Recent Improvements to the GOES Microburst Products

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ABSTRACT

The downburst is defined as a strong downdraft produced by a deep convective storm that induces strong or damaging winds on or near the earth's surface. Because of the intense wind shear they produce, downbursts are a hazard to aircraft in flight, especially during takeoff and landing phases. Retrieved profiles of temperature and moisture obtained from the Geostationary Operational Environmental Satellite (GOES) sounders have been shown to be useful in assessing the potential for convective downbursts. Sounder-derived parameters examined in this paper include the wind index (WINDEX), used to estimate maximum wind gusts; a dry microburst index (DMI), used to estimate dry microburst potential; and maximum theta-e deficit (TeD), used to estimate wet microburst potential. Currently under development is a new wet microburst index that will summarize the physical processes of convective storm development and downburst generation to quantify the potential severity of convective wind gusts. The experimental indices are plotted on regional GOES images (visible, infrared, or water vapor) and are made available on the GOES microburst products Web page.

This paper briefly reviews the development of each of the GOES microburst products, describes recent improvements, provides updated validation data and a case study, and discusses future plans. Recent improvements in the processing of sounding data to generate the microburst products include a change in the first-guess numerical model, use of single field-of-view retrievals, a filter for removing high DMI values where convection is unlikely, and a change in the calculation of nighttime WINDEX values to reduce a nighttime low bias. Improvements to the display of the microburst products include animation of many sectorized products, color coding of TeD and WINDEX ranges for data plots, plotting of numerical values of WINDEX instead of color-coded boxes, and the plotting of Storm Prediction Center (SPC) severe weather reports. Validation continues by comparing product output values to preliminary severe weather reports from the SPC as well as surface observations. Mean absolute error was <2 kt (1 m s\(^{-1}\)) for 43 daytime events during summer 2002, a significant improvement over a mean absolute error of 3 kt (1.5 m s\(^{-1}\)) for the 2001 convective season. A marked reduction in mean error for nighttime events was noted, improving from >6 kt (3 m s\(^{-1}\)) for the 2001 convective season to 4 kt (2 m s\(^{-1}\)) for summer 2002. A case study is presented that discusses the improved performance of the WINDEX during a nighttime convection event in the central plains.

1. Introduction

Convective storms can pose serious threats to life and property. Of great concern are those storms that produce downbursts, defined as strong convective downdrafts that result in damaging winds on or near the earth's surface (Fujita and Wakimoto 1983). Detailed discussions of the classification of downbursts, atmospheric conditions favorable for downbursts, and the physical processes that contribute to downburst development are featured in Atkins and Wakimoto (1991), Ellrod (1989), and Wakimoto (1985). It should be noted that many downburst events do not produce severe winds as defined by the National Weather Service (>50 kt or 26 m s\(^{-1}\)), yet are operationally significant for aviation interests. For example, a 4-yr data sample from the Cape Canaveral, Florida, mesonet revealed that 90% of peak wind speeds for 282 microbursts were between 25 and 44 kt (13–23 m s\(^{-1}\)) (Ellrod et al. 2000; Sanger 1999).

Data from Geostationary Operational Environmental Satellite (GOES) sounders have proven to be useful in the assessment of the short-term potential for convective storms in an operational forecasting environment (Zehr et al. 1988). GOES atmospheric sounders provide nearly instantaneous observations through a column in the atmosphere, with 10-km spatial resolution, and with one uniformly calibrated sensor making all of the measurements. Complete descriptions of the atmospheric sounding process are presented in Zehr et al. (1988) and Menzel et al. (1998). This paper will briefly review each of the GOES sounder-derived microburst products: a wind index (WINDEX) for estimating maximum wind gusts, a dry microburst index (DMI) for estimating dry microburst potential, and a maximum theta-e deficit (TeD) for estimating wet microburst potential. See Ellrod et
al. (2000) for a more detailed description of the microburst products. This paper will expand the discussion of the microburst products presented by Ellrod et al. (2000) by describing recent product improvements since 1999. Updated validation will be presented, as will a case study that highlights the utility of the microburst products in forecasting operations. In addition, future plans will be outlined, including further improvements of the microburst products, additional product validation, and incorporation of the microburst products into the National Weather Service (NWS) Advanced Weather Interactive Processing System (AWIPS) at NWS forecast offices. Finally, this paper will outline and discuss the development of a new wet microburst index.

2. Review of the GOES microburst products

Three GOES microburst products are currently being generated: one to determine the maximum possible convective wind gusts, and two other indices to assess conditions associated with either dry or wet microbursts. The GOES microburst products are generated hourly at the National Oceanic and Atmospheric Administration (NOAA) science center in Camp Springs, Maryland, and are available on the GOES microburst products Web page (http://www.orbit.nesdis.noaa.gov/smcd/opdb/aviation/mb.html). The program that generates the GOES microburst products ingest temperature and moisture data from the GOES-derived soundings.

a. Wind index

The wind index is defined as a parameter, developed by McCann (1994), that indicates the maximum possible convective wind gusts that could occur in thunderstorms. WINDEX is represented by the following equation:

\[ WI = 5[H_mR_o(\Gamma^2 - 30 + Q_L - 2Q_M)]^{0.5}, \]

where \( WI \) is maximum wind gusts (kt) at the surface, \( H_m \) is the height of the melting level (km) above the ground, \( \Gamma \) is the temperature lapse rate (°C km⁻¹) from the surface to the melting level, \( Q_L \) is the mixing ratio (g kg⁻¹) in the lowest 1 km above the surface, \( Q_M \) is the mixing ratio (g kg⁻¹) at the melting level, and \( R_o = Q_o/12 \) but not greater than 1. For a complete discussion of the GOES microburst products, the reader is referred to Pryor et al. (2002).

The GOES WINDEX product consists of color-coded numerical values representing expected convective wind gusts displayed at sounding retrieval locations, superimposed on to a visible (VIS) or infrared (IR) image from the GOES imager. It is important to understand that the GOES microburst products can only be calculated from sounding data obtained in clear-sky conditions or in conditions of partial cloudiness. The GOES sounder distinguishes clear versus cloudy fields of view (FOVs) by intercomparing brightness temperatures in adjacent bands and comparing the window band to surface observations (Menzel et al. 1998). The determination of cloudy pixels is accomplished by comparisons of the 11-μm channel temperatures with an objective analysis of the surface skin temperatures, obtained from surface observations (Ellrod 1989). If the warmest 11-μm value in a sample is more than 10°C colder than the surface temperature at that location, the sample is assumed to be cloudy and is rejected. The process of producing sounding profiles, referred to as retrievals, consists of algorithms to produce profiles of temperature and moisture from satellite-measured radiances at different levels in the atmosphere (Zehr et al. 1988; Menzel et al. 1998). The presence of overcast cloud cover in the GOES sounder field of view precludes the production of a complete retrieval of temperature and moisture profiles. The WINDEX program is dependent upon complete sounding retrievals to compute the temperature lapse rate (\( \Gamma \)) and low-level mixing ratio (\( Q_o \)). Ellrod et al. (2000) note that there are circumstances in which WINDEX values cannot be calculated from clear-sky retrievals, including the failure of the GOES sounder ingest program or the unavailability of the numerical model [Global Forecast System (GFS)] first-guess or ancillary surface data.

Figure 1a is an example of a WINDEX image. In this image of the northern plains sector, a squall line extends from eastern North Dakota to northwestern Kansas, while new thunderstorm activity is developing over the western high plains. High WINDEX values are indicated east of the squall line, with extremely high WINDEX values, in excess of 70 kt (36 m s⁻¹), apparent east of the developing convection over western South Dakota. A comparison with a previous version of a WINDEX image (Fig. 1b), displays significant improvements in the presentation. The plotting of numerical values, as opposed to colored boxes, increases the precision of the display and results in a less “cluttered” image. Also, WINDEX gradients are more apparent, and areas of excessively high WINDEX values are highlighted more effectively.

The following is an example of one general application of the improved WINDEX process in forecast operations. Due to conservation of mass, surface convergence results in vertical motion. Thus, boundaries along which convergence is concentrated, such as cold fronts, sea-breeze fronts, or outflow boundaries, are zones of lift that could serve as an initiating mechanism for deep convection. The extrapolation of low-level convergence boundaries into convectively unstable regions with high WINDEX can be useful in locating regions of deep convective development and subsequent production of damaging downbursts. Plotted numerical values have utility in producing a more precise forecast of maximum surface wind gusts.

b. Theta-e deficit

The theta-e deficit is defined as the maximum vertical difference in equivalent potential temperature (\( \theta_e \)) from
the surface to the middle troposphere (Ellrod et al. 2000). Research by Atkins and Wakimoto (1991), based on the Microburst and Severe Thunderstorm (MIST) project conducted in northern Alabama during June and July 1986, noted five very active microburst days. The afternoon soundings were determined to best represent the thermodynamic properties of the wet microburst environment. Upon analysis of afternoon soundings [1300 central daylight time (CDT)] from four of the five active microburst days, Atkins and Wakimoto found the following similarities among the sounding profiles: the vertical $\theta_e$ difference computed from the afternoon soundings was greater than or equal to 20 K and the $\theta_e$ minimum was typically located between 650 and 500 mb. Wheeler and Roeder (1996), in the first operational application of the Atkins and Wakimoto (1991) study findings, indicated a $\theta_e$ difference threshold of 30 K for the occurrence of microbursts over the Cape Canaveral and Kennedy Space Center, Florida, area. This area has 44 weather observation towers in a 30 km × 40 km area, which greatly facilitates ground truth in verifying and tuning downburst forecast products. The 30-K threshold
was based on local empirical tuning and demonstrates the importance of regionally adjusting $\theta_e$ difference thresholds based on local climatology. The Applied Meteorology Unit (AMU) and the U.S. Air Force's 45th Weather Squadron (45th WS) developed and implemented the microburst-day potential index (MDPI) in support of the U.S. space program operations at Kennedy Space Center. The MDPI is computed by dividing TeD by a critical threshold, determined to be 30 K at Kennedy Space Center. MDPI values of 1.0 or greater indicate a high likelihood of wet microbursts, assuming development of heavy precipitation (Wheeler and Roe 1996).

The $\theta_e$ minimum aloft is important in indicating the presence of a layer in the atmosphere favorable for the production of large negative buoyancy due to evaporative cooling. If a precipitation core within a thunderstorm reaches the level of minimum $\theta_e$, evaporative cooling takes place as dry air is entrained into the thunderstorm cell. The result is the generation of large negative buoyancy and the formation of a strong downdraft that becomes a downburst when reaching the surface (Atkins and Wakimoto 1991).

c. Dry microburst index

The dry microburst index is defined as

$$DMI = \Gamma + (T - T_d)_{700} - (T - T_d)_{500},$$  \hspace{1cm} (2)

where $\Gamma$ is the temperature lapse rate ($^\circ$C km$^{-1}$) from 700 to 500 mb, $T$ is the temperature ($^\circ$C), and $T_d$ is the dewpoint temperature ($^\circ$C). Dry microbursts occur frequently in regions where cloud bases are high and the subcloud environment is sufficiently dry so that little or no rainfall reaches the surface (e.g., the high plains). A deep, dry subcloud layer with a dry-adiabatic lapse rate is favorable for evaporative cooling of precipitation within a downdraft and the subsequent formation of a downburst (Wakimoto 1985). Based on previous research, dry microbursts typically occur when the DMI $> 6$ (Ellrod et al. 2000).

3. Improvements to GOES microburst products

a. First guess

The Global Forecast System (GFS) [formerly the Aviation (AVN)] model was implemented as the first guess for GOES retrievals during November 1999. Based on a National Environmental Satellite, Data, and Information Service (NESDIS) evaluation, it was found that corresponding precipitable water and stability indices were significantly improved when the GFS model was used as a first guess instead of the Eta Model. The improvement was most apparent in moist atmospheric conditions when convection was most likely. The internal NESDIS study, which compared Eta and GFS model first-guess profiles, also found that a larger root-mean-square error (rmse) for low-level temperature (e.g., 950 mb) existed in the Eta Model first guess. The reduced rmse in the GFS model first-guess temperature could be a possible factor in the superior retrieval produced by the utilization of the GFS model as a first guess. The higher temperature error in the lower layers of the atmosphere in the Eta Model might originate from the steplike representation of horizontal coordinate surfaces. Errors in the Eta Model would then translate to the sounding retrieval through the perturbation process, where the model first-guess profile is applied to the sounder-derived profile to produce a unique solution profile, known as the satellite sounding-derived retrieval. Using the GFS first-guess data in the initial retrieval processing resulted in an improvement upon the first guess in more than 46% of a limited sample of cases (Ellrod et al. 2000).

b. Animation of products

During May 2000, animations of the WINDEX and DMI products were made available for each region between 1200 and 2300 UTC each day on the GOES microburst products Web page. Animation of the TeD product was implemented in March 2002. Animation allows easier detection of changes in parameter values and gradients with time, especially when combined with color coding.

c. Single field-of-view retrievals

During October 2000, GOES sounding retrievals were changed from 3 x 3 pixel retrievals to single FOV retrievals. The main purpose of reducing the number of FOVs in retrieval processing was to increase the spatial resolution as well as to increase the available sounding coverage in regions of partial cloudiness. Since infrared satellite retrievals can only be obtained in conditions of clear skies or partial cloudiness, reducing the FOV coverage area will, in some cases, reduce the cloud fraction in a retrieval box and, therefore, increase the likelihood of a clear-sky sounding retrieval in regions of scattered cloudiness. In the 3 x 3 retrieval system, five of the nine pixels were required to be clear before a sounding retrieval could be obtained. In the analysis of many convective environments, clear skies allow for maximum incoming solar radiation and surface heating, an important precursor to convective storm initiation. The single FOV sounding increases the likelihood of obtaining the GOES sounder-derived products later in the day, as convective clouds begin to form and preclude future GOES soundings. This would lengthen the time period in which an operational forecaster could monitor atmospheric modification before cloud contamination effects impact the display of the sounder-derived parameters. The single FOV retrieval produces GOES sounder-derived parameters closer in time to a downburst event, thus increasing the “representativeness” of
the parameters for each event. Also, increased spatial resolution reduces the amount of averaging of the convective parameters (i.e., CAPE, lifted index, etc.) over the FOV, yielding an improved display of gradients, which are important in downburst prediction. In addition to the increased resolution and coverage, and an improved display of the gradients, single FOV retrievals have demonstrated a decrease in error and bias, thus increasing the sounding-derived product quality (Gray and Daniels 2001).

d. Reduction of DMI false alarms

The NWS Storm Prediction Center (SPC) has designated a CAPE value of 50 J kg$^{-1}$ as a minimum threshold in assessing the likelihood of “dry” thunderstorms (Ellrod et al. 2000). Beginning in June 2001, GOES sounding retrievals, which contain CAPE values $<50$ J kg$^{-1}$ were filtered out to make the displayed DMI correspond to where convection, and any associated downdrafts, are most likely. The calculation of CAPE by the GOES sounder is based on the most unstable parcel lifted in the lowest 300 mb of the atmosphere. Figure 2 is an example of the DMI product with stable soundings (CAPE $<50$ J kg$^{-1}$) filtered and removed from the image.

e. Correction of nighttime low bias for WINDEX

Based on 2001 convective season validation data, a low bias for WINDEX in excess of 6 kt (3 m s$^{-1}$) was revealed for nighttime downbursts. The nighttime low bias for WINDEX was believed to be attributable to the diminished boundary layer (BL) lapse rate, due to radiational cooling, that typically begins around sunset (Ellrod et al. 2000) and the subsequent development of a nocturnal surface-based temperature inversion. Due to the strong dependence of WINDEX on the square of the temperature lapse rate, the development of an inversion results in the significant decrease of WINDEX values, particularly during the evening hours. Figure 3 demonstrates the development of a nighttime temperature inversion. Beginning in December 2001, WINDEX was calculated at night (after 2300 UTC) from the top of the BL instead of at the earth’s surface in an effort to reduce a nighttime low bias. The top of the BL was determined as the level where the maximum $\theta_v$ was observed in the sounding. This change to the calculation of WINDEX for nighttime microburst events has resulted in a 30% reduction in the nighttime low bias (see section 4). The remaining low bias (70%) could be attributable to factors not explicitly accounted for in the WINDEX algorithm such as the translational speed of individual convective cells and convective systems as well as large amounts of CAPE available to “fuel” nocturnal convective systems. WINDEX estimates the maximum downdraft velocity due to negative buoyancy from a stationary storm while the maximum relative winds typically observed at the surface produced by a rapidly moving convective system are the sum of the maximum downdraft velocity and the translation of the storm. Thus, WINDEX can underestimate the magnitude of convective wind gusts produced by rapidly moving convective storms. In addition, CAPE has a major impact on the development of intense downdrafts. Since updraft strength is proportional to CAPE (Weisman and Klemp 1986), large CAPE will result in strong updrafts in a convective cell that enhance the size of raindrops by the process of accretion. The precipitation water content increases within the cell, subsequently initiating a downdraft by the process of water loading (Doswell 2001; Wakimoto 2001). See section 5 for a detailed discussion of the development and evolution of a nocturnal downburst-producing mesoscale convective system (MCS) over the central plains.

Duke and Rogash (1992), in the study of a 1991 severe squall line, identified that the downward transport of higher momentum possessed by winds in the mid-troposphere was a factor in the generation of damaging convective winds. Parcels in the elevated dry layer can
conserve horizontal speeds as they become negatively buoyant and descend to the surface. The wind direction associated with the downbursts generated by the process of downward transport of higher momentum will often indicate a contribution from the downward momentum transfer. Thus, the downward transport of higher momentum can result in observed surface wind gusts that are significantly higher than the indicated WINDEX values.

\( f. \) Display of TeD and WINDEX

Beginning in July 2001, TeD values plotted in the GOES TeD product were assigned colors based on the range in which each value is designated. An advantage of color-coding TeD values is to highlight those areas with a high risk of wet microbursts using a locally defined threshold based on empirical tuning and regional climatology.
Beginning in May 2002, color-coded numerical values were plotted on WINDEX graphics instead of color-coded boxes. As discussed in section 2, the plotting of color-coded numerical values on WINDEX images resulted in a less cluttered display as well as an increase in precision. The ability to observe how high WINDEX values relate to cumulus fields and cloud lines related to areas of instability and vertical lifting greatly increases the usability of the product. This was not always possible with the old displays. New virtual graphics files were being used, as well as a new magnification for the Florida area microburst products. New Florida area image magnification, as displayed in Fig. 4, extended the coverage area into southern Alabama, southern Georgia, and southern South Carolina.

4. WINDEX validation: 2001–02 convective season

a. Methodology

Data from WINDEX were collected for two convective seasons, 2001 and 2002, and validated against conventional surface data. In this study, the convective season was considered to comprise the months of June–September. Measured wind gusts from SPC storm reports and surface weather observations, recorded during downburst events, were compared with adjacent WINDEX values. In order to assess the predictive value of WINDEX, GOES data used in validation were obtained for retrieval times 1–3 h prior to the observed surface wind gust. Weather Surveillance Radar-1988 Doppler (WSR-88D) base reflectivity imagery was utilized for each downburst event to verify that observed wind gusts were produced by convective systems. Particular radar reflectivity signatures, such as the bow echo and the weak-echo channel (Fujita 1978; Przybylinski and Gery 1983), were effective indicators of the occurrence of downbursts. Validation statistics were computed for both the 2001 and 2002 convective seasons. WINDEX values and corresponding observed wind gusts for each convective season were further subdivided into daytime events, occurring between 1000 and 2000 local standard time (LST), and nighttime events, occurring between
2000 and 1000 LST. Statistics were then computed separately for daytime and nighttime events for each convective season. Parameters computed included mean error, defined as the difference in the mean values of WINDEX from the observed wind gusts, and correlation ($r$). In this study, mean error expressed the degree of accuracy of WINDEX in predicting the magnitude of convective wind gusts while correlation expressed the degree of a linear relationship between WINDEX values and actual measured wind gusts at a particular location for each downburst event. The degree of correlation can range between zero and one, where zero indicates no linear relationship between WINDEX and the surface convective wind gusts and one indicates a perfect linear relationship. Hypothesis tests were then conducted for daytime and nighttime events in each convective season to determine the significance of a linear relationship between WINDEX and surface wind gusts. The “null hypothesis” stated that no linear relationship exists between WINDEX values and surface convective wind gusts. The “research hypothesis” stated that some degree of correlation exists between the two variables. A one-tailed $t$ test (Gray 1983) was selected as the test statistic and tests were conducted for daytime and nighttime events in each convective season. Validation statistics as well as $t$ test results are presented in Table 1.

In addition, hypothesis tests were conducted to determine if the mean error, based on 2002 data, was significantly different from zero. Similar to the analysis of correlation data, a null hypothesis was constructed that stated that there should be no difference between the mean values of WINDEX and the observed wind gusts. In effect, the null hypothesis can imply that the mean error is equal to zero. Alternatively, a research hypothesis was constructed that stated that the mean WINDEX and mean observed wind gust velocities are different, implying that the mean error is different from zero. A one-tailed $t$ test (Gray 1983) was selected as the test statistic and tests were conducted for daytime and nighttime events during the 2002 convective season.

Table 1. Comparison of WINDEX to measured wind gusts.

<table>
<thead>
<tr>
<th></th>
<th>Daytime events ($N = 43$)</th>
<th>Nighttime events ($N = 47$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean error</td>
<td>-1.58</td>
<td>-4.59</td>
</tr>
<tr>
<td>Correlation ($r$)</td>
<td>0.42</td>
<td>0.20</td>
</tr>
<tr>
<td>$t$ value</td>
<td>2.96</td>
<td>1.40</td>
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<td>Critical value</td>
<td>1.68</td>
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<table>
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<th></th>
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<th>Nighttime events ($N = 55$)</th>
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<tr>
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<td>-6.90</td>
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<tr>
<td>Correlation ($r$)</td>
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<td>0.03</td>
</tr>
<tr>
<td>$t$ value</td>
<td>4.14</td>
<td>0.22</td>
</tr>
<tr>
<td>Critical value</td>
<td>1.67</td>
<td>1.68</td>
</tr>
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</table>

b. Analysis of statistics

As noted earlier, the most significant indicator of the improved accuracy of WINDEX was the reduction of the nighttime mean error, from $-6.9$ to $-4.6$ kt ($-3.6$ to $-2.4$ m s$^{-1}$) between the 2001 and 2002 convective seasons. However, hypothesis testing revealed, for nighttime events during the 2002 convective season, that the mean error $t$ value was greater than the critical value. Therefore, the null hypothesis could be rejected in favor of the research hypothesis, indicating that the mean error is statistically significant and different from zero. Hypothesis testing revealed, for daytime events in both the 2001 and 2002 convective seasons, that correlation $t$ values were greater than the corresponding critical values. Thus, the null hypothesis could be rejected in favor of the research hypothesis, indicating that the linear relationship between WINDEX and the surface wind gusts was statistically significant. Accordingly, the $t$ value for daytime events during the 2002 convective season was less than the corresponding critical value, favoring the null hypothesis that the mean error is statistically insignificant. In contrast, for nighttime events during the 2001 convective season, the $t$ value was less than the critical value, favoring the null hypothesis that there is no statistically significant linear relationship between WINDEX and the surface wind gusts. For nighttime events during the 2002 convective season, there was an increase in the correlation $t$ value; however, the $t$ value was still less than the critical value. This signified that the increase in correlation for nighttime downburst events was not statistically significant.

The possibility exists that the slight positive correlation for nighttime events could be an artifact of the sampling process. Also, as discussed in section 3, other factors may be mitigating the linear relationship between WINDEX and the observed surface convective wind gusts at night, including translational speed of convective systems and large amounts of CAPE available for convective storm development. The poor nighttime correlation between WINDEX and the measured wind reports, compared to the small mean error, indicates that only a very weak linear relationship exists between WINDEX values and the actual wind gusts for nocturnal events. Thus, for nighttime downburst events, a decrease in WINDEX values does not necessarily correspond to a decrease in the magnitude of the convective wind gusts. This again suggests that factors not accounted for in WINDEX influence convective wind gust magnitude. Pryor et al. (2002) discuss the role of the translational motion of convective systems in the underestimation of WINDEX. As stated in Ellrod et al. (2000), the WINDEX algorithm is designed to estimate the maximum downdraft velocity due to negative buoyancy from a stationary storm.

Other trends noted between the 2001 and 2002 convective seasons were 1) a shift from a 3-kt (1.5 m s$^{-1}$) high bias for daytime events to a 1.6-kt (0.8 m s$^{-1}$) low
prior to the observed downburst and more representative slower decline in WINDEX values during the 3-h period in the vicinity of Dodge City would have resulted in a delay of sunset. However, the presence of a cirrus shield over the eastern United States during 2002. Finally, inherent natural variability should be considered as a possible factor in the previously discussed trends in the performance of WINDEX between the 2001 and 2002 convective seasons.

5. Case study: Kansas–Oklahoma downbursts

During the evening of 26 August 2002, a derecho (Johns and Hirt 1987) tracked southeastward at a speed of approximately 40 kt (21 m s$^{-1}$) over western Kansas and Oklahoma. Widespread surface wind damage, rated F1 at times (Fujita 1971) along the derecho’s 800-km-long path, occurred during the period 0145–0500 UTC 27 August (2045 CDT 26 August–0000 CDT 27 August). The peak measured gust, 81 kt (42 m s$^{-1}$), occurred at Dodge City, Kansas, at 0305 UTC 27 August 2002 (2205 CDT 26 August). The expansive cirrus shield associated with the MCS precluded the calculation of a WINDEX value in the vicinity of Dodge City during the 1–3-h period prior to the observed downburst. Although early evening WINDEX values were not utilized in the calculation of mean error for this event, it was noted that the early evening WINDEX values in the Dodge City area were in excess of 60 kt (31 m s$^{-1}$). Since there was not a significant airmass change prior to the onset of the MCS, early evening WINDEX values (calculated from the top of the BL) could be considered representative for the time of the downburst occurrence. Also, the cirrus shield associated with the MCS would have reduced the effect of radiational cooling during the early evening hours. Since WINDEX is heavily dependent upon the temperature lapse rate, a decline in WINDEX values would typically occur during the evening due to radiational cooling, especially around the time of sunset. However, the presence of a cirrus shield over the vicinity of Dodge City would have resulted in a slower decline in WINDEX values during the 3-h period prior to the observed downburst and more representative WINDEX values during the evening hours. Other measured wind reports in the area are indicated in Table 2.

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>Location</th>
<th>Measured (kt)</th>
<th>WINDEX (kt)</th>
<th>Retrieval time (UTC)</th>
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</tbody>
</table>

Based on numerous and widespread reports of damage rated F1 on the Fujita scale (Fujita 1971) in a swath greater than 800 km in length, this system can be considered a derecho (Johns and Hirt 1987). In this case, an MCS developed over southwestern Nebraska during the afternoon of 26 August. The air mass over western Kansas and Oklahoma, into which the MCS was propagating, was convectively unstable with a lifted index (LI) as low as $-6$ while CAPE (most unstable parcel) was greater than 3000 J Kg$^{-1}$. Surface dewpoints were greater than 16°C (60°F) over southern Kansas and Oklahoma. Figure 5a exhibits the 2345 UTC 26 August 2002 WINDEX data overlying an enhanced infrared image, and displays an MCS over western Kansas with a well-developed enhanced-V signature. An enhanced-V, appearing as a V-shaped notch of cold IR temperatures in the cloud tops of a thunderstorm complex, is frequently associated with thunderstorms that produce intense convection and downbursts. In this image, the WINDEX values were well in excess of 50 kt (26 m s$^{-1}$) over southwestern Kansas and in excess of 60 kt (31 m s$^{-1}$) over the Oklahoma panhandle. The 0115 UTC 27 August 2002 WINDEX image, displayed in Fig. 5b, indicates values greater than 50 kt (26 m s$^{-1}$) over southwestern Kansas and western Oklahoma as the derecho continued to progress to the south, fed by a low-level warm and moist easterly flow. An enhanced-V signature was still apparent in Fig. 5c, the 0245 UTC WINDEX image, as the MCS approached the Oklahoma border. The 0300 UTC GOES sounding for Woodward, Oklahoma, displayed in Fig. 5d, indicated a profile favorable for (wet) downbursts: a dry-adiabatic subcloud layer extended from the surface to 850 mb, a moist layer extended from 850 to 500 mb, and a dry midlevel layer served as a cap (Atkins and Wakimoto 1991). The sounding indicated a significant amount of buoyant energy (CAPE = 2772 J Kg$^{-1}$) was available to “fuel” strong convection. The presence of a midlevel dry air layer resulted in enhanced evaporational cooling, negative buoyancy, and the development of strong down drafts. Favorable conditions for downbursts resulted in numerous reports of severe wind over southwestern Kansas and western Oklahoma between 0200 and 0500 UTC (Table 2), well after sunset (approximately 0120 UTC) in this region. It is important to emphasize that...
WINDEX estimates the maximum downdraft velocity for a stationary convective storm. WINDEX in this case may have also had utility in predicting the magnitude of the convective wind gusts produced by the convection triggered by the strong outflow of the MCS. Although not apparent in the satellite imagery of this MCS event, it is possible that strong outflow propagated away from the system, interacting with the convectively unstable region ahead of the MCS. The interaction between the storm outflow and the unstable environment ahead of the MCS could have triggered new deep convection that produced additional downburst activity.

The calculated mean error for this event was based on the data listed in Table 2. The mean error, defined as the difference between mean WINDEX and mean measured wind reports, was determined to be $-4 \text{ kt} (-2.1 \text{ m s}^{-1})$. In a similar manner to the validation statistics computed for the 2001 and 2002 convective seasons, hypothesis testing was conducted to determine if the mean error for this event was statistically significant. A one-tailed $t$ test (Gray 1983) was performed. It was determined that the mean error for this event was statistically insignificant and that there was no significant difference between WINDEX values and the observed convective wind gusts. In effect, the mean error for this event was not different than zero, suggesting that WINDEX accurately portrayed this nighttime convection event.

6. Future plans

a. New wet microburst index

A new wet microburst index is currently under development. The new index will summarize the physical processes of convective storm development and downburst generation by incorporating such parameters as CAPE and TeD to quantify the potential severity of convective wind gusts. The parameter CAPE will represent the process of updraft formation while TeD will represent downburst development.

1) BACKGROUND

Previous research (Ellrod et al. 2000; Pryor et al. 2002) has noted that the current suite of microburst products including WINDEX, DMI, and TeD are effective in assessing the maximum possible convective wind
gust magnitude (WINDEX) and the potential for wet (TeD) and dry (DMI) microbursts. However, the utility of these products in forecast operations is conditional upon the occurrence of convection. It has been found that deep convective storms that produce wet microbursts require the presence of large CAPE in the ambient atmosphere prior to convective initiation (Atkins and Wakimoto 1991). Ellrod (1990) also identified that large CAPE was a requirement in the development of downburst-producing convective storms. An early study of the utility of GOES sounder-derived parameters in the analysis of favorable preconditions for deep convection by Zehr et al. (1988) found that CAPE was easily computed from sounding data. Since convective storms derive most of their energy from CAPE, the analysis of CAPE is important in the determination of the probability of the development of deep convective storms that could generate wet microbursts. The present suite of GOES microburst products does not explicitly use CAPE in the calculation of microburst risk values (the DMI product only uses CAPE to filter regions that are too stable for microburst production). Thus, the new wet microburst index calculation will utilize the combination of TeD, already shown to be effective in the assessment of wet microburst potential, and CAPE.

2) Algorithm Development

The new wet microburst index will account for both positive and negative buoyancy in a convective storm, governed by the inviscid vertical momentum equation (Doswell 2001). It has been noted previously in this paper that the TeD product was effective in indicating the presence of a dry (low \( \theta_e \)) layer in the middle troposphere that would be favorable for the production of large negative buoyancy due to evaporative cooling. In order for the process of evaporative cooling and downburst generation to evolve, it is necessary for the precipitation core to be elevated to or above the level of minimum \( \theta_e \), where dry air entrainment is likely to occur. Since updraft strength is proportional to CAPE (Weisman and Klemp 1986), large CAPE (positive buoyancy) would result in strong updrafts that could lift the precipitation core within a convective storm to the minimum \( \theta_e \) level. As discussed earlier, CAPE also displays a major role in the formation of precipitation. The strong updrafts resulting from large CAPE will also increase the size of precipitation particles that grow by the process of accretion. This process, in turn, increases the precipitation content within the convective cell, which will then enhance the effect of precipitation loading (Doswell 2001; Wakimoto 2001). Once the process of precipitation loading has initiated a downdraft, entrainment of dry (low \( \theta_e \)) air in the midlevels of a convective storm will enhance the downdraft strength by the process of evaporative cooling. In addition to serving as an indicator of moisture stratification, TeD is also an effective indicator of the presence of potential instability in a region of interest. In effect, the new wet microburst index would be a nondimensional parameter, based on the thermodynamic structure of the ambient atmosphere that would indicate both the potential for deep convective storm development as well as the relative strength of convective wind gusts. Similar to the TeD product, the threshold for severe wet microburst occurrence utilized by the wet microburst index would be subject to local empirical tuning and adjusted regionally based on climatological “representativeness.”

The new wet microburst index will be implemented in the suite of GOES microburst products in which index values at each sounding retrieval location will be plotted on GOES imagery. The new wet microburst index product will be similar in appearance to Fig. 6, an example of GOES sounder-derived TeD values plotted over a GOES visible satellite image. In forecast operations, the new wet microburst index can be applied to deduce the possibility of severe convection, especially if utilized in conjunction with other parameters. One such parameter is the bulk Richardson number (Weisman and Klemp 1986). The bulk Richardson number represents the relationship between storm type, wind shear, and CAPE. Use of the new wet microburst index in combination with the bulk Richardson number can provide a forecaster with information pertaining to storm type (e.g., supercell, multicell) as well as the potential severity of wind gusts produced by the convective storm.

b. Improvements to existing products

Further investigation into the reduction of the nighttime low bias will be conducted. One possible approach considered is to correct for the low bias using a statistically derived nighttime bias correction. The bias correction could consist of adding the calculated mean error to nighttime WINDEX values.

Isopleths or contouring of microburst risk values is also being considered. Isopleths would enhance the display of gradients as well as emphasize regions with particularly high-risk values. As discussed earlier, the extrapolation of low-level convergence boundaries into convectively unstable regions with high microburst risk values can be useful in locating regions of deep convective development and the subsequent production of damaging downbursts.

Investigations into generating timelines of microburst risk values at a point location are under way. Identification of trends in microburst risk values is important in the forecast process, especially in regions where risk values are increasing with time. In a similar manner to isopleths, timelines would have utility in linear extrapolation, particularly in regions with high-risk values or where risk values are increasing. For example, a low-level convergence boundary moving into a region of increasing microburst risk could be identified to have
the potential to initiate deep convection that could produce damaging convective winds.

7. Summary and conclusions

Since 2001, several changes have been implemented into the display and calculation of the GOES WINDEX. These changes have resulted in an improved display of WINDEX products and an increased reliability of the WINDEX product in forecast operations, especially for nighttime convection events. The plotting of numerical WINDEX values have (a) increased the precision of the display of WINDEX results as well as resulted in a less “cluttered” image, (b) improved the display of WINDEX gradients, and (c) increased the utility of the image to monitor small-scale convection and boundaries that could result in the initiation of deep convection (i.e., outflow boundaries, sea-breeze fronts). Plotting of SPC storm reports has proven to be useful in the validation process in addition to demonstrating utility in the short-term forecasting of downburst winds by extrapolation. Most importantly, implementation of a nighttime calculation in the WINDEX program has resulted in a 30% decrease in the nighttime low bias of WINDEX, increasing the “representativeness” of WINDEX values. A case study was presented that highlighted the improved accuracy of the WINDEX product during a nocturnal MCS event in the central plains. Implementation of WINDEX and TeD [expressed as the microburst day potential index (MDPI)] into the NWS AWIPS system has been completed, effective spring 2003. In addition, improvements in the quality of satellite soundings derived from GOES-11/12 since their activation will be monitored to assess the possibility of incorporating the soundings into WINDEX generation (Pryor et al. 2002).

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REFERENCES


Fujita, T. T., 1971: Proposed characterization of tornadoes and hur-


