OBSERVED DIFFERENCES BETWEEN DENVER AND KANSAS CITY GUST FRONTS AND THEIR IMPACT UPON THE PERFORMANCE OF THE GUST FRONT DETECTION ALGORITHM *

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1. INTRODUCTION

The Terminal Doppler Weather Radar (TDWR) testbed radar (known as FL-2) collected data near Denver's Stapleton Airport during 1988 and near the Kansas City International Airport (MCI) during 1989. One objective of the TDWR Program is to detect gust fronts and their associated wind shifts. This information can be used by an Air Traffic Control (ATC) supervisor to plan runway changes and for warnings of potentially-hazardous gust front-related wind shears to arriving and departing pilots. This function is performed by the gust front detection algorithm.

An ongoing assessment of the performance of the current TDWR gust front algorithm is necessary to ensure that the algorithm performs consistently in different environments. Such assessments were performed after the 1988 TDWR Operational Test and Evaluation in Denver and after the 1989 operational season in Kansas City. This paper presents a comparison of gust front characteristics such as length, duration, strength, and propagation speed and direction that occurred in Denver and Kansas City and a comparison of algorithm performance at each location.

In the following, the term **gust front** refers to the leading edge of the thunderstorm outflow throughout its life cycle. A **gust front event** is a single observation of a gust front (on a radar volume scan) by the National Severe Storms Laboratory (NSSL) ground-truth analyst.

2. GUST FRONT CHARACTERISTICS

In order to compare the frequency of gust front occurrence in Denver and Kansas City, gust fronts during the months of June, July, and August in Denver in 1988 and in Kansas City in 1989 were tabulated. Although FL-2 operated outside these months at both locations, only these months of operation were common to both demonstrations. The distribution of these gust fronts is provided in Figure 1. More gust fronts were observed in Denver (133) than in Kansas City (49) during this three-month period. In Denver, the month of peak gust front activity was July, while in Kansas City August was the month of peak activity.

Gust front strength is determined by the change in Doppler velocity (ΔV) across the gust front. The strength of a gust front is defined as "weak" for 5 m/s $\leq \Delta V <$ 10 m/s; "moderate" for 10 m/s $\leq \Delta V <$ 15 m/s; "strong" for 15 m/s $\leq \Delta V <$ 25 m/s; and "severe" for $\Delta V \geq$25 m/s. The percent of gust front events in each strength category are shown in Figure 2. Kansas City gust events were stronger than Denver gust events.

The distribution of lengths of gust front events is provided in Figure 3. Denver gust fronts tend to be shorter than Kansas City gust fronts. The average gust front length for Denver and Kansas City was 29 km and 31 km, respectively.

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Figure 1. Number of observed gust fronts during the months of June, July, and August at Denver (1988) and Kansas City (1989).

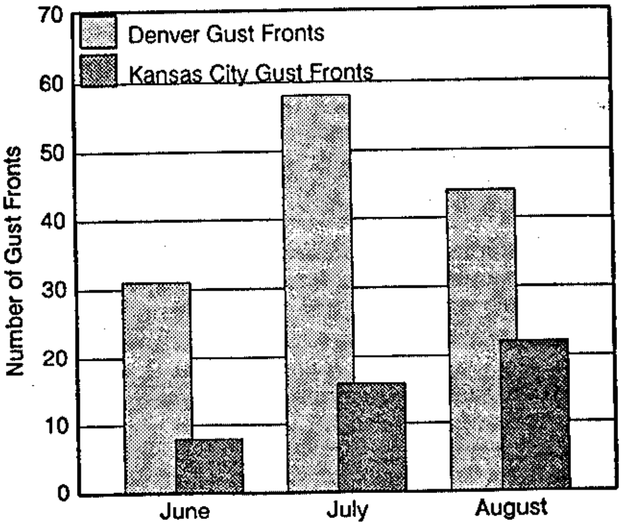


Figure 2. Percent of gust front events in each strength category.

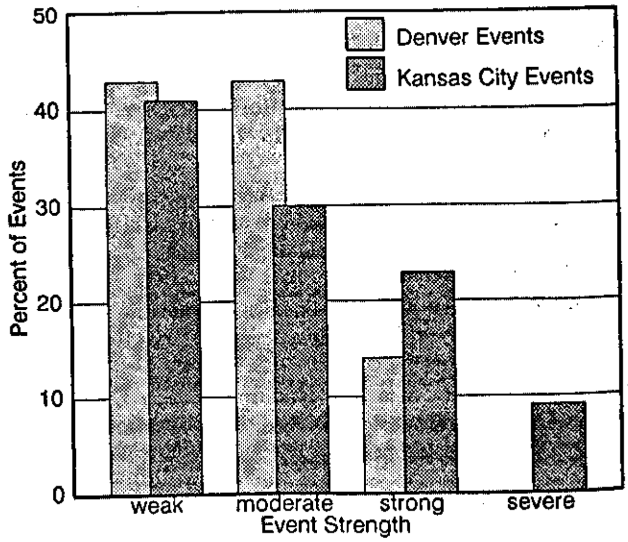
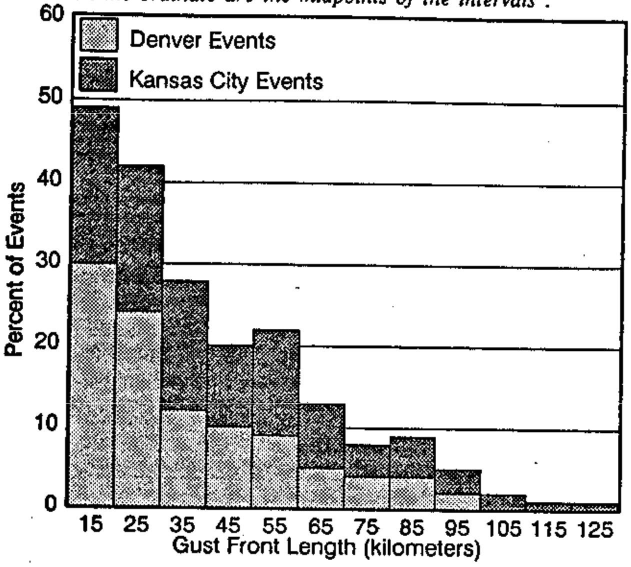
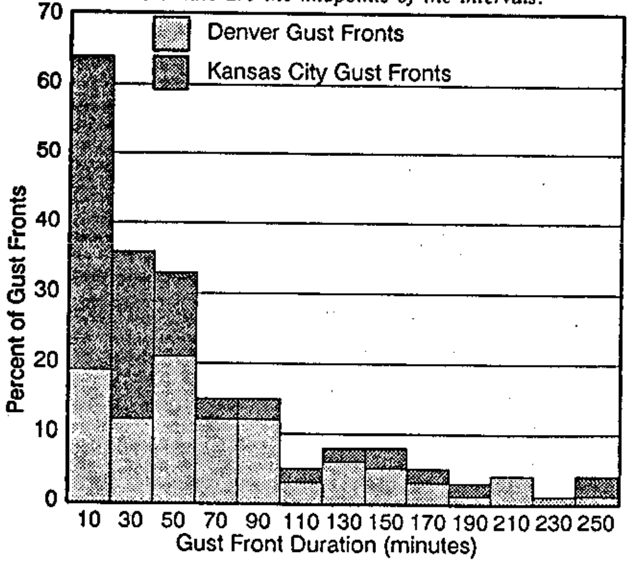


Figure 3. Percent of gust front events in each length category. The values on the ordinate are the midpoints of the intervals.



Seventy-seven Denver (1988) and 66 Kansas City (1989) gust fronts were chosen from the complement of gust fronts for analysis of duration and propagation. The distribution of gust front duration is shown in Figure 4. About 82% of Kansas City gust fronts had durations of less than 60 minutes, as compared to 52% of Denver gust fronts. The mean duration of Denver and Kansas City gust fronts was 71 and 42 minutes, respectively. Thus, Denver gust fronts are longer-lived than Kansas City gust fronts.

Figure 4. Percent of gust fronts in each duration category. The values on the ordinate are the midpoints of the intervals.



The distribution of gust front propagation speed is shown in Figure 5., which indicates that Kansas City gust fronts propagated faster than Denver gust fronts. The average propagation speed of Denver and Kansas City gust fronts was about 7 m/s and 10 m/s, respectively.

The distribution of the direction toward which the gust front propagated is given in Figure 6. In both Denver and Kansas City, the preferred direction of propagation was from the northwest quadrant to southeast quadrant.

Figure 5. Percent of Gust Fronts in each propagation speed category. The values on the ordinate are the midpoints of the intervals.

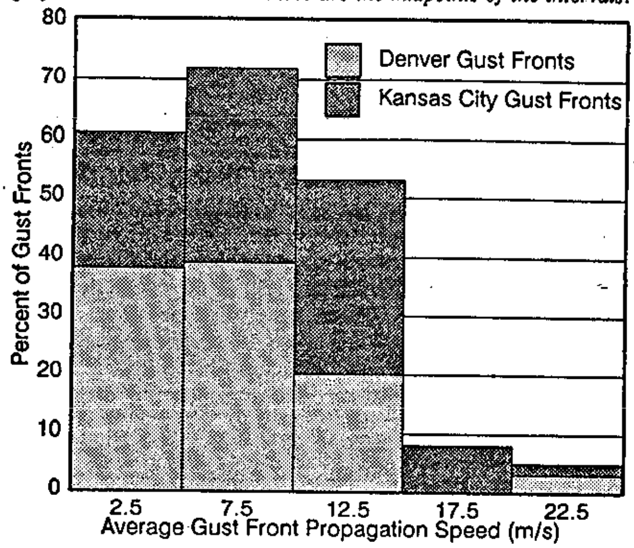
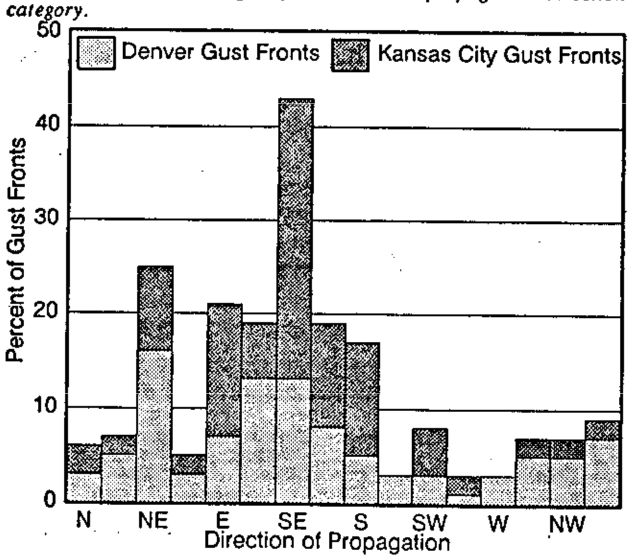


Figure 6. Percent of gust fronts in each propagation direction category.



3. GUST FRONT/WIND SHIFT DETECTION AND PREDICTION PERFORMANCE

The gust front algorithm serves two functions: warning and planning. Wind shear hazard warnings are issued when a gust front impacts the runways or within 3 miles of the ends of the runways. The alarm message consists of the type of hazard (wind shear for gust fronts), the location and expected gain in wind speed (*e.g.* wind shear alert, 35 knot gain, one mile final). The planning function consists of alerting an Air Traffic Control Supervisor when a change in wind speed and/or direction due to a gust front at the airport is imminent. A description of the algorithm and an assessment of its performance during the 1988 Denver operational demonstration are found in Klingle-Wilson, *et al.*, (1989), Merritt, *et al.* (1989), and Smith, *et al.*, (1989).

3.1. Warning Performance

The ability of the algorithm to produce timely, useful warnings rests upon its ability to detect convergent shears in the Doppler velocity data. Two basic statistics were used to quantify detection performance: Probability of Detection (POD) and Probability of False Alarm (PFA). These statistics are defined as:

$$POD = \frac{\text{detected events}}{\text{total events}}$$

$$PFA = \frac{\text{false alarms}}{\text{correct alarms + false alarms}}$$

An event is a single observation (on a volume scan) by the NSSL ground-truth analyst of a gust front in the radar data. **A detected event** is an algorithmic declaration of a gust front that overlaps ground truth. **A false alarm** is an algorithmic declaration that does not overlap ground truth. Only those gust fronts that are located within 60 km of the radar are truthed and scored. In general, it is more important to detect the stronger gust fronts since they represent the greatest hazard to aviation. For that reason, the following discussion deals only with gust fronts of moderate or greater strength.

3.2. Gust Fronts Within 60km of the Radar

POD, for all truthed gust fronts (of moderate or greater strength) as a function of gust front strength, for 1989 Kansas City is shown in Table 1. (ALL refers to all gust fronts of moderate or greater strength.) Corresponding POD results from the 1988 Denver operational demonstration are provided for comparison. In general, there is little difference in performance between 1988 and 1989. The largest POD differences are in the strong and severe categories. However, one must take care in interpreting the POD for severe gust fronts since there was only one severe event during 1988.

Table 1. Probability of Detection

	MODERATE	STRONG	SEVERE	ALL	PFA
1988	73%	91%	100%	78%	2%
1989	72%	81%	92%	77%	13%

The POD does not indicate how well a gust front is detected. One measure of the goodness of the detection is the percent of the length of the event that is detected by the algorithm. The average Percent of Length Detected as a function of gust front strength is given in Table 2.

Table 2. Average Percent of Length Detected.

	MODERATE	STRONG	SEVERE	ALL
1988	66%	69%	73%	67%
1989	59%	61%	50%	60%

For the 1988 Denver and 1989 Kansas City data, the Probability of False Alarm (PFA) was 2% and 13% respectively. A common producer of false alarms in Kansas City was the vertical shear in the horizontal wind (i.e., winds increasing, decreasing, or veering with height). This change of wind with height produced an apparent convergence in the Doppler velocity field that was detected by the gust front algorithm. In addition, the locations of these regions were roughly equal to the range of the airport from the radar, resulting in false warnings to pilots. Techniques for discriminating vertical wind shear-induced false alarms are under investigation at NSSL.

A second source of false alarms was ground clutter that was not completely removed by the clutter residue editing process. Since ground clutter exhibits a near-zero Doppler velocity, a false convergence is created by winds blowing against clutter. This was observed on the bluffs surrounding the Missouri River.

3.3. Gust Fronts at the Airport

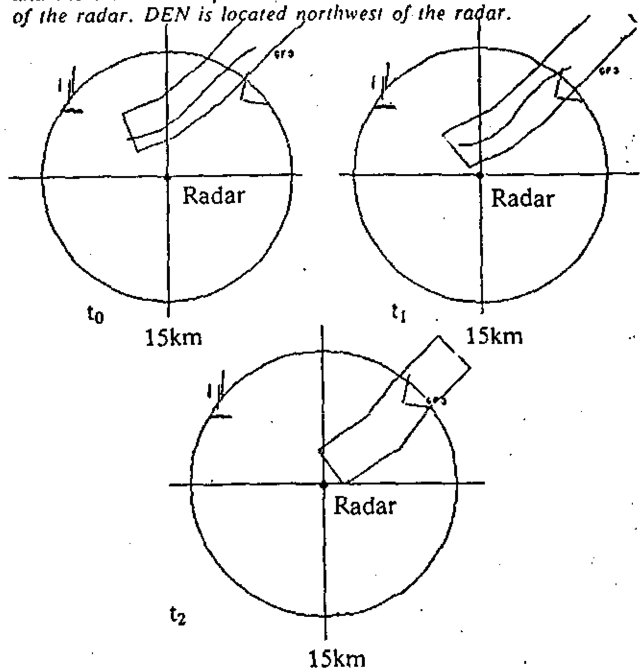
The gust front algorithm estimates the wind shear hazard associated with each gust front and issues a warning if the gust front is over the airport. The warning is composed of two parts, the location of the wind shear and the intensity. A warning is viewed as correct only if the gust front alarm is issued for the appropriate location along a runway center line. The probability of correctly locating the wind shear event is determined by computing the number of wind shear alerts issued at the airport divided by the number wind shear alerts that should have been issued. The results of this analysis for 1988 (Denver) and 1989 (Kansas City) are shown in Table 3. It is important to note that the ability to correctly locate wind shear over MCI is significantly less than over Stapleton. The reason for this is the location of the radar relative to the respective airports.

Table 3. Probability of Correctly Detecting Wind Shear at Airport

	MODERATE	STRONG	SEVERE	ALL	PFW
1988	64%	86%	-	70%	0%
1989	29%	68%	40%	45%	40%

The primary cause of missed detections was inadequate convergence in the radial direction. Because the algorithm detects only radial convergence, it is easier to detect gust fronts that are oriented perpendicular to the radar beam. As gust fronts move closer to the radar, less of their lengths are oriented perpendicular to the beam, making them more difficult to detect. An example of the loss of detection of a gust front as it moves over the radar is given in Figure 7. The locations of the Stapleton and MCI airports relative to FL-2 are shown.

Figure 7. Example of the loss of a gust front detection as the gust front passes over the radar. The rectangles represent ground truth and the solid lines represent detections. MCI is located northeast of the radar. DEN is located northwest of the radar.



The preferred propagation direction for gust fronts at both locations was northwest to southeast. If one assumes that gust front orientation is perpendicular to propagation direction, then the preferred gust front orientation is northeast to southwest. In Denver, Stapleton Airport was located to the northwest of FL-2 and therefore most gust fronts that passed over Stapleton were oriented perpendicular to the radar beam and the probability of detecting them was quite good. However, when those gust fronts moved too close to the radar (*i.e.*, overhead) the detections were lost.

In Kansas City, MCI was located northeast of FL-2 with the result that most of the gust fronts that impacted MCI were oriented parallel to the beam. In addition, those gust fronts typically passed over the radar at the same time they were impacting the airport. Therefore, the probability of detecting gust fronts over MCI and issuing warnings to pilots was small. The ability to detect reflectivity thin lines and/or azimuthal shears is essential in cases where the TDWR radar site is unfavorable with respect to the local gust front climatology.

The Probability of False Warning (PFW) is defined as the number of false alarms issued divided by the total number of alarms issued. For Kansas City 1989, the PFW was 40% versus 0% for Denver 1988. The Kansas City false warnings were due entirely to vertical shears in the horizontal winds over the airport.

The accuracy of the wind shear intensity estimates is scored by comparing the intensity expressed in the alert to pilot reports as logged by observers in the tower. For 1989 and 1988, the average difference between pilot reports and alerts was about 15 kts, with alerts overestimating wind shear relative to pilot reports.

The number of pilot reports available for the analysis of the wind shear hazard estimate is quite small (less than 10). There is some evidence in the literature (Wolfson, 1990) that suggests that the wind shear hazard associated with a gust front may not be appropriately characterized by the simple calculation used in the algorithm. From 1986 through 1989, the UND Citation aircraft performed a number of gust front penetrations. These data will be analyzed to determine if the gust front wind shear hazard estimation algorithm should be refined.

3.4. Planning Product Performance

Runway management is improved with the TDWR by alerting an Air Traffic Control (ATC) Supervisor when a wind shift is expected at the airport (forecasted location) and the winds that will result after the gust front passage (wind shift estimate). The forecasted location is scored by determining if a forecast overlaps the truth region for the time at which the forecast is valid. If so, a valid forecast is declared. There are two type of errors in forecasts: forecasts whose locations do not agree with the ground truth (a missed forecast) and forecasts for gust fronts that no longer exist (a false forecast). Forecasts are made for 10 and 20 minutes into the future. The statistics for evaluation of the performance of the forecasting function are the Probability of a Correct Forecast (POCF) and Probability of False Forecast (PFF) and are given by:

$$\text{POCF} = \frac{\text{number of valid forecasts}}{\text{number of events forecasted}}$$

$$\text{PFF} = \frac{\text{number of false forecasts}}{\text{number of (forecasted events + false forecasts)}}$$

POCF, as a function of gust front strength, is given in Table 4. For Denver (1988), the PFF for the 10 and 20 minute forecasts was 11% and 18%, respectively. For Kansas City (1989) the PFF for the 10 and 20 minute forecasts was 18% and 21%, respectively. Forecasts were generated only about 56% of the time. The high POCF values show that, when generated, forecasts were very accurate.

Table 4. Probability of Correct Forecast

	MODERATE	STRONG	SEVERE	ALL	PFF
		1988			
10 MIN	97%	98%	100%	97%	11%
20 MIN	82%	84%	-	83%	18%
		1989			
10 MIN	95%	100%	67%	97%	18%
20 MIN	95%	93%	100%	94%	21%

The accuracy of the wind shift estimate is determined by comparing the wind shift estimate to the mesonet data. The average absolute difference in wind speed and direction between the wind shift estimate and the mesonet data was 3 m/s and 30°, respectively. The wind shift speed was, on the average, about 2 m/s larger than that determined from the mesonet data and the wind shift direction was about 5° counterclockwise of the mesonet wind direction. These results are nearly identical to the 1988 Denver results.

4. CONCLUSIONS

A comparison of the gust fronts that occurred at each location shows significant differences in gust front characteristics. Although Kansas City gust fronts were fewer in number, they tended to be stronger, longer, faster-moving, and shorter-lived than Denver gust fronts.

In general, there was no significant difference (between Kansas City and Denver) in the ability of the algorithm to detect gust fronts within 60 km of the radar. However, the ability of the current algorithm (which uses only radial convergence) to generate wind shear hazard warnings at MCI was less than at Denver. There appears to be a preferred gust front orientation (northeast to southwest) in both Denver and Kansas City. Stapleton airport was located northwest of FL-2 and gust fronts moving over the airport were perpendicular to the beam. MCI was located northeast of FL-2 and gust fronts over MCI were aligned along the radar beam. The incorporation of reflectivity thin line and/or azimuthal shear detection into the gust front algorithm would improve detection capability in cases of unfavorable viewing angle.

5. REFERENCES

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