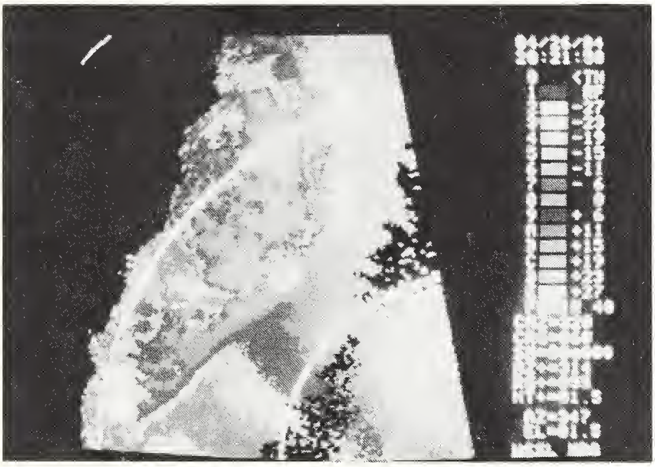

FIGURE 4(b)

FIGURE 4. Plan Position Indicator displays of (a) reflectivity and (b) mean Doppler velocity from the Norman, OK Doppler radar for 26 April 1984, 20:21:58 CST.

end of the line. Figure 5 shows the reflectivity (5a) and Doppler velocity (5b) fields for this gust front. The outflow is defined in the reflectivity field as a thin line echo (cursor) with an average reflectivity of 7dBZ (10dBZ has been added to the display). In this case there is no pronounced radial shear in the Doppler velocity field (Figure 5b) to indicate the presence of the outflow boundary. The only evidence of a gust front is the velocity field is the slight decrease in inbound velocities from about 23 ms^{-1} (east of the cursor) to 23 ms^{-1} behind the boundary (cursor).

As the storms propagate to the northeast, the parent cell of the southern gust front continues to create a boundary which moves eastward. Figure 6 shows the reflectivity and Doppler velocity displays of the southern gust front at 22:04:53 CST after it has moved east of the radar. The thin line echo (Figure 6a; cursor) is still evident (average reflectivity is 21dBZ), but a change has taken place in the velocity field (Figure 6b). In Figure 5, it was noted that there was no radial shear line associated with this gust front. In Figure 6b, the zero velocity line separating the positive velocities near the radar from the negative velocities of the environmental air is quite pronounced (cursor). Thus, as this gust front evolved, it developed both the thin line and radial shear signatures.

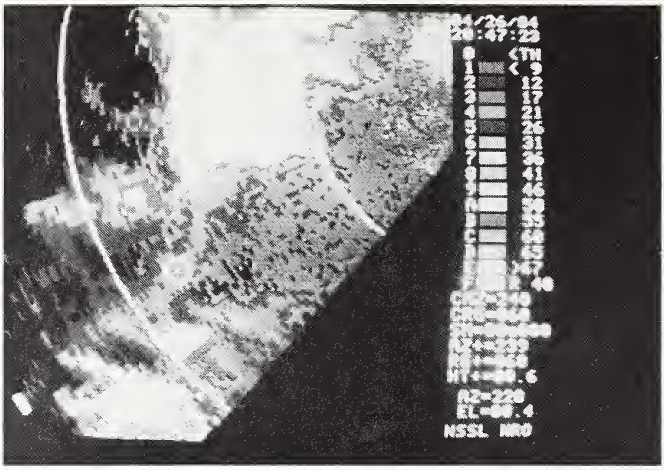

FIGURE 5(a)

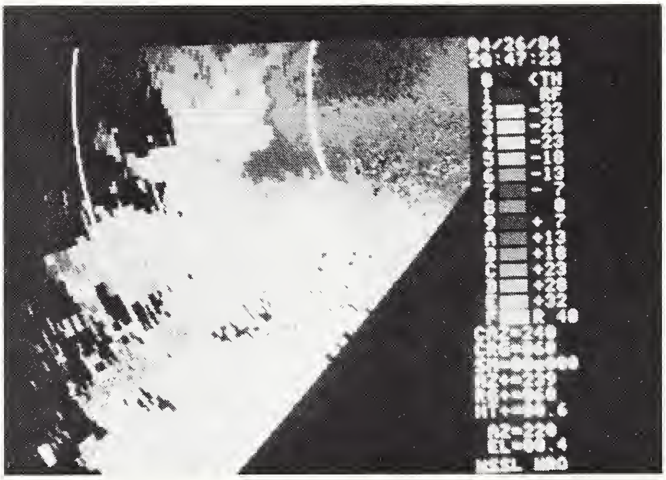

FIGURE 5(b)

FIGURE 5. Plan Position Indicator displays of (a) reflectivity and (b) mean Doppler velocity from the Norman, OK Doppler radar for 26 April 1984, 20:47:23 CST.

The Doppler radar displays are very useful not only for qualitative descriptions of phenomena such as gust fronts and their associated signatures, but also for quantitative measurements of outflow characteristics such as wind speed within the outflow, peak reflectivity along the gust front, etc. Data from ten gust fronts were collected, tabulated, and analyzed (11) to determine the expected Doppler velocities within the outflow, presence or absence of a thin line echo or radial shear signature and value of Doppler radial shear at the outflow leading edge. It was reported that:

A) Doppler winds within the outflow usually never exceeded 32 ms^{-1}.

B) The Doppler radial shear was greatest in areas where the gust front was perpendicular to the radar beam.

C) A thin line echo was present in seven of the ten gust fronts and in two of the seven, the thin line developed after the radar had begun to scan the gust front.

D) In nine of the ten cases, the gust front could be identified as a line of radial shear in the Doppler wind field.

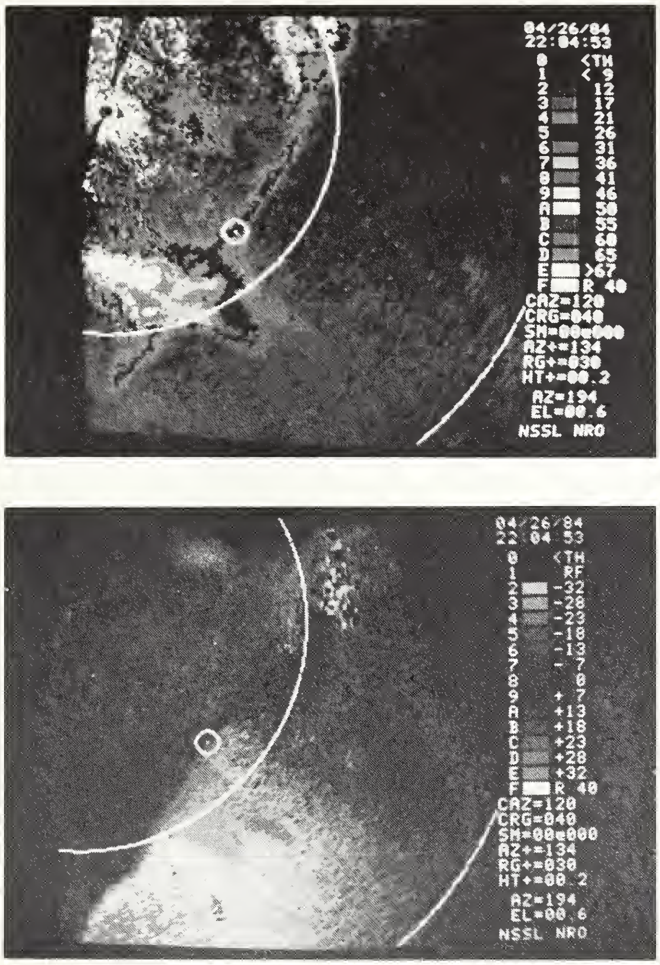

FIGURE 6(a)

FIGURE 6(b)

FIGURE 6. Plan Position Indicator displays of (a) reflectivity and (b) mean Doppler velocity from the Norman, OK Doppler radar for 26 April 1984, 22:04:53 CST.

Conclusions

The gust front produces low altitude wind shear which can be hazardous to aircraft, particularly during takeoff and landing. As shown here, these outflow boundaries can sometimes be identified as thin lines of reflectivity or lines of radial shear or both. The thin line echo is detected only after the gust front has separated from the parent storm whereas the radial shear line, if present, is detectable at any stage in the gust front life cycle. Gust fronts that do not separate from the storm are not dangerous because pilots do not usually fly into high reflectivity areas. When an outflow boundary moves away from the storm, its reflectivity decreases and the gust front becomes more difficult to detect. Relying on reflectivity alone as a measure of the potential hazard is unwise because these low-reflectivity outflows can harbor significant, possibly dangerous wind shear. Consequently, the use of Doppler velocity is essential to adequately detect the gust front outflow. The Doppler velocity field clearly displays the zone of wind shear associated with the thunderstorm outflows, thereby providing a distinctive signature of the gust front. Also, the ability to detect hazardous shear in its formative stages allows one to track the shear line as its signal strength decreases.

Such a capability can provide the pilot with sufficient advanced warning to avoid the potential hazard of low altitude wind shear associated with thunderstorms.

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