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PREDICTING SUMMER MICROBURST HAZARD FROM THUNDERSTORM DAY STATISTICS *

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1. INTRODUCTION

Low-altitude wind shear, specifically, the aviation-hazardous form of wind shear known as the microburst, has been cited as the cause of several aviation disasters over the past two decades (Zorpette 1986). Microbursts are strong, small-scale convective storm downdrafts that impact the ground and cause a violent divergent outflow of wind. The Federal Aviation Administration (FAA) recently awarded a contract for the production of 47 Terminal Doppler Weather Radars (TDWRs) to detect microbursts (Evans and Turnbull 1989, Turnbull et al. 1989). Since the TDWR systems are expensive, only a limited number will be available for use at major U.S. airports. In deciding which airports will receive the TDWRs or any other advanced detection equipment, such as the ASR-9 with wind shear detection capability (Weber and Noyes 1988) or the Enhanced Low Level Wind Shear Alert System (Barab et al. 1985), a detailed cost-benefit study will be performed (Martin Marietta Information Systems Group 1989). One factor that would aid in determining the benefit of advanced wind shear detection equipment is a knowledge of the average relative microburst threat at each major airport. Using "thunderstorm day" statistics and the results of measurements by the FAA TDWR testbed systems, we propose a method for predicting this threat.

2. THE STUDY

Microburst statistics are not routinely collected, so some other convective storm related data must be used to determine the level of microburst hazard at each U.S. airport. One thunderstorm related statistic with a long archive and nationwide coverage is the "thunderstorm day", a calendar day on which thunder is heard at least once by a weather observer (Department of Commerce 1958). Thunderstorm day statistics have been gathered at NWS offices around the country for approximately 100 years.

Using actual TDWR testbed microburst data obtained in Memphis (1984 and 1985), Huntsville (1986), and Denver (1987 and 1988) and the reported number of thunderstorm days at these sites, we use statistical regression techniques to derive a mathematical relationship between microburst occurrence and the number of thunderstorm days recorded at each location.

The time period common to all our data is June 8 to September 8. This corresponds closely to the climatological definition of summer (June 1 to August 31), the season in which microburst activity is known to be at its peak. Thus, our derivation will predict the average number of summer microbursts occurring at most airports for which thunderstorm day data is available.

3. RELATING MICROBURSTS TO THUNDERSTORM DAY STATISTICS

3.1. Determining a Region of Applicability

The method for comparing the number of microbursts that occur around an airport to the actual number of thunderstorm days recorded there requires an estimate of the actual distance over which thunder can be heard by weather observers. Ideally, thunder can be heard at distances as great as 25-30 km (Viemeister 1961), but a weather observer stationed at an airport would hear thunder over a smaller area because 1) the observer spends most of the time indoors performing various duties and 2) the din of air traffic drowns out thunder originating at great distances. Thus, we define the *Thunderstorm Day Observation Region* (TDOR) as a circle of radius 15 km around the weather observation site. Only the microbursts that occur within the TDOR will be related to the thunderstorm day statistics.

3.2. Tallying Microbursts in the TDOR

To count microbursts in the TDOR, we chose to use mesonet data instead of Doppler radar data, or a combination of both, because the mesonet operated continuously and also provided us with an additional year of data (Wolfson 1989). Even though the mesonet does not sample uniformly, we can be assured that most microbursts that did fall in the net were detected because of the fairly dense station spacing

Table 1 . Average station spacing (only those stations within 15 km of NWS site were used), coverage areas and scale factors used for each mesonet site.

MESONET SITE	AVERAGE SPACING BETWEEN STATIONS (km)	APPROX. AREA OF COVERAGE (sq km)	SCALE FACTOR
Memphis 1984	1.90	190	3.72
Memphis 1985	2.16	240	2.95
Huntsville 1986 (w/ PAM) *	1.89	300	2.36
Huntsville 1986 (w/o PAM)	2.51	250	2.83
Denver 1987 & 1988	1.36	200	3.53

* The 1986 mesonet was enhanced by the presence of 41 additional portable automated mesonet stations during the COHMEX Project (Dodge et al. 1986) in June and July. This resulted in two different average station spacings for that year.

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(Table 1). Microbursts which impacted the mesonet were identified by DiStefano (1987, 1988), Clark (1988), and DiStefano and Clark (1990). They found only a few microbursts that were detected by Doppler radar but not by the surface weather station network. Since these misses represent a very small percentage of the total number of observed microbursts, a correction for microburst misses by the mesonet was deemed unnecessary.

Given that mesonet data is to be used for counting microbursts in the TDOR, an *area of coverage* for each mesonet must be determined. The coverage area will be the sum of the individual mesonet station *influence areas* and will determine the fraction of the TDOR that was sampled. The influence area for a single mesonet station can be estimated from the working definition of a microburst. Fujita (1985) defines a microburst as a wind velocity differential of at least 10 m/s over a distance of 4 km or less. Therefore, if we assign an influence area equal to a circle of radius 2 km to each mesonet station, even a weak microburst, with a velocity differential of 10 m/s impacting two mesonet stations exactly 4 km apart, will be detected just within the influence area of the two stations. The average station spacing for each network provides solid areal coverage over most of the mesonet.

Since we ultimately want to project how many microbursts occurred within the TDOR based on our mesonet-detected microbursts that also occurred there, we need to determine the intersection of the solid area of mesonet coverage (given by the union of all the stations' influence areas) with the TDOR. This intersection yields an approximate area of coverage. An example of a mesonet's areal coverage is shown in Figure 1 along with the 15-km radius circle bounding the TDOR.

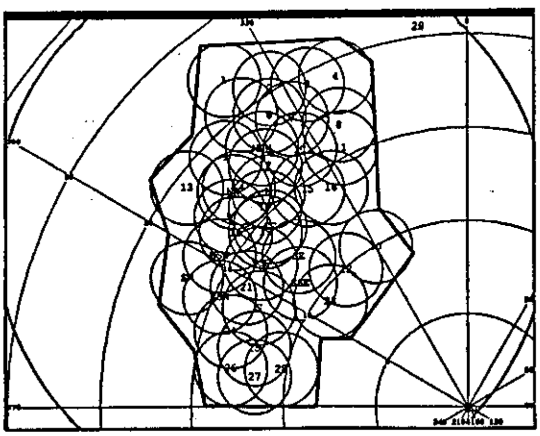

Figure 1 . Area of coverage for mesonet at Denver, CO. Circles of radius 2 km represent influence areas of individual mesonet stations, outer boundary of TDOR is visible at corners of illustration, and total area of mesonet coverage is represented by irregularly shaped polygon.

If we assume microburst occurrence is random and evenly distributed, multiplying the number of microbursts detected within the mesonet coverage area by a scale factor equal to the ratio of the area of the TDOR to the mesonet coverage area will yield a projected number of microbursts occurring within 15 km of the observation site. This assumption of isotropic microburst occurrence is supported by the observed distribution of mesonet-detected microbursts (e.g., Figure 2). The scale factors used for each network are given in Table 1. The actual thunderstorm days recorded by NWS observers from June 8 through September 8 at each of the sites (T) and the scaled number of microbursts appropriate for comparison (M) are given in Table 2 .

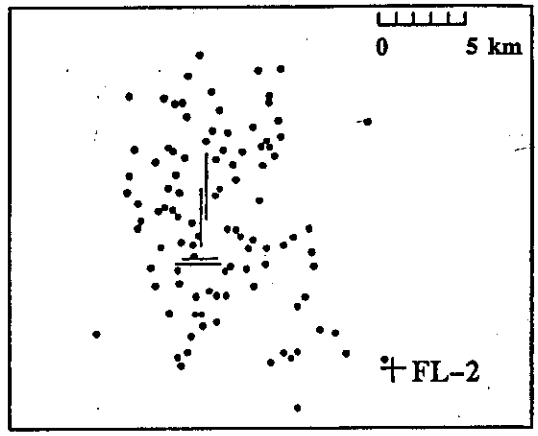

Figure 2 . Locations of the 1987 mesonet-impacting microbursts at the times of their peak strength (DiStefano, 1988). Solid horizontal and vertical lines represent position of runways at Stapleton International Airport. Similar isotropic distributions were observed during 1985 and 1986 in Memphis and Huntsville, respectively (DiStefano 1987, Clark 1988).

4. RELATING WET AND DRY MICROBURSTS TO THUNDERSTORM DAYS

Our results show that microbursts occur mainly on thunderstorm days in the southeastern part of the country, whereas many microbursts occur on days that are not thunderstorm days in the Denver area (Table 2). This is due to the common occurrence of *dry* microbursts in the Western Plateau. Dry microbursts originate from benign-looking, high-based cumulonimbus clouds that produce little if any surface rain (Krumm 1954; Wakimoto 1985; Wilson et al. 1984). These clouds are less likely to produce lightning (and therefore thunder) than the more typical low cloud base, heavy rain thunderstorms (Williams et al. 1989a).

Table 2 . Summary of scaled microburst and thunderstorm day data for each mesonet site. T is the observed number of thunderstorm days, M the total number of microbursts, MT the number of microbursts on thunderstorm days, MX the number of microbursts on non-thunderstorm days, Mwet the number of wet microbursts, and Mdry the number of dry microbursts.

MESONET SITE	T	M	MT	MX	Mwet	Mdry
M 84	21	48	37	11	48	0
M 85	24	77	71	6	77	0
H 86	23	132	125	7	132	0
D 87	30	297	177	120	92	205
D 88	27	406	289	117	120	286

To check this assumption, we examine the surface rainfall characteristics of microbursts that occur both on thunderstorm days (given the symbol M_T) and on non-thunderstorm days (M_X). The total number of microbursts may be subdivided according to:

$$M = M_{wet} + M_{dry}$$

where M is the total number of microbursts that occur, M_{wet} the number that occur with measurable surface rainfall, and M_{dry}, those without measurable surface rainfall. However, it is also true that

$$M = M_T + M_X .$$

Because the type of microbursts in Denver appear different from those typical of the Southeast, we can anticipate that it will be necessary to derive two different equations to predict summer microburst occurrence in these regions.

4.1. Rainfall Characteristics of M_X and M_T

All of the microbursts on non-thunderstorm days (M_X) in Denver 1987 were "dry" (Table 2); no measurable rainfall was detected at the surface. In Denver 1988, radar and mesonet data indicate only 21% of the microbursts on non-thunderstorm days were wet. Thus, as expected, the vast majority of microbursts occurring on non-thunderstorm days in Denver were dry.

In contrast to Denver, microbursts rarely occurred on non-thunderstorm days in the Southeast. During the study period, only 9% of the microbursts were observed on non-thunderstorm days (M_X) in Memphis and Huntsville (Table 2). Radar and mesonet rainfall data indicate at least 75% of these microbursts were wet. The rainfall characteristics of the other two events could not be determined because of lack of radar and rain gage data. (Interestingly, 38% of these microbursts on non-thunderstorm days occurred near the outer boundary of the TDOR.)

Based on the surface rainfall information, we found that the microbursts on non-thunderstorm days (M_X) were both wet and dry in Denver and only wet in Huntsville and Memphis. The observation of wet microbursts on non-thunderstorm days suggests possible observer error. Williams et al. (1989b) found only a small percentage of wet microbursts in 1987 and 1988 in Huntsville that were not accompanied by lightning, and these microbursts were very weak. Radar data for 6 of the 7 microbursts on non-thunderstorm days in Denver 1988 showed 40–55 dBz cells were present within 10 km of the observation site (Stapleton International Airport). Corona current measurements (Williams 1989) showed lightning was in the area during at least 5 of the events. However, the relationship between high radar reflectivity and lightning occurrence, and the exact locations of the lightning detected by the corona probe measurements are uncertain, so we cannot state conclusively that these occurrences represent observer error.

All microbursts in Memphis and Huntsville occurring on thunderstorm days (M_T) were associated with surface rainfall. However, in Denver only 52% of the events in 1987, and 33% in 1988 were associated with surface rainfall.

4.2. The Dependence of M_{wet} on T

Because two distinct types of microbursts occur in Denver and only one type occurs in the Southeast, an attempt to relate M, the *total* number of microbursts, to T using data from the two climatological regions would be inappropriate. It is more appropriate to relate similar types of microbursts to thunderstorm days. For Denver, M_{wet} is equal to only a fraction of the total number of microbursts. However, we assume that $M_{wet} = M$ in the Southeast, where we believe all microbursts are wet. Dry microburst occurrence in the Denver area will be considered in Section 5.

A least-squares statistical regression can be performed to determine the relationship between M_{wet} and T. The data was fit using the three basic mathematical models shown in Figure 3 . Since the data consists of only six points (including the origin), only integer exponents are considered.

The rms error resulting from the least-squares fit of each model is indicated in parentheses in Fig. 3 . Based on these errors, the linear model provides the best fit for the data and will be used as the expression relating M_{wet} to T. The coefficient "a" resulting from this fit is 3.7 ± 0.5, where 0.5 is the standard deviation of the regression coefficient. This implies that, on average, 3 or 4 wet microbursts occur within a TDOR on a given thunderstorm day. It is worth noting that the errors here are quite large. Not only is the sample small, but the available thunderstorm day data all falls within a very limited range, indicated by the shaded region in Fig. 3 . More data over a larger number of years and a greater range of thunderstorm days is needed before much confidence can be placed in the linear model.

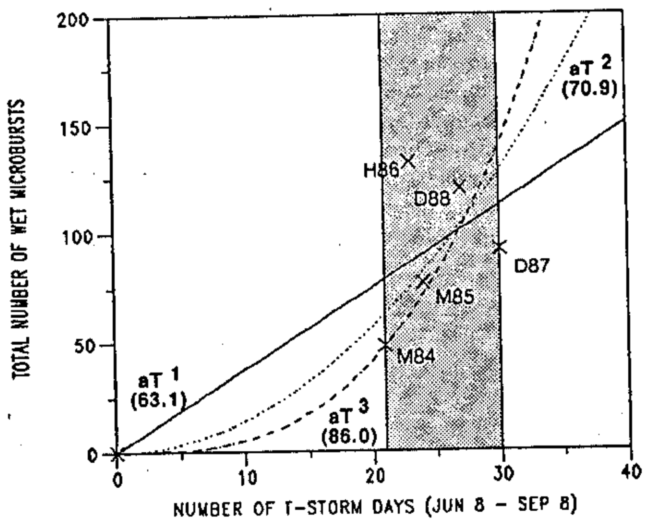

Figure 3 . Results of least-squares fits of selected models to the M_{wet} and T data shown in Table 2. Shaded region accentuates the limited range of data currently available for T.

Assuming that each individual thunderstorm has the potential to spawn a microburst, we can speculate that more microbursts are likely to occur within a confined area (i.e., the Thunderstorm Day Observation Region) on a given thunderstorm day in the southern regions of the country (where thunderstorms are more frequent) than are likely to occur within the same area in the northern regions. Remembering that a weather observer records a thunderstorm day if he hears thunder *at least once* during any calendar day, it is plausible that the relationship between wet microbursts and thunderstorm days is nonlinear. The limited data we have to date suggests a linear relationship, but the acquisition of additional data may change this result.

5. PREDICTING MICROBURST OCCURRENCE

5.1. Predicting M_{wet}

To predict wet microburst totals in the Southeast and the Western Plateau region, direct use of the linear relationship between wet microburst totals and thunderstorm days is appropriate. This results in the following expression for the total number of wet microbursts.

$$M_{wet} = (3.7 \pm 0.5)\ T$$

The problem of predicting the total number of *dry* summer microbursts in the Western Plateau region is discussed in the following section.

5.2. Predicting M_{dry}

Dry microbursts occurred commonly on both thunderstorm days and non-thunderstorm days in Denver, and in inconsistent proportions to the wet microbursts on those days in the two different years of data. Remarkably consistent, though, was the percentage of the *total* summer microbursts that were dry; this was 69% in 1987 and 70% in 1988.

This observed consistency can be exploited in predicting M for Denver and the Western Plateau; assume M_{wet} determined in Section 5.1 is equal to 30% of the total number of microbursts. Then, if the wet to dry microburst ratio in Denver is characteristic of the *entire* Western Plateau, the equation projecting the total number of microbursts in the Western Plateau region is given by

WESTERN PLATEAU
$M_{wet} = (12.3 \pm 1.7)\ T$

where the standard deviation of the regression coefficient determined in Section 4.2 has also been increased by 70% to 1.7. Thus, the average number of microbursts per recorded thunderstorm day in a Western Plateau TDOR is more than three times greater than in the rest of the country.

6. PREDICTING AVERAGE SUMMER AIRPORT MICROBURST HAZARD

To convert the equations for predicting mean summer microburst frequency in a TDOR into equations for predicting the average *summer hazardous* microburst frequency for an *airport* area, two additional factors need to be taken into account. These are described below.

6.1. Minimum Wind Shear Threshold for Hazard

The first TDWR Operational Demonstration conducted during July and August of 1988 at Stapleton International Airport in Denver (Turnbull et al. 1989) revealed that microbursts with differential velocities less than 15 m/s have very little impact on aircraft performance. However, the data used in this derivation defined a microburst as having a differential velocity of 10 m/s or more. Single Doppler peak estimates for microbursts which impacted the mesonet from 1985–1988 indicate that approximately 65% of both wet and dry microbursts detected by mesonet had a differential velocity greater than 15 m/s. The single Doppler peak estimate is comparable to the headwind–tailwind shear an aircraft would encounter during microburst penetration. Therefore, microburst totals predicted by our derived equations, multiplied by 0.65, will give the number of aviation–hazardous microbursts.

6.2. Airport Microburst Hazard Region

The TDWR Users Working Group recommends that a wind shear alarm region extend 3 nautical miles (5.6 km) from the end of airport runways (to protect the glideslope paths) and be 1 nautical mile (1.6 km) in width. Since most airport runways are not longer than 4 km in length, the region to be protected corresponds to approximately 25 square km per runway. The total area of the alarm region will vary from airport to airport, depending on the number of runways in use. However, our derived equations predict the number of microbursts expected within a circle of radius 15 km around an airport (the "TDOR"). Thus, to provide microburst totals that represent the aviation microburst hazard at each site, the number of predicted microbursts must be reduced by a factor **R**, the ratio between the areas of the wind shear alarm region of the airport of interest and the TDOR region.

$$\mathbf{R} = \frac{\text{wind shear alarm region area (km)}^2}{\pi\ (15\ \text{km})^2}$$

6.3. Final Microburst Airport Hazard Equations

The inclusion of the factors mentioned in the preceding sections yields the final equations to be used to predict relative summer microburst hazard at U.S. airports. They are

EQUATION A: To be used for all parts of the country except the Western Plateau
$(2.4 \pm 0.3)\ \mathbf{T}\ \mathbf{R}$

EQUATION B: To be used for the Western Plateau region only
(8.0 ± 1.1) T R

where T represents the mean number of *summer* thunderstorm days, and R is defined in Section 6.2.

6.4. Applicability of Microburst Hazard Equations

The final equations derived for relating microbursts to thunderstorm days are appropriate for summer only. In Denver, 69% of the annual thunderstorm days occur in the three summer months, on average (e.g., Court and Griffiths 1986). However, only 51% of the annual number in Huntsville, and 41% of the annual number in Memphis occur during the summer. Thus, a prediction of summer microburst totals clearly underestimates the *annual* microburst hazard in Memphis and Huntsville, relative to Denver. Furthermore, the microburst/thunderstorm day relationship could be different for the spring and fall seasons. Unfortunately, TDWR testbed mesonet data for these seasons is incomplete, so this relationship cannot be determined.

Since we currently lack data in regions where summer thunderstorm day totals are significantly lower or higher than in the regions used in this analysis, we suggest the resulting equations be used only for those locations where mean summer thunderstorm day totals fall within the range bounded by the Denver, Memphis, and Huntsville mean summer totals (22–30 thunderstorm days).

7. FUTURE WORK

TDWR testbed mesonet data obtained in Kansas City, Missouri in 1989 will be analyzed and additional data will be collected in Orlando, Florida (1990 and 1991) and possibly Washington, D.C. (1992). These data points can be included in this study as they become available. The data we have at present falls within a narrow range of thunderstorm days (21–30). Although Kansas City's mean summer thunderstorm day total also falls in this range, this data will be useful because it provides data from another climatological regime. The inclusion of microburst and thunderstorm day data from Orlando and Washington, which typically experience approximately 49 and 17 thunderstorm days during the summer months, respectively, would certainly add confidence to our predictions made with the resulting equations. The prospect of obtaining two years of data from another site (Orlando) would also increase our confidence in the resulting equations since the significance of interannual variability in our derivation is still uncertain.

To check our argument that dry microburst occurrence is indeed rare in all regions of the country except the Western Plateau, statistics on wet and dry microbursts will also be computed for the Kansas City, Orlando, and Washington D.C. microbursts.

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