WINDEX—A New Index for Forecasting Microburst Potential

DONALD W. MCCANN

Experimental Forecast Facility, National Severe Storms Forecast Center, Kansas City, Missouri

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ABSTRACT

Microbursts are small-scale phenomena that have been viewed by many meteorologists as difficult to predict. However, there exists sufficient knowledge of microburst evolution by some in the research and operational communities that can be applied on the mesoscale to provide some warning to the public and aviation. This paper introduces a wind index or WINDEX that is based on this knowledge. It can be easily computed from soundings. The WINDEX is calculated from soundings known to have been taken in microburst environments and previously presented in the literature. The WINDEX can also be computed from surface observations using appropriate assumptions. This paper shows how to use the hourly surface-based WINDEX information (data) by showing its application to the infamous DFW microburst on 2 August 1985 and for three consecutive days in August 1993. The surface-based WINDEX analyses reveal a common pattern first noted by Ladd (1989); that is, microbursts primarily occur with new convection on old thunderstorm outflow boundaries. When an outflow boundary moves perpendicular to the WINDEX contours, into an area of high WINDEX values, conditions are favorable for microbursts. With this conceptual model it is possible for forecasters to give one to two hours warning that microbursts are probable for a small area.

1. Introduction

Thunderstorms process the atmosphere to relieve vertical instabilities by several means, one of which is to bring middle tropospheric air down to the surface. Occasionally this occurs violently, and the result is damaging thunderstorm winds called downbursts. Fujita (1985) divided downbursts into two categories according to size; those larger than 4 km in horizontal dimension are called macrobursts, whereas the smaller are called microbursts.[1] He further classified microbursts into wet and dry types depending on surface rainfall rates during a microburst.

Statistics from several microburst experiments (Table 1) imply that about one microburst per day occurred in the small experimental areas during the investigations. If this frequency were extended throughout the central and southern United States, as many as 100 microbursts a year may occur in a county-size area depending on the length of the season. This statistic may startle some forecasters who have thought that while microbursts can be dangerous, they are rare and small scale, and therefore difficult to predict. There exists considerable knowledge of microburst evolution by some in both the research and operational communities that can be applied to the microburst forecast problem. Many microbursts can now be forecast, at least on the mesoscale, with sufficient lead time to the public and aviation.

High-resolution Doppler radar can detect some microbursts and show some short-term precursors that may help accurately locate microbursts (Roberts and Wilson 1989; Hermes et al. 1993), but the research clearly shows that microbursts often evolve from an updraft stage to a dangerous microburst in just minutes (Wilson et al. 1984; Caracena and Maier 1987; Proctor 1988; Wakimoto and Bringi 1988; Roberts and Wilson 1989). If a forecaster were not alert to the potential for the microburst, then the short, valuable time between precursor detection and occurrence would be lost. If a forecaster can anticipate microbursts, then he/she can respond quickly. More importantly, if the weather-sensitive users were also anticipating microbursts, they could react wisely as the event was beginning. Clearly the forecaster needs a method with which to foresee microburst potential.

This paper introduces a new index called the "Wind INDEX" or WINDEX for identifying air masses favorable for microbursts. The WINDEX is based on studies of observed and modeled microbursts. It can be simply computed from environmental conditions

[1] In this study, the resolution of damaging wind reports makes it almost impossible to attempt classifying downbursts as to size. Almost all are probably small. While the term downburst includes all scales, the term microburst was coined for small downbursts. To have an arbitrary 4-km size limitation confines the term to artificial boundaries. Therefore, this paper will use the term "microburst" as synonymous with "small downburst."

Corresponding author address: Donald W. McCann, NOAA/NWS, Room 1728, Federal Building, 601 E. 12th Street, Kansas City, MO 64106-2808.

TABLE 1. Microburst frequency in various experiments.

NIMROD	1978	NErn IL	50 in 42 days	(Fujita 1985)
JAWS	1982	DEN area	186 in 86 days	(Wakimoto 1985)
MIST	1986	Nrn AL	62 in 61 days	(Atkins and Wakimoto 1991)

measured by soundings or forecasted by numerical weather prediction models. Combining horizontal analyses of WINDEX with boundary-tracking tools such as visible satellite imagery or radar, a forecaster can give one to two hours lead time for probable microbursts over a small area.

2. Development of the WINDEX

Wolfson (1990) developed a model of microburst strength based on the vertical momentum and continuity equations. The vertical momentum equation is

$$\frac{dw}{dt} = g\frac{\theta'}{\theta_0} - g(l + i) - \frac{P'_z}{\rho_0}, \quad (1)$$

where w is the vertical velocity, t is time, g is the gravitational acceleration, θ_0 is the potential temperature of the environment, and θ' is the difference in potential temperature between a parcel and the environment, $(l + i)$ is the mass mixing ratio of liquid water plus ice, P' is the perturbation pressure, ρ_0 is the density of the environment, and the subscript z means partial differentiation with height. Making some simplifying assumptions, the left-hand side of Eq. (1) can be approximated as

$$\frac{dw}{dt} \sim \left(\frac{w^2}{2}\right)_z. \quad (2)$$

Substituting Eq. (2) into (1) and integrating with height, the vertical velocity is dependent on the depth of the downdraft:

$$w^2 \sim \text{forcing} \times \Delta z. \quad (3)$$

The forcing consists of buoyancy, which can be estimated from environmental soundings, precipitation loading, and differential vertical pressure perturbation, which depend on the characteristics of the microburst-producing storm. Looking just at the buoyancy term, Wolfson showed, by using Srivastava's (1985) data, that this forcing is proportional to the square of the environmental lapse rate, Γ, through which a downdraft descends.

$$\theta' \sim \Gamma^2 \quad (4)$$

or

$$w^2 \sim \Gamma^2 \Delta z. \quad (5)$$

Observations (Wakimoto and Bringi 1988) and numerical models (Srivastava 1987; Knupp 1989; and Proctor 1989) of microbursts strongly suggest that microbursts develop as a result of frozen precipitation falling through the melting level. The absorption of latent heat due to melting cools air parcels, and they become negatively buoyant and accelerate downward. Evaporation typically continues the process. Therefore, the relevant environmental lapse rate to consider is from the surface to the melting level, and the appropriate Δz corresponds to the height above ground of the melting level. Proctor (1989) presented an index for wet microbursts that included these terms, but its form is $w^2 \sim \Gamma(\Delta z)^2$. Further, while correlating well with his modeled microburst intensities, Proctor's index did not compare well with actual microburst intensities, measured by the observed maximum wind gusts. The WINDEX uses the identical parameters found in Proctor's index but reformulates it into Wolfson's form and is

$$\text{WI} = 5[H_M R_Q(\Gamma^2 - 30 + Q_L - 2Q_M)]^{0.5}, \quad (6)$$

where H_M is the height of the melting level in km above the ground; $R_Q = Q_L/12$ but not greater than 1; Γ is the lapse rate in degrees Celsius per kilometer from the surface to the melting level; Q_L is the mixing ratio in the lowest 1 km above the surface; and Q_M is the mixing ratio at the melting level. Note that in the WINDEX equation, the lapse rate, Γ, is squared, whereas the melting level height, H_M, is only raised to the first power, which is in the form of Eq. (5). The WINDEX formulation is highly empirical, like the Proctor index. Many combinations of $\Gamma^2 H_M$ were tried before settling on this combination. Also slightly different from the Proctor index is the handling of Q_L. In Proctor's formulation Q_L is the mixing ratio at 1 km AGL, whereas in the WINDEX it is the mean mixing ratio in the lowest 1 km AGL. It was felt that a bulk handling of low-level mixing ratio is more representative of low-level conditions than a single-level observation at 1 km AGL.

The radicand in the WINDEX equation is multiplied by five to estimate the maximum potential wind gust at the surface in knots. The soundings used to "calibrate" the WINDEX were those in Proctor's (1989) paper where there was good knowledge of the probable maximum wind gust (see Table 2).

A couple of notes about the WINDEX equation are in order. When the lapse rate is low—that is, the lapse rate squared is less than thirty—the radicand may become less than zero. When this happens, WI is set to zero. Thirty is about 5.5^2, and if the lapse rate is lower than $5.5°\text{C km}^{-1}$, microburst probabilities are nil (Srivastava 1985). This is a similar "cutoff" lapse rate used in Proctor's index.

The term R_Q is an empirical attempt to account for an overestimation of the basic WINDEX in dry

TABLE 2. WINDEX calculations for known microburst environments.

Location	Date	H_M	Q_M	Q_L	Γ	WINDEX	Obsvd gust	Source
				Wet microbursts				
Dallas, TX	2 Aug 1985	4850	1.8	13.8	7.79	70	70	Proctor (1989)
southern FL	1 Jul 1975	4575	4.9	15.9	6.99	53	60 (est)	Caracena and Maier (1987)
northern AL	20 Jul 1986	4700	3.8	15.8	7.17	59	60 (est)	Wakimoto and Bringi (1988)
northern AL	13 Jul 1986	4700	3.4	17.2	6.81	56	56	Wakimoto and Bringi (1988)
San Antonio, TX	7 Sep 1987	4530	2.9	15.6	7.24	63	>59	Ladd (1989)
San Antonio, TX	2 Sep 1982	4690	1.7	13.0	7.70	68	53	Ladd (1989)
Norman, OK	26 Aug 1987	4600	2.4	14.7	6.74	54	55	Stewart (1991)
Tampa, FL	19 Jul 1988	4337	6.0	17.0	7.38	56	52	Stewart (1991)
Vero Beach, FL	4 Jun 1990	4490	4.2	18.0	7.42	61	50	Stewart (1991)
near Denver, CO	30 Jun 1982	3330	4.3	9.7	8.47	54	56	Proctor (1989)
				Dry microbursts				
Amarillo, TX	21 May 1986	3300	1.9	4.3	9.69	44	47	Sohl (1987)
near Denver, CO	14 Jul 1982	3310	3.6	5.0	9.34	44	55	Proctor (1989)
near Denver, CO	8 Jul 1982	2890	3.9	5.0	9.67	43	36	Fujita (1985)
near Denver, CO	5 Aug 1982	3410	5.6	9.6	8.92	57	32	Proctor (1989)
near Denver, CO	19 May 1982	3350	5.2	6.9	8.96	47	48	Wakimoto (1985)
near Denver, CO	18 Jul 1982	3300	4.2	4.4	9.85	44	57	Wakimoto (1985)
Denver, CO	7 Aug 1975	3300	6.0	6.5	8.63	42	40	Wakimoto (1985)
Tucson, AZ	4 Jun 1977	3700	2.9	5.5	8.92	46	49	Wakimoto (1985)

Here, H_M is height of melting level; Q_M is mixing ratio at melting level; Q_L is low level mixing ratio; Γ is lapse rate between surface and melting level.

environments. The dynamics of precipitation-driven downdrafts demonstrate that the steeper the sounding lapse rate, the stronger the downdraft because air parcels are more negatively buoyant. But what happens when there is no more precipitation to evaporate? Downdraft parcels begin descending dry adiabatically, and the process described by Eq. (5) no longer is valid. The buoyancy forcing and the resulting downdraft and outflow intensity are therefore reduced. Wakimoto (1985) has an excellent discussion of this process. In a dry microburst environment there is limited moisture available to become precipitation. The R_Q term assumes that when the low-level mixing ratio is less than 12 g kg^{-1}, there is insufficient moisture available to produce a high precipitation rate storm, and the lower the mixing ratio, the more likely precipitation will evaporate before reaching the ground. This threshold number was chosen by comparing dry microburst environments found in Wakimoto (1985) and wet microburst environments found in Atkins and Wakimoto (1991). In dry cases the low-level mixing ratios are about 4–10 g kg^{-1}, and in wet cases the low-level mixing ratios are about 14–18 g kg^{-1}. Ellrod (1989) observed that the 2 August 1985 microburst sounding had characteristics of both wet and dry microburst soundings. The low-level mixing ratio was estimated to be about 12–14 g kg^{-1}, and the microburst was a wet microburst. Therefore, the R_Q reduction term threshold of 12 g kg^{-1} seems reasonable.

The addition of low-level and melting-level mixing ratios in the WINDEX equation is to account for moisture lowering the air density (raising the virtual temperature). As stated above, the WINDEX is most sensitive to the environmental lapse rate. Note that it is the virtual temperature difference between parcel and environment, not the actual temperature difference, that drives negatively buoyant parcels downward. Therefore, high mixing ratios in the low levels increase the effective environmental lapse rate. Similarly, the lack of melting-level moisture (favorable for microburst production) can also increase the virtual temperature lapse rate because the virtual temperature at the melting level is not much different than the actual temperature. Also accounted for with a low melting-level mixing ratio is the increased potential for evaporation of precipitation in a drier environment.

3. WINDEX application

a. *Sounding analysis*

To calculate a WINDEX, one needs only data from low levels and from the melting level. With these data and a calculator or a small computer, a forecaster can easily assess microburst potential for any sounding. Table 2 shows WINDEX calculations for known microburst environments. The data to calculate WINDEX values were taken from soundings given in various research papers and include the dependent dataset from Proctor (1989) used to "calibrate" the

WINDEX. Note the good correlation between the WINDEX calculations and the observed wind gusts.[2]

Figure 1 shows two different soundings on 0000 UTC 20 August 1993 at Salt Lake City, Utah (SLC), and Paducah, Kentucky (PAH), with identical WINDEX values of 57. Figure 1a (SLC) is a characteristic inverted-V dry microburst sounding, whereas Fig. 1b (PAH) is characteristic of a wet microburst environment. Both these soundings represent air masses in which downbursts occurred on this day. This illustrates that the WINDEX can assess microburst potential for different kinds of sounding.

Note the large difference in the more traditional Lifted Index (LI) with the SLC LI only −1 while the PAH LI is −8. Johns and Doswell (1992) distinguish between updraft instability and downdraft instability. The WINDEX is a measure of downdraft instability, while the LI is a measure of updraft instability. These two soundings point out that the two instabilities represent different physical processes and must be measured differently.

b. *Surface-based WINDEX case studies*

If one assumes that an observation of moisture at the surface represents the moisture in the lowest 1 km AGL, then one can compute a WINDEX from surface observations to get a detailed hourly analysis of the potential for microbursts. An hourly update of surface-based WINDEX better reflects ongoing atmospheric changes and has a definite advantage over relying on conventional soundings at 12-h intervals. Figure 2a shows an analysis of the surface-based WINDEX for 2100 UTC 2 August 1985, about 2 h before the infamous Dallas, Texas (DFW), microburst. Analysis of data from the regional 0000 UTC 3 August soundings determined the height and mixing ratio of the melting level at each surface observation site. Surface temperatures were more than 100°F (38°C) over much of northeastern Texas, which made low-level lapse rates very steep. WINDEX values were more than 75 in many places with a maximum value of 77 at DFW. Contrast this analysis with a more conventional surface-based Lifted Index (LI) (Fig. 2b) using 0000 UTC 3 August 500-mb temperatures. The axis of maximum WINDEX and the axis of lowest LI do not coincide. WINDEX values are more sensitive to the lower-level temperature lapse rate, whereas the LI is more sensitive to the low-level moisture distribution. Large thunderstorms were occurring along the Texas–Louisiana border and across northeastern Texas in association with the low LI axis. As Ellrod (1989) pointed out, outflow from the latter storm complex moved into the DFW area where the WINDEX maximum was located. When the outflow spawned new convection, conditions, as revealed by the WINDEX, were favorable for the storm to produce a microburst. Other damaging microbursts occurred over southeastern Texas and south-central Louisiana after 2100 UTC in association with high WINDEX values surrounding the strong thunderstorm outflow over central Louisiana.

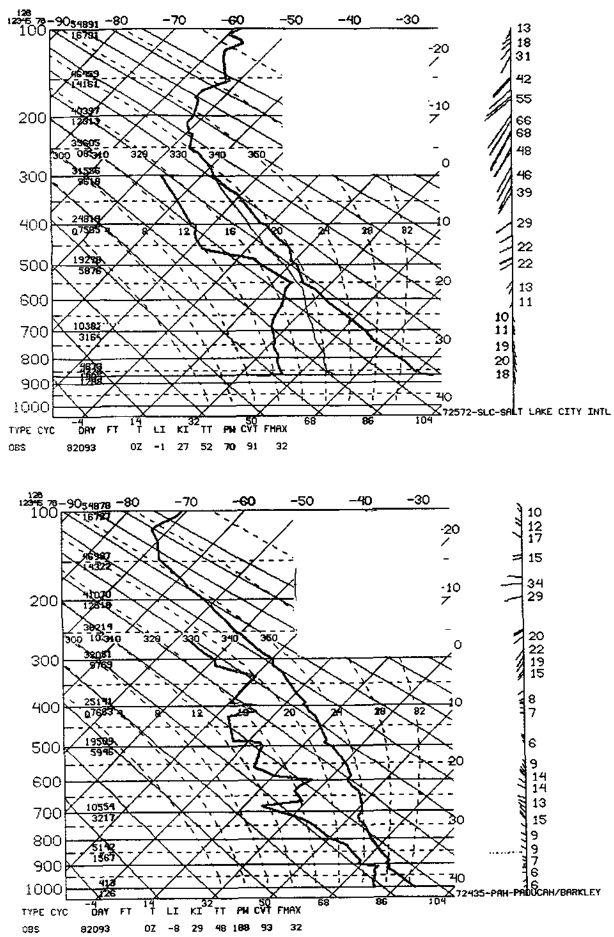


FIG. 1. Skew T–log$p$ diagrams of soundings at 0000 UTC 20 Aug 1993 at a) Salt Lake City, Utah (SLC), and b) Paducah, Kentucky (PAH). Wind speeds are in knots. Both soundings have identical WINDEX values of 57.

Figures 3, 4, and 5 show surface-based WINDEX values for three consecutive days in August 1993 on which damaging microbursts occurred. Surface data are from objective analyses of temperature and mixing ratio. Numerical model forecasts of the melting-level height and mixing ratio are used in these calculations of the WINDEX.

[2] In the cases when the WINDEX values are higher than the measured wind gust, the measurement may not have been at the location of the microburst's maximum strength. The cases when the WINDEX underdiagnoses the maximum microburst gust illustrate additional physical factors at work not captured by WINDEX's emphasis on buoyancy processes.

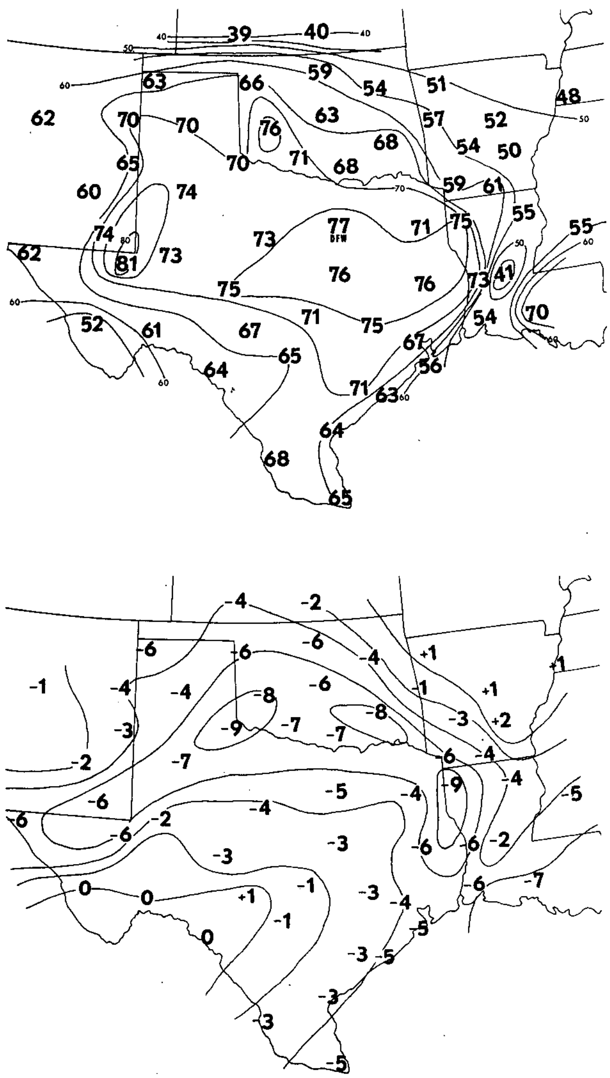


FIG. 2. a) Surface-based WINDEX analysis and b) surface-based Lifted Index values for 2100 UTC 2 AUG 1985. Dallas–Fort Worth, Texas (DFW), is labeled on the WINDEX analysis.

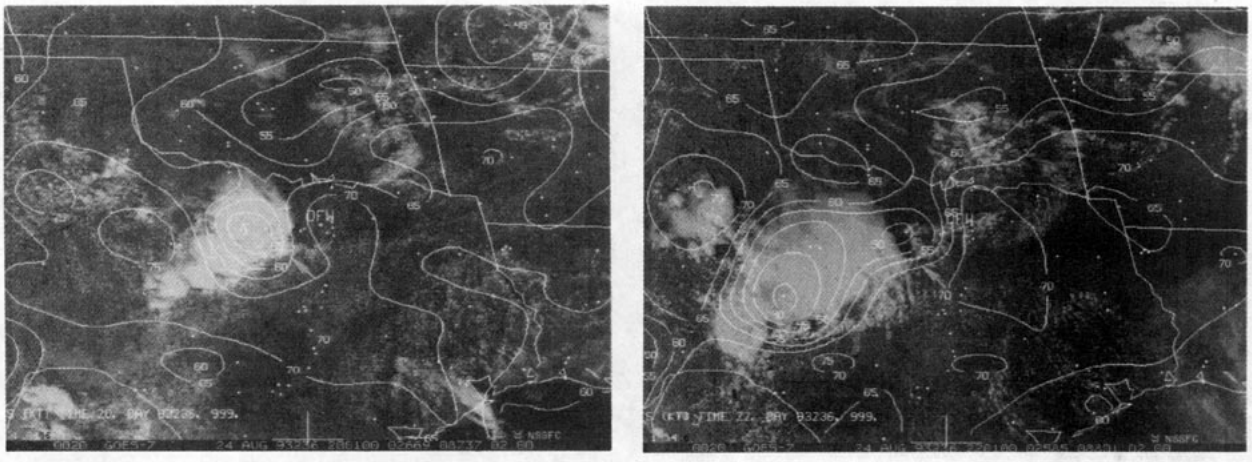
On 24 August 1993, an outflow boundary from overnight convection moved southward from Oklahoma into northern Texas during the morning. At midday new thunderstorms had formed on this boundary and had become quite extensive by 2000 UTC (Fig. 3a). About this time this convection began sending cold outflow to the east and south. The areas to the east and south were very favorable for microburst production with WINDEX values greater than 70. The new outflow boundary was moving to the east at 15 kt and to the south at 8 kt. The outflow boundary is visible on the 2200 UTC satellite image (Fig. 3b) just to the west of the Dallas–Fort Worth, Texas (DFW), area as a line of small convective cells. Note that the outflow boundary is moving directly into the WINDEX maximum. The 2300 UTC satellite image shows continued progress of the outflow boundary through the DFW area. There were reports of damaging microbursts west and north of the DFW area from 2115 UTC to 2330 UTC where the outflow boundary was moving the fastest. No severe microburst reports were received with the convection that initiated the outflow boundary or along the boundary's southwest end, which was moving much slower. Note the thunderstorms further west that developed in a high WINDEX area but for unknown reasons moved away from the maximum WINDEX. No reports of damaging microbursts were received with these storms, although much of this area is sparsely populated.

On the next day thunderstorms had already begun over central Kentucky by 1800 UTC (Fig. 4a). WINDEX values greater than 65 were located to the south and west of this activity on an axis from southwest Indiana to central and southeast Tennessee. Although it is difficult to see in the still satellite imagery at this time, an outflow boundary began moving southwestward toward the Nashville, Tennessee (BNA), area at 15 kt. By 2000 UTC (Fig. 4b), new convection formed on this boundary in the BNA vicinity. This boundary continued to move southwestward through the BNA area by 2100 UTC (Fig. 4c). Reports of 2–2.5-cm hail (very likely the initiator of the microburst) and wind damage occurred in the BNA area between 2000 UTC and 2100 UTC. Again, other convection developed over the Kentucky/Tennessee area where the WINDEX values were high, but that convection was apparently not a result of a moving outflow boundary like at Nashville, nor did the initial convection cause any apparent microbursts.

For the third consecutive day, damaging microbursts occurred near a major airport hub; this time it was Memphis, Tennessee (MEM). During the morning on 26 August there was a northward-moving line of clouds of unknown origin across northern Mississippi. Thunderstorms began firing on it by midday. By 1900 UTC (Fig. 5a) an outflow boundary began moving northwestward at 19 kt from these storms into an area with a greater than 65 WINDEX maximum. By 2100 UTC (Fig. 5b), new convection had begun on the boundary just east of the MEM area. The MEM airport observation never reported any rain but between 2100 UTC and 2200 UTC had wind gusts to 34 kt with thunder and blowing dust. During this time less than 30 km east of the Memphis airport there was a report of wind damage. Note that again in this case there were no severe microbursts with the initial convection, only the secondary convection.

c. Boundaries and microburst production

Tracking low-level boundaries is important to thunderstorm forecasting (Purdom 1982). Wilson and



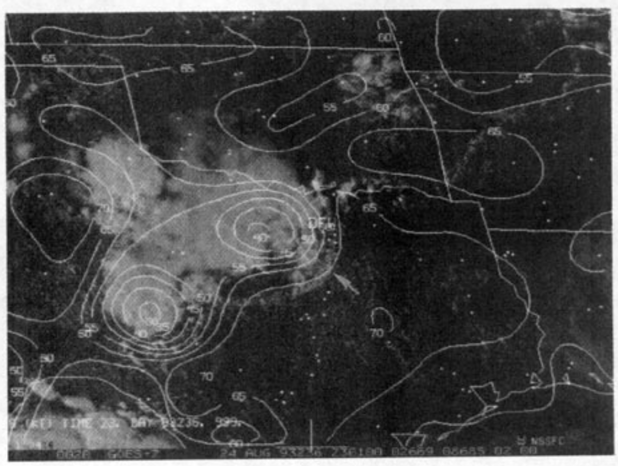
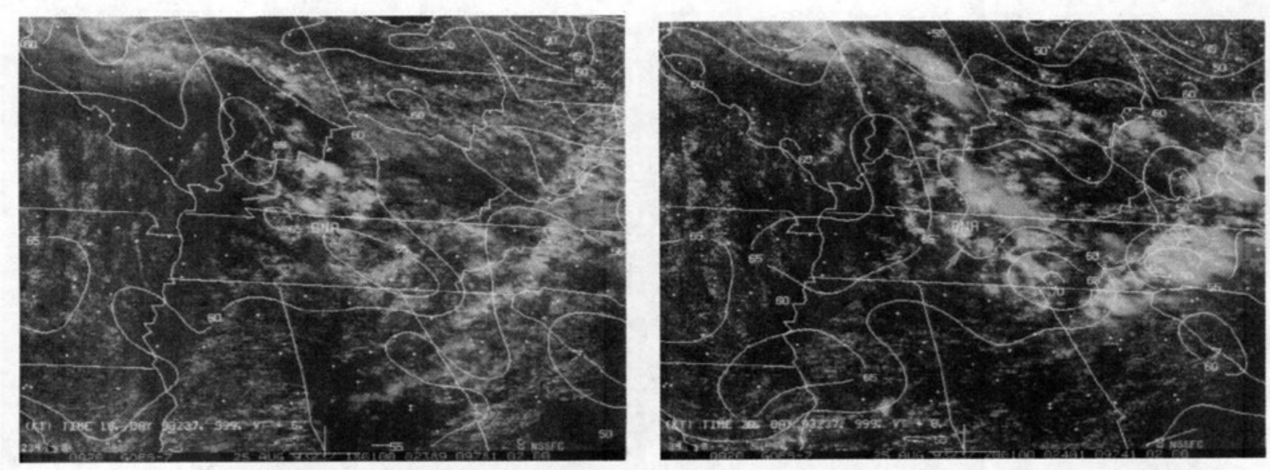


FIG. 3. Four-kilometer resolution visible satellite imagery and surface-based WINDEX for 24 Aug 1993 a) 2000 UTC, b) 2200 UTC, and c) 2300 UTC. Arrows indicate position of outflow boundary. Dallas–Fort Worth, Texas (DFW), is labeled on the image.

Schreiber (1986) showed that at least 80% of the thunderstorms in the Denver, Colorado, area formed along *radar-detected* boundaries. Ladd (1989) and Read and Elmore (1989) both stressed the significance of low-level boundaries in the vicinity of microbursts. A major finding by Rydell and Ladd (1992) was that south Texas microburst storms are secondary developments and are not usually spawned by initial convection. All of the microbursts in the previous subsection developed from storms that formed on secondary outflow boundaries.

To supplement Rydell and Ladd's findings, objective surface-based WINDEX analyses (computed identical to the three cases above) preceding 207 damaging microbursts by 30 to 120 min were examined to determine if there were patterns in the WINDEX that preceded the microbursts. These microbursts occurred over the United States south of 40°N latitude from July–September 1992. Only the southern half of the United States was examined in order to avoid contaminating the dataset with larger downbursts typically associated with dynamic systems. Each microburst report has an entry in the severe weather log at the National Severe Storms Forecast Center, which means each produced surface wind gusts of at least 50 kt (25 m s^{-1}) or had reports of surface wind damage. So only strong microbursts were included in the dataset. Many other weaker microbursts probably occurred during this time. To put this in perspective, only 6% of the microbursts reported in Table 1 had peak winds greater than 25 m s^{-1}.

The frequency distribution of the WINDEX values at the closest grid point is shown in Fig. 6a with the mean WINDEX value at 58. Grid points were spaced 1/2 degree latitude/longitude so the microburst report was always within 40 km of a grid point. More importantly, on the average, the minimum WINDEX anywhere within three grid points (120 km) was 25 lower than the gridpoint value near the microburst. See Fig. 6b for the frequency distribution of the difference between the WINDEX value nearest the microburst report and the nearby minimum. Most of the time the report did not occur with the maximum WINDEX within three grid points. Rather, the event often occurred in an already established WINDEX gradient, so the difference between nearby minimum and maximum values was typically greater than 25. The strength of these gradients is most likely due to thunderstorm outflows since frontal boundaries typi-



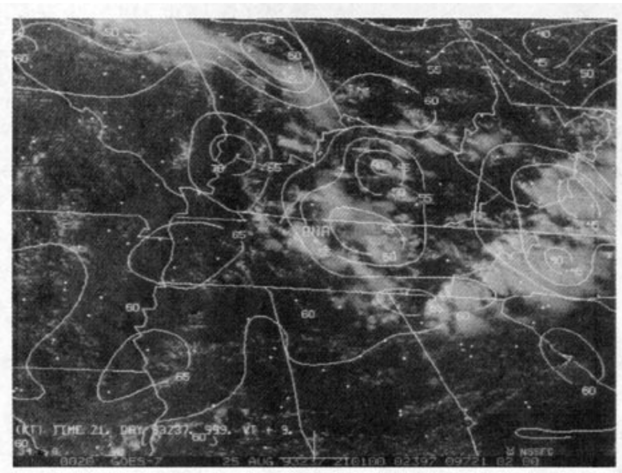


FIG. 4. Four-kilometer resolution visible satellite imagery and surface-based WINDEX for 25 Aug 1993 a) 1800 UTC, b) 2000 UTC, and c) 2100 UTC. Arrows indicate position of outflow boundary. Nashville, Tennessee (BNA), is labeled on the image.

cally do not have such sharp temperature gradients that far south during the summer. Because these gradients usually are resolved by the surface-observing network, the implication is that the cold outflow typically covered a large area.

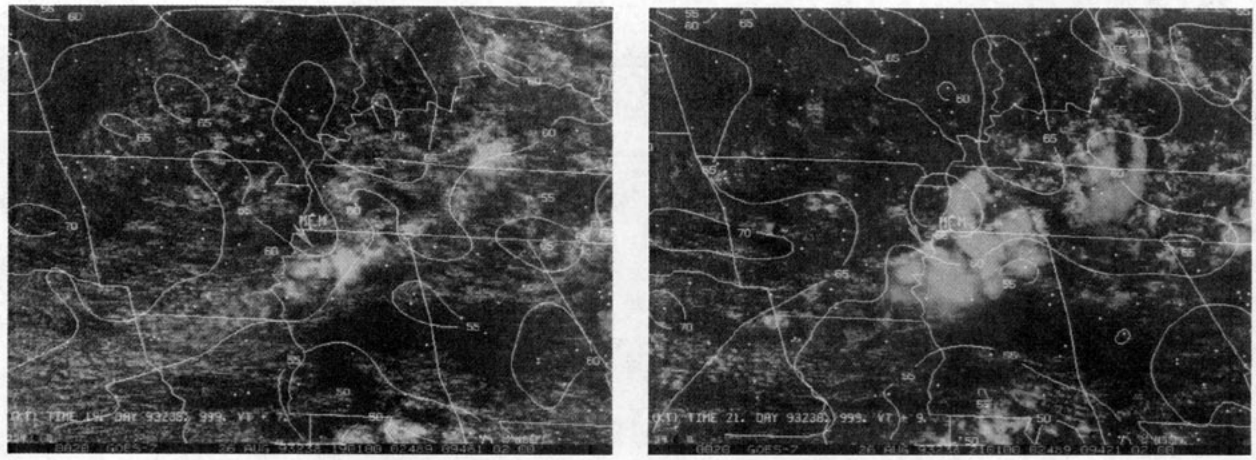
Case studies such as the ones shown above and statistics from the 207 cases in 1992 confirm the Rydell and Ladd (1992) findings that outflow boundaries play an important role in development of microburst-producing thunderstorms. A common scenario illustrated in the case studies and observed in many other cases is that if microbursts are to develop, the outflow boundary must move directly into the WINDEX maximum. Outflow boundaries moving away from WINDEX maxima or even along a WINDEX gradient do not, as a rule, produce strong microbursts.

An outflow boundary may or may not be depicted in the WINDEX analysis prior to the microburst. As shown in Fig. 6b, the vast majority of outflow boundaries are captured by objective analysis of the surface observation sites. However, three of the four case studies in the previous subsection did not show a substantial gradient in the analysis prior to the microburst. Obviously, the thunderstorm outflow was not located over synoptic surface observations. In these cases the outflow boundary, evident in the visible satellite imagery, did exist prior to the microburst, so the common scenario still fits. Viewing satellite imagery in animation makes it easier to see moving outflow boundaries.

The outflow boundary speed may also play a role. The faster-moving boundaries seem to be more conducive for microburst generation as illustrated in the 24 August 1993 case where the microbursts occurred near the fastest moving portion of the outflow boundary.

Satellite imagery is a good way to track low-level boundaries as shown in the 1993 cases presented. Advanced radars such as the WSR-88D can track boundaries in a local area with great accuracy (Klazura and Imy 1993). If a boundary is moving into an area with known microburst potential—that is, large WINDEX values—a forecaster can respond appropriately when new convection does develop on the boundary.

By using these guidelines, forecasters can assess the prospects for microbursts over the upcoming one to two hours.



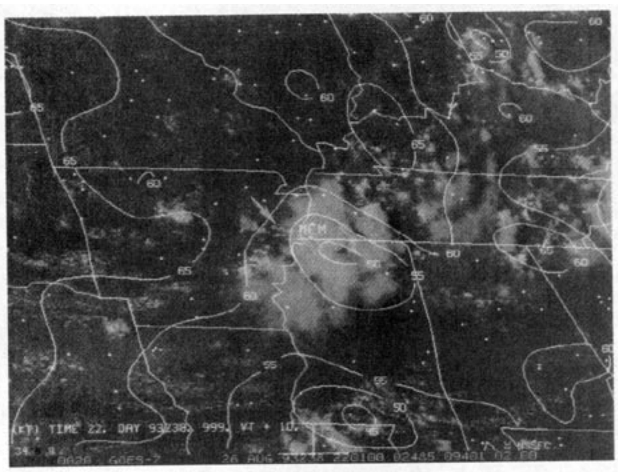


FIG. 5. Four-kilometer resolution visible satellite imagery and surface-based WINDEX for 26 Aug 1993 a) 1900 UTC, b) 2100 UTC, and c) 2200 UTC. Arrows indicate position of outflow boundary. Memphis, Tennessee (MEM), is labeled on the image.

4. Conclusions

The WINDEX is a new index that is designed specifically to help forecast microburst potential. It is physically meaningful because it is based on the studies of the dynamics of microburst production. It is better at assessing microburst potential than traditional stability indices such as the Lifted Index, which measure updraft potential.

Like other stability indices, the WINDEX is conditional on realizing the convection. Large areas of high WINDEX often exist on an analysis in which, because of no secondary outflow boundaries, no damaging microbursts develop. That does not mean that no microbursts develop; any microbursts that develop are likely to be weaker. Aviation interests have a lower microburst "threshold of pain" than public interests. While this paper has emphasized the latter concern, aviation forecasters using WINDEX probably should remain cautious and expect microbursts when any convection develops in a high WINDEX area.

The WINDEX provides a tool that can streamline the checklist proposed by Rydell and Ladd (1992). The WINDEX takes into account sounding features such as subcloud lapse rates and low-level moisture. Of course, it is necessary to modify 1200 UTC soundings for expected afternoon temperatures to get an appraisal of microburst potential during maximum heating time for the forecaster's local area. Hourly maps of surface-based WINDEX combined with diligent examination of satellite and advanced radar imagery for boundary locations and movements will help pinpoint the location of probable microburst occurrence.

Why do microbursts develop more readily with secondary convection than they do with primary convection? What role does an outflow boundary play in microburst evolution? Why do large outflows develop with some storms, which later cause microburst storms to develop, and other storms do not develop large outflows? These are some natural questions raised by this study that will be left for future research to answer.

The concepts for using the WINDEX, while developed for wet microburst situations, should apply in dry microburst situations as well. The WINDEX does take into account sounding characteristics of dry microburst environments noted by Wakimoto (1985). Hjelmfelt (1987) has documented that dry microburst

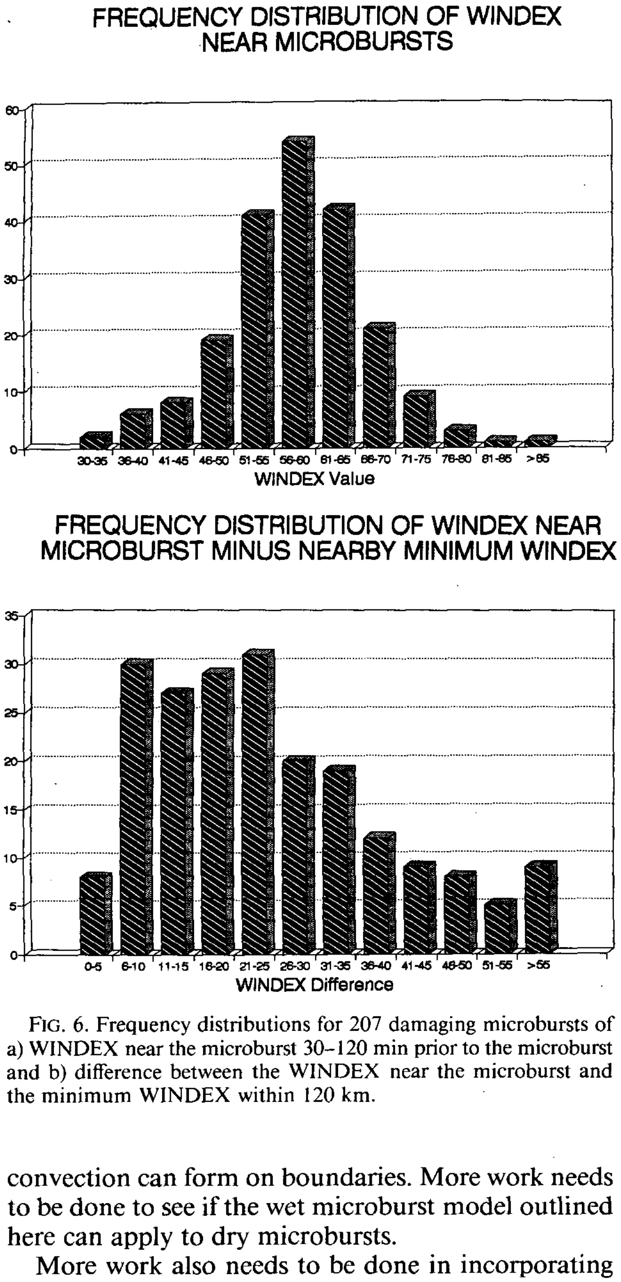


FIG. 6. Frequency distributions for 207 damaging microbursts of a) WINDEX near the microburst 30–120 min prior to the microburst and b) difference between the WINDEX near the microburst and the minimum WINDEX within 120 km.

convection can form on boundaries. More work needs to be done to see if the wet microburst model outlined here can apply to dry microbursts.

More work also needs to be done in incorporating the differential vertical pressure perturbation term into a formula that computes microburst wind gusts. This term probably was substantial in cases presented by Stewart (1992) and Smith (1993). Both these cases were associated with substantial vertical wind shear, which can cause a differential vertical pressure perturbation (Newton and Newton 1959).

The WINDEX is a useful tool that meteorologists can use to forecast microburst possibilities. By combining the WINDEX with interpretation of boundaries in satellite and radar imagery, forecasters now have useful tools to give the public and aviation a 1–2-h lead time of microburst potential on a relatively small scale.

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