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CHARACTERISTICS OF GUST FRONTS *

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1. INTRODUCTION

A gust front is the leading edge of a thunderstorm outflow. A gust frontal passage is typically characterized by a drop in temperature, a rise in relative humidity and pressure, and an increase in wind speed and gustiness.

Gust front detection is of concern for both Terminal Doppler Weather Radar (TDWR) and Next Generation Weather Radar (NEXRAD) systems. In addition, airborne systems using radar, lidar, and infrared sensors to detect hazardous wind shears are being developed (Bowles and Hinton, 1990). The automatic detection of gust fronts is desirable in the airport terminal environment so that warnings of potentially hazardous gust front-related wind shears can be delivered to arriving and departing pilots. Information about estimated time of arrival and accompanying wind shifts can be used by an Air Traffic Control (ATC) supervisor to plan runway changes. Information on expected wind shifts and runway changes is also important for terminal capacity programs such as Terminal Air Traffic Control Automation (TATCA; Spencer, *et al.*, 1989) and wake vortex advisory systems.

In addition, the convergence associated with gust fronts is often a factor in thunderstorm initiation and intensification. Knowledge of gust front locations, strengths, and movement can aid forecasters with thunderstorm predictions.

Current gust front detection systems generally are reliable in that the probability of false alarms is low. However the probability of detecting gust fronts with these systems is less than desired (Evans, 1990). Improved characterization of gust fronts is a key element in improving detection capability.

Typically, the basic products from the algorithms are the location of the gust front (for hazard assessment) and its propagation characteristics (for forecasting). This paper discusses the thermodynamic and radar characteristics of gust fronts from three climatic regimes, highlighting regional differences and similarities of gust fronts. It also compares propagation speeds, estimated by two techniques, to measured propagation speeds.

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2. DATA AND METHODOLOGY

Measurements made as a part of the Federal Aviation Administration (FAA) TDWR operational demonstrations held in Denver, CO (1988); Kansas City, MO (1989); and Orlando, FL (1990) are used to characterize gust fronts. To support the operational demonstrations, a 30- to 40-station mesoscale network (mesonet) of automatic weather stations, with an average inter-station spacing of 1.4 - 2.1 km, was sited at each airport to measure surface winds, temperature, relative humidity, pressure, and rainfall amounts every minute (Wolfson, 1989). Only gust fronts that passed through the mesonet were considered in this study.

The requirement that a gust front pass over the mesonet limited the number of gust fronts available for analysis. Ten Denver, nine Kansas City and 13 Orlando gust fronts were chosen. Mesonet data were used to determine the surface thermodynamic and kinematic characteristics of gust fronts, while reflectivity thin line characteristics were derived from the TDWR testbed radar (FL-2). Wolfson, et al. (1990) present statistics on gust front strength, length, duration, propagation, depth, and temperature difference between the ambient and outflow air. This paper extends that analysis by characterizing the thermodynamic structure and radar reflectivity thin line signatures of gust fronts from the different climatic regimes.

Gust front temperature and relative humidity were taken from the mesonet data. Figure 1 shows a time series

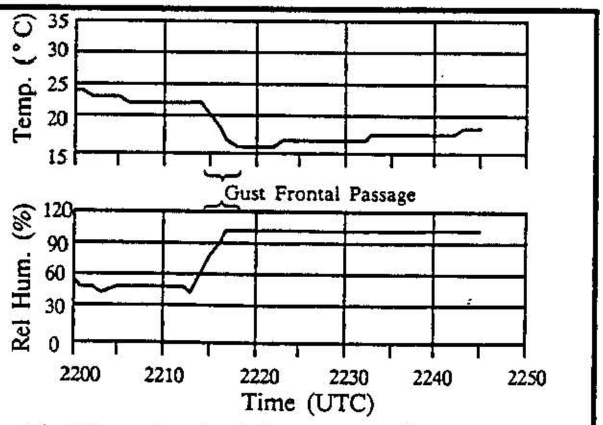

Figure 1. Time series of typical temperature (°C) and relative humidity associated with a gust frontal passage.

plot of the typical temperature and relative humidity associated with a gust frontal passage over a mesonet station. The sharp decrease in temperature and rise in relative humidity at 2215 UTC mark the passage of the gust front. For this gust front, the ambient temperature was 23°C, the outflow temperature was 18°C, and the temperature difference was 5°C. The ambient relative humidity was 50%, the outflow relative humidity was 100%, and the relative humidity difference was 50%. These data were tabulated for each station that experienced the passage of a gust front. The data were then averaged to derive characteristic temperatures and humidities for each gust front.

Gust front propagation speeds and reflectivity thin line characteristics were derived from single-Doppler radar data. The average and peak reflectivities, as well as the average reflectivity ahead of and behind the thin line, were extracted from each gust front event that exhibited a thin line. An event is a single observation of a gust front on a radar volume scan as determined by subjective analysis. Thus, a single gust front scanned five times by the radar would result in five gust front events.

3. GUST FRONT CHARACTERISTICS

Figure 2 provides the distribution of some temperature and relative humidity characteristics of Denver, Kansas City, and Orlando gust fronts. Negative temperature differences indicate that the outflow air was cooler than the ambient air. Averages computed from these data are presented in Table 1. For one Kansas City gust front the outflow was silghtly warmer and less moist than the ambient air.

Table 1. Averages of maximum outflow temperature ($max\overline{T_{gf}}$), minimum outflow temperature ($min\overline{T_{gf}}$), outflow temperature ($\overline{T_{gf}}$), ambient temperature ($\overline{T_{amb}}$), ambient–outflow temperature difference ($\overline{\Delta T}$), maximum outflow relative humidity ($max\overline{RH_{gf}}$), minimum outflow relative humidity ($min\overline{RH_{gf}}$), outflow relative humidity ($\overline{RH_{gf}}$), ambient relative humidity ($\overline{RH_{amb}}$), and outflow–ambient relative humidity difference ($\overline{\Delta RH}$). Temperatures are in °C and relative humidities are in percent.

	Denver	Kansas City	Orlando	All
$max\overline{T_{gf}}$ (°C)	30	27	29	30
$min\overline{T_{gf}}$ (°C)	18	14	20	14
$\overline{T_{gf}}$ (°C)	24	21	25	23
$\overline{T_{amb}}$ (°C)	29	25	32	29
$\overline{\Delta T}$ (°C)	-5	-4	-7	-6
$max\overline{RH_{gf}}$ (%)	82	100	100	100
$min\overline{RH_{gf}}$ (%)	23	53	65	23
$\overline{RH_{gf}}$ (%)	50	86	84	74
$\overline{RH_{amb}}$ (%)	30	74	58	54
$\overline{\Delta RH}$ (%)	20	12	26	20

Kansas City outflows exhibit the greatest range in outflow temperatures (13°C), followed by Denver and then Orlando. Kansas City average ambient and average outflow temperatures are colder than Denver and Orlando temperatures, but the average temperature difference between the outflow and ambient air is smallest in Kansas City.

The relative humidity data show that outflows are driest in Denver. On average, the largest difference in ambient–outflow relative humidity is associated with Orlando, followed by Denver and Kansas City.

Outflows from thunderstorms have been shown to be dynamically similar to density currents (Charba, 1974). A density (gravity) current is generated whenever a fluid of greater density moves through a fluid of lesser density. The motive force of the gravity current is the hydrostatic pressure difference between the two fluids. Equation 1 expresses gust front propagation speed in terms of the depth of the outflow head and the difference in virtual temperature between the warm and cold air (Seitter, 1983). This equation

$$V = k'\left[gH\frac{\Delta T_v}{T_v}\right]^{1/2} \qquad \text{(Eqn. 1)}$$

where:

- V = gust front propagation speed
- k' = redefined Froude number (~1)
- g = acceleration of gravity
- H = depth of gust front head
- ΔT_v = difference in virtual temperature between warm and cold air
- T_v = virtual temperature of the warm air.

was used to estimate the propagation speed of the Denver, Kansas City, and Orlando gust fronts for comparison to measured propagation speeds, as deduced from radar data. Head depth was estimated from radar data and virtual temperature was estimated from temperature and relative humidity. The comparison of propagation speeds computed from Seitter's technique and measured propagation speeds is given in Figure 3. In two Denver and three Kansas City cases, the gust fronts did not propagate away from the leading edge of the parent storm and outflow depth could not be estimated. These gust fronts are not represented in Figure 3.

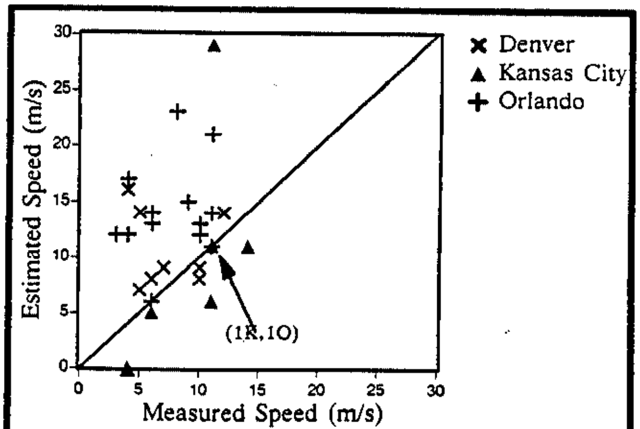

Figure 3. Estimated versus measured gust front propagation speed. Estimated values were computed from Seitter's technique. In cases where data points overlap, the numbers of points for each location (D: Denver, K: Kansas City, O: Orlando) are shown in parentheses.

GUST FRONT THERMODYNAMIC CHARACTERISTICS

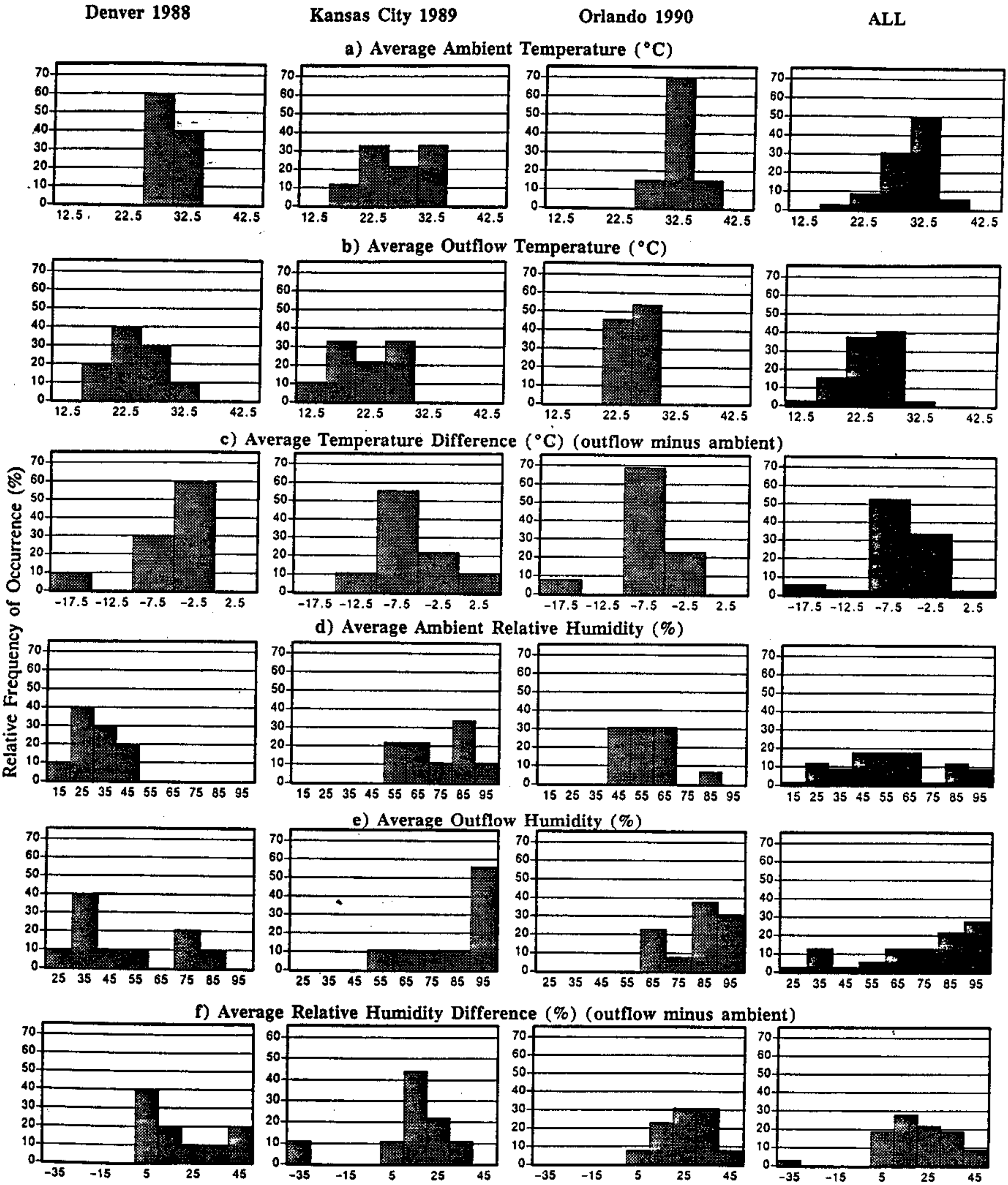

Figure 2. Relative frequency (%) of the average (a) ambient temperature (°C); (b) outflow temperature (°C); (c) temperature difference (°C) between the outflow and ambient air; (d) ambient relative humidity (%); (e) outflow relative humidity (%); and (f) relative humidity difference (%) between the outflow and ambient air. The values on the abscissa are the midpoints of the interval.

Goff (1976) found that propagation speed was roughly 67% of the maximum wind speed in the outflow. This estimate of propagation speed is compared to the measured speeds in Figure 4.

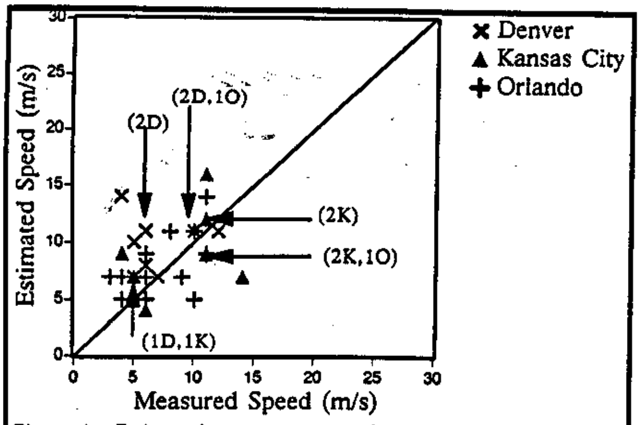

Figure 4. Estimated versus measured propagation speed. Estimated values were derived from Goff's technique. In cases where data points overlap, the numbers of points for each location (D: Denver, K: Kansas City, O: Orlando) are shown in parentheses.

Propagation speed is generally overestimated using Seitter's technique, although the estimated speeds for Kansas City gust fronts were less than the measured values. Goff's technique also tends to overestimate propagation speed, but to a lesser degree than Seitter's technique. The average differences and average absolute differences between the measured and estimated speeds are given in Table 2. The two techniques provide about the same performance for Denver gust fronts, but Goff's estimate is better for Kansas City, Orlando, and over all.

Table 2. Average and average absolute differences between estimated and measured propagation speed for Denver, Kansas City, Orlando, and All locations.

Location	Average Difference	Average Absolute Difference
Seitter's Technique		
Denver	3.3	4.0
Kansas City	0.8	5.2
Orlando	6.3	6.3
All	4.2	5.4
Goff's Technique		
Denver	3.0	3.2
Kansas City	0.1	3.0
Orlando	0.8	2.4
All	1.3	2.8

Figure 5 shows gust front duration, propagation speed and outflow depth as functions of the ambient-outflow temperature and relative humidity differences for gust fronts at the three sites. Since the gust front motive force is the hydrostatic pressure difference between the outflow and ambient air, one would expect those outflows exhibiting the largest temperature differences to move fastest and last longest. The data do not support this expectation, possibly because the velocity of the opposing ambient flow is not considered. In addition, gust front strength is determined from Doppler velocities. Since the radar senses only the along-the-beam component of the flow, strength estimates may be incorrect.

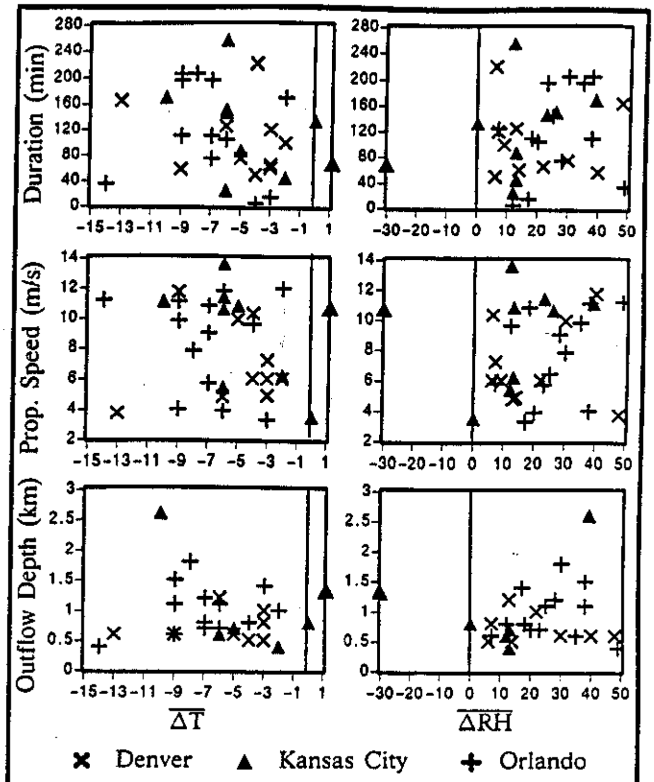

Figure 5. Gust front duration, propagation speed, and outflow depth as functions of the average ambient-outflow temperature difference ($\overline{\Delta T}$) and relative humidity difference ($\overline{\Delta RH}$).

Reflectivity data from gust front events is provided in Figure 6. For detection algorithms, it is important to know not only the reflectivity characteristics of the thin line, but also the reflectivity characteristics of the air on either side of the thin line. For this reason, reflectivities ahead of and behind the gust front are given. Mean values for the measured variables are shown in the upper right corner of each plot. There appears to be no strong regional influence on the peak and average reflectivities in the thin line or in the average reflectivity behind the thin line (*i.e.*, in the cold air). However, the reflectivities of the air ahead of the thin line (*i.e.*, in the warm air) are lower in Denver (-7 dBZ) than in Kansas City (-4 dBZ) and Orlando (-3 dBZ), although these differences are small. If the thin line is visualized as a "wrinkle in a rug" then the wrinkle is higher, and therefore possibly easier to detect, in Denver.

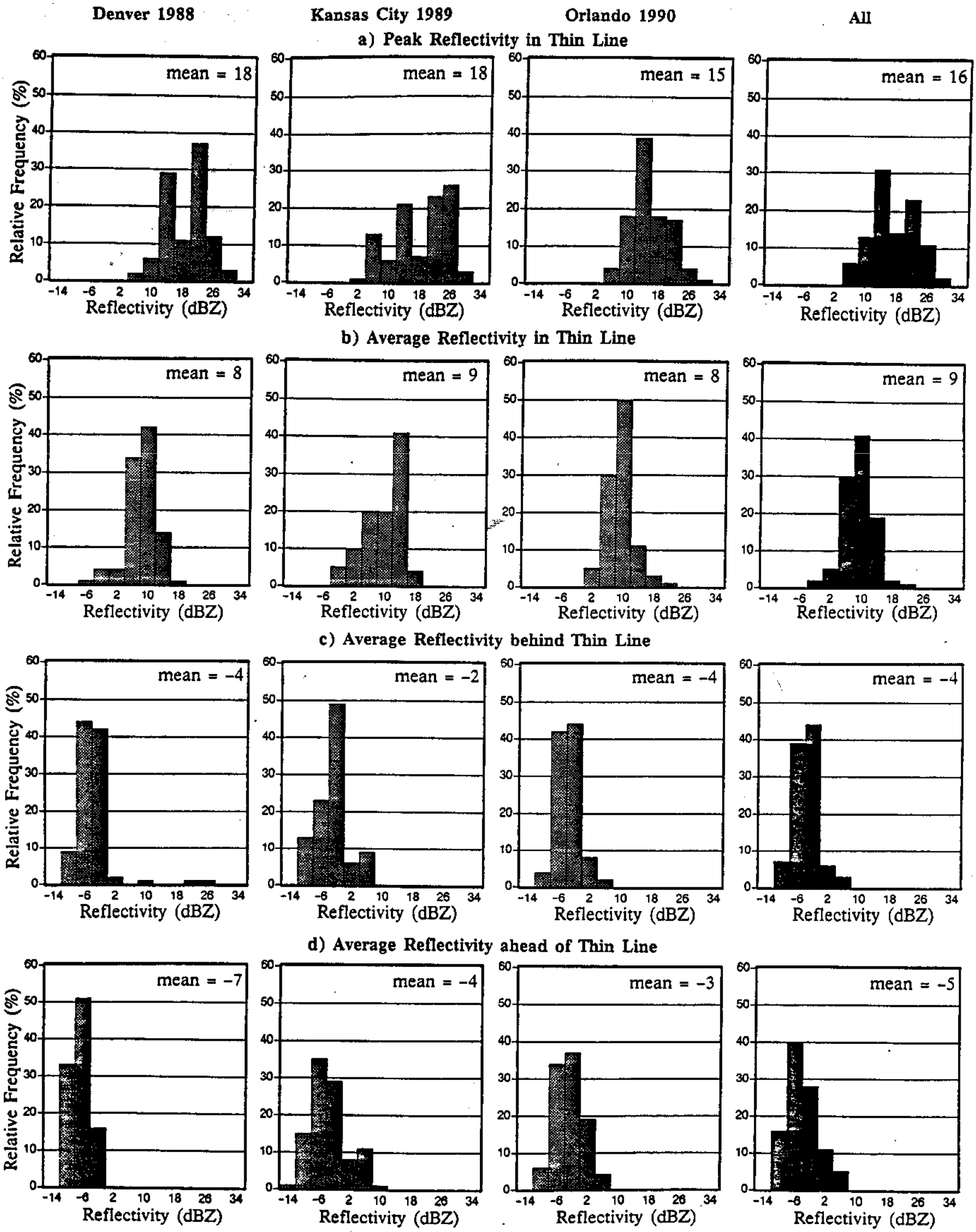

Figure 6. Reflectivity characteristics of gust fronts represented by relative frequency of events at three airports (Denver, Kansas City, and Orlando) for the measured variable. The rightmost graph in each row shows the relative frequency of the measured characteristic for all gust fronts (ALL).

4. SUMMARY

The key to detecting gust fronts is the accurate characterization of the phenomena. Some algorithms rely heavily on radar signatures of gust fronts, while others are based upon sensors that measure temperature changes across the gust front. Regardless of the sensor used to detect gust fronts, it is important to understand the differences and similarities in gust fronts over a variety of climatic regimes.

This paper has shown for the cases studied here that Kansas City outflows are colder than Denver and Orlando outflows; and that Denver outflows are driest. However, the ambient-outflow temperature and relative humidity differences are greatest in Orlando.

Two techniques were used to estimate gust front propagation speed. Seitter's method, which used virtual temperature and outflow head depth, overestimated propagation speed. Goff's method also overestimated propagation speed, but to a lesser degree.

Reflectivity thin lines were also analyzed. The values of reflectivity in the thin lines showed no regional bias. However, the reflectivity of the ambient air was lowest in Denver, which may make Denver thin lines easier to detect.

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