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1. INTRODUCTION

A favorable environment for downbursts associated with deep convective storm systems that occur over the central and eastern continental United States includes strong static instability with large amounts of convective available potential energy (CAPE) and the presence of a mid-tropospheric layer of dry (low theta-e) air. CAPE has an important role in precipitation formation due to the strong dependence of updraft strength and resultant precipitation content on positive buoyant energy. Also, mid-tropospheric dry air, laterally entrained into a convective storm cell during downdraft initiation, is instrumental in the increase of negative buoyancy due to evaporational cooling. A Geostationary Operational Environmental Satellite (GOES) sounder-derived wet microburst severity index (WMSI) (Pryor and Ellrod 2004) was developed and implemented to assess the potential magnitude of convective downbursts, incorporating CAPE as well as the vertical theta-e difference (TeD) between the surface and mid-troposphere to infer the presence of a dry air layer. However, previous research (Fujita 1985, Ellrod 1989) has identified that over the central United States, especially in the Great Plains region, an environment between that favorable for wet microbursts (Atkins and Wakimoto 1991) and dry microbursts (Wakimoto 1985) may exist during the convective season, resulting in the generation of "hybrid" type microbursts. Hybrid microbursts have been found to originate from deep convective storms that generate heavy precipitation, with sub-cloud evaporation of precipitation a significant factor in downdraft acceleration. This intermediate type environment, as described by Caracena et al. (2005), is characterized by conditions favorable for both wet and dry microbursts:

1. Significant CAPE.
2. A deep, dry adiabatic lapse rate layer below the cloud base, which is typically near the 700 mb level.
3. A dry (low theta-e) layer overlying a moist midtropospheric layer.

Accordingly, a new GOES sounder derived product is under development that is designed to indicate the potential for convective downbursts that develop in an intermediate environment between a “wet” type, associated with heavy precipitation, and a “dry” type associated with convection in which very little to no precipitation is observed at the surface. The GOES Hybrid Microburst Index (HMI) algorithm is designed to infer the presence of a convective boundary layer (CBL) by incorporating the sub-cloud temperature lapse rate (between the 670 and 850 millibar (mb) levels) as well as the dew point depression difference between the typical level of a convective cloud base (670 mb) and the middle of the sub-cloud layer (850 mb). In a typical dry microburst thermodynamic environment, Wakimoto (1985) identified a convective cloud base height near the 500 mb level. In contrast, Atkins and Wakimoto (1991) identified a typical cloud base height in a pure wet microburst environment near 850 mb. Thus, an intermediate cloud base height of 670 mb was selected for a hypothetical hybrid microburst environment. This selection agrees well with the mean level of free convection (LFC) of 670 mb computed from the inspection of twenty GOES proximity soundings corresponding to downburst events that occurred in Oklahoma between 1 June and 31 July 2005. In a free convective thermodynamic environment (i.e. no convective inhibition (CIN)), the mean

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LFC of 670 mb can be considered to represent the "upper limit" for convective cloud base heights that occur in an environment favorable for hybrid microbursts. CAPE, as well as the presence of a mid-tropospheric dry air layer, is already accounted for in the WMSI algorithm. Thus, the Hybrid Microburst Index, intended to serve as a supplemental index to the WMSI, is defined as

$$HMI = G + (T - T_d)_{850} - (T - T_d)_{670} \quad (1)$$

where G is the lapse rate in degrees Celsius (C) per kilometer from the 850 to the 670 mb level, T is temperature in degrees Celsius, and T_d is the dewpoint temperature (C). Inspection of representative proximity soundings revealed that a large HMI value results from a sub-cloud lapse rate that is nearly adiabatic, typically associated with a large lifting condensation level (LCL) and LFC, and a large difference in dew point depression between the approximate level of the convective cloud base (near 670 mb) and the sub-cloud dry air layer (near 850 mb). Figure 1 illustrates the diurnal tendency of HMI values over the High Plains. Note the gradual increase in HMI values over the Oklahoma Panhandle between 1700 and 2000 UTC (1200 and 1500 CDT) 11 September 2005. This increasing trend in HMI values is most likely associated with surface heating and the resultant deepening of the boundary layer between midday and mid-afternoon. In a thermodynamic environment favorable for hybrid microbursts, a typical sounding, as portrayed in Figure 2, will exhibit an "inverted-v" or "hourglass" profile with a large positive area (CAPE) and a well-defined mid-tropospheric dry air layer. A climatology of severe storm environmental parameters (Nair et al. 2002) has found that a deeper convective mixed layer, as represented by large LFCs and LCLs, predominates in the warm season over the southern Plains. The presence of a deep, dry sub-cloud (mixed) layer will enhance evaporational cooling and downdraft intensification as precipitation falls below the convective storm cloud base. In fact, Nair et al. (2002) have found that moderately high LFCs, which coexist with large CAPE over the Great Plains, are associated with an observed maximum in severe convective storm occurrence. Used in conjunction with the GOES WMSI product, the HMI product is intended for short-term prediction of the magnitude of convective downbursts associated with intermediate type thermodynamic environments over the Great Plains of the United States.

In addition, the thermodynamic structure of the lower and middle troposphere that results in large HMI values signifies the presence of an enhanced convective mixed layer, typically found along the dryline zone over the southern Plains. The dryline is defined as a narrow zone of extremely sharp moisture gradient that separates moist air originating over the Gulf of Mexico from dry air originating from the semi-arid high plateau regions of Mexico and the southwestern United States (Schaefer 1986). Through the dependence of CAPE on low-level moisture, a sharp gradient of WMSI risk values could serve to locate the dryline by inferring the presence of a virtual potential temperature gradient. Stull (1988) has identified that the characteristics of a deep convective mixed layer are caused by a combination of buoyant heat flux, due to strong solar heating of the surface, and wind shear. These conditions are typically found along the dryline. Also, Ziegler and Hane (1993) found the presence of a deeper, well-mixed CBL along and in close proximity to the dryline. In addition, increased vertical circulation, resulting from the sharp temperature and moisture gradients along the dryline zone, is believed to be responsible for enhanced mixing and the subsequent deepening of the CBL and hence, the sub-cloud layer. Thus, it is speculated that the presence of the dryline can establish a thermodynamic setting favorable for hybrid microburst generation by increasing the role of sub-cloud evaporational cooling in the process of downdraft acceleration.

The GOES HMI product appears similarly to the GOES Dry Microburst Index (DMI) product, with color coded boxes, representing a range of risk values, plotted over a water vapor satellite image. A sample real-time image is available via FTP(ftp://ftp.orbit.nesdis.noaa.gov/pub/smcd/opdb/wmsi/HMI.GIF).

The downburst risk associated with each range of risk values is listed in Table 1:

HMI	Box Color	Downburst risk
< 8	Red	Downbursts Unlikely
> or =8	Green	Downbursts Likely
> or =16	Yellow	Downbursts Likely
> 24	Orange	High Risk of Downbursts

Table 1. Downburst risk corresponding to HMI values.

2. METHODOLOGY AND PRELIMINARY VALIDATION

Data from the GOES HMI and WMSI was collected over Oklahoma from 1 June to 31 August 2005 and validated against conventional surface data. The State of Oklahoma was chosen as a study region due to the wealth of surface observation data provided by the Oklahoma Mesonet (Brock et al. 1995), a thermodynamic environment typical of the southern Plains region during the warm season, and its proximity to the dryline. Atkins and Wakimoto (1991) discussed the effectiveness of using mesonet observation data in the verification of the occurrence of downbursts. Validation was conducted in the manner described by Pryor and Ellrod (2004). In addition, GOES sounding profile data, most representative of the preconvective environment, was collected for each downburst event, if available. Correlation between GOES WMSI values and observed surface wind gust velocities, associated with HMI values in each category listed in Table 1, was computed for the period. Hypothesis testing was conducted to determine the statistical significance of linear relationships between observed downburst wind gust magnitude and WMSI values for the HMI value categories presented in Table 1.

The purpose of the validation is to compare the performance of the microburst products for convective downburst events that occur in an "intermediate" thermodynamic environment characterized by a combination strong static instability and a relatively deep convective mixed layer. A statistically significant correlation of 0.55 was found between GOES WMSI values and the magnitude of convective wind gusts for 72 hybrid microburst events that occurred during the validation period. Partitioning the downburst events by HMI categories resulted in a much stronger correlation of 0.69 for downburst events (N=31) associated with an HMI value greater than 16 (considered to be a significant risk). This result highlights the importance of both sub-cloud evaporational cooling as well as static instability in the generation of convective downbursts in an environment typical of the Southern Plains region of the United States during the warm season. Compared to a correlation between WMSI values and observed wind gusts of 0.66 found over the central and eastern United States (Pryor and Ellrod 2005), this result demonstrates the more robust statistical relationship that can be derived when reducing the validation region of interest from a national scale (i.e. central and eastern U.S.) to a regional scale (i.e. Oklahoma) and conducting validation for a specific thermodynamic environment (i.e. hybrid microbursts).

3. CASE STUDIES

3.1 *12 July 2005 Microbursts*

During the afternoon of 12 July 2005, an extensive outflow boundary, generated by earlier convective storm activity over northeastern Oklahoma, moved southward across central Oklahoma. A line of enhanced cumulus, as apparent in Figure 3, indicated the presence of the boundary. In addition, GOES WMSI displayed elevated risk values along and ahead of the outflow boundary. A convective storm, triggered by the boundary, produced a severe microburst (60 knots) at Marshall, Oklahoma.

Initial convective storm activity was generated in a region of strong static instability and weak vertical wind speed shear along the Oklahoma-Kansas border, north of Tulsa. By 1900 UTC 12 July, a well-defined outflow boundary was becoming apparent as scattered convective storm activity was organizing into a multicellular cluster. Outflows from individual convective cells were merging to reinforce the boundary as the convective cluster was propagating south-southwestward into a region of elevated WMSI values over north-central Oklahoma. Evolution and propagation of the outflow boundary was effectively portrayed in Figures 3 and 4, Oklahoma WMSI imagery between 2100 UTC 12 July and 0000 UTC 13 July.

Early convective storm activity associated with the outflow boundary did not produce severe winds. However, severe microburst activity commenced at the time that the convective cluster moved into a region with moderate WMSI (52 at 2100 UTC) and elevated HMI (>8), indicative of the potential for hybrid microbursts. During the following two to three hours, as illustrated in Figure 4, the convective cluster and associated outflow boundary continued to propagate southwestward into the region of marginal static instability over western Oklahoma. Wind profiler data from Vici, Oklahoma (not shown) indicated that this region was also characterized by weak vertical wind speed shear. The first observed microburst of the event occurred at Marshall at 2200 UTC (1700 CDT) with a wind gust of 60 knots. Another strong microburst of 43 knots occurred at Hinton at 0005 UTC 13 July (1905 CDT 12 July) as the outflow boundary interacted with the dryline over west-central Oklahoma, triggering further convective storm development. The presence of the dryline could be inferred from the sharp gradient in WMSI values over west-central Oklahoma. The corresponding surface analysis (not shown) revealed a virtual potential temperature gradient over west-central and northwestern Oklahoma. Ziegler and Hane (1993), in their observational analysis of a dryline event in western Oklahoma, found a horizontal gradient of virtual potential temperature along and to the east of the dryline. Associated with the dryline was a deep CBL, indicated in Figure 5 by an HMI value of > 16 in the vicinity of Hinton. The deep CBL can also be inferred from the large surface dewpoint depression (37°F or 21°C) that evolved during the afternoon and early evening hours as displayed in Figure 5 by the Hinton meteogram. Stull (1988) noted that a large surface dewpoint depression (> 17°C) is associated with a well-developed CBL. The gustiness of surface winds served as further evidence of the existence of the convective mixed layer. The combination of marginal static instability and the presence of a deep CBL resulted in the generation of the strong microburst at Hinton. The meteogram displayed a well-defined wind speed peak and temperature drop associated with the microburst. The possible interaction of the outflow boundary and dryline resulted in further convective initiation during the time in the diurnal cycle in which thermal forcing was becoming less significant.

3.2 *11 September 2005 Beaver Microburst*

During the afternoon of 11 September 2005, intense convective storms developed along the dryline over the Oklahoma Panhandle. The presence of the dryline was indicated by a strong virtual potential temperature gradient extending from southeastern Colorado to central Oklahoma. Over the eastern panhandle and northwestern Oklahoma, the pre-convective environment was characterized by moderate static instability and the presence of a deep CBL, again resulting from strong solar heating. GOES sounding profiles at Liberal, Kansas (Figure 2) and a meteogram from Beaver, Oklahoma (Figure 5) display the evolution of the CBL between mid-morning (1400 UTC) through late afternoon (2100 UTC). Similar to the previous case, gusty surface winds were associated with the development of the turbulent mixed layer. Note the development of an "inverted-v" profile between 1400 and 2100 UTC (0900 and 1600 CDT) as well as a large surface dew point depression (34°F or 19°C) at Beaver, corresponding to a gradual increase in HMI values over the Oklahoma Panhandle. By mid-afternoon (2000 UTC), HMI values over the eastern panhandle were in excess of 16 (Figure 1) with corresponding WMSI values near 50 (Figure 6), indicating the presence of an intermediate thermodynamic environment favorable for hybrid microbursts. The wind profile from nearby Vici (not shown) displayed weak vertical wind speed shear in place over northwestern Oklahoma. Thus, the pre-storm environment over the eastern panhandle region was considered to be in a state of free convection with moderate static instability and weak vertical wind shear.

Between 2100 and 2200 UTC, as shown in Figure 6, an area of convective storms developed over the eastern Oklahoma Panhandle along the dryline, as indicated by visible satellite imagery. A severe convective wind gust of 53 knots associated with a microburst was observed at Beaver at 2255 UTC (1755 CDT). In a similar manner to the previous case, this case demonstrated the increased role of sub-cloud evaporational cooling in downdraft instability and the subsequent generation of a microburst in an environment of marginal to moderate static instability with weak dynamic forcing. As discussed earlier, the dryline zone has been identified as a region of enhanced mixing and vertical circulation. As expected during the warm season, these two cases emphasize the effects of buoyancy and stability in convective wind gust magnitude. It is also demonstrated that the presence of the dryline can establish a favorable thermodynamic structure for hybrid microburst generation.

4. CONCLUSIONS

The GOES WMSI product was developed to parameterize and approximate the cloud physical and thermodynamic properties (i.e. CAPE, TeD) associated with downbursts that occur over the eastern United States. The HMI product is thus intended to serve as a supplement to the WMSI by inferring the thermodynamic structure of the boundary layer, especially over the Great Plains. Based on previous research and the validation data presented above, the following modification to convective wind gust prediction using the GOES WMSI is proposed in Table 2. The data in Table 2 exemplifies the importance of sub-cloud evaporational cooling of precipitation in the magnitude of convective downbursts. It is apparent that convective storms that develop in an environment of marginal instability (i.e. WMSI of 10 to 50) are capable of producing severe downbursts if HMI values are large (> 16).

HMI	WMSI	Wind Gusts (kt)
<8	10 – 49	< 35
	50 - 79	35-49
	> 80	>50
> or =8	10 - 30	< 35
	30 - 49	35-49
	50 - 79	>50
	> 80	> 50
> or =16	10 - 30	35 – 49
	30 - 49	>50
	50 - 79	>65
	> 80	>65

Table 2. Convective Wind Gust Prediction Matrix

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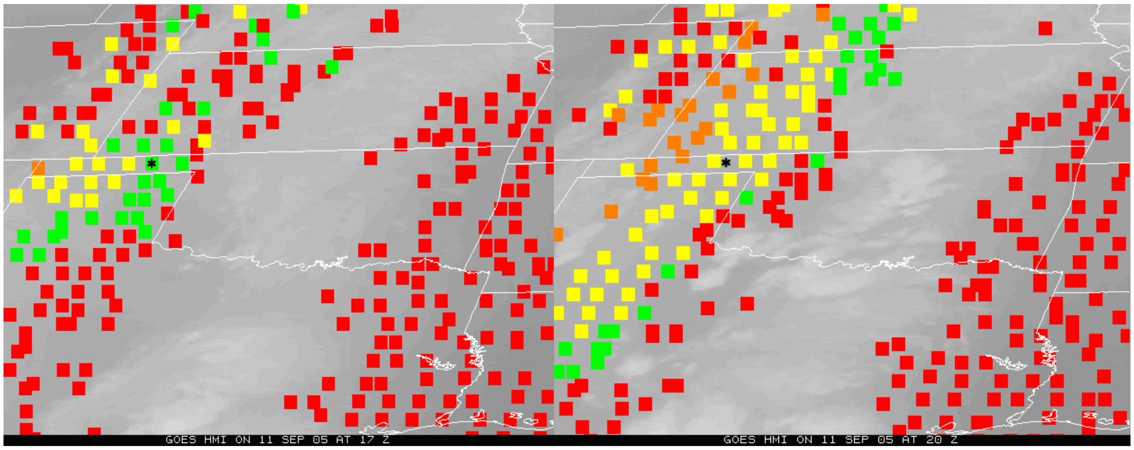

Figure 1. GOES HMI images at 1700 UTC (left) and 2000 UTC (right) 11 September 2005. Location of Beaver, Oklahoma mesonet station indicated by asterisk.

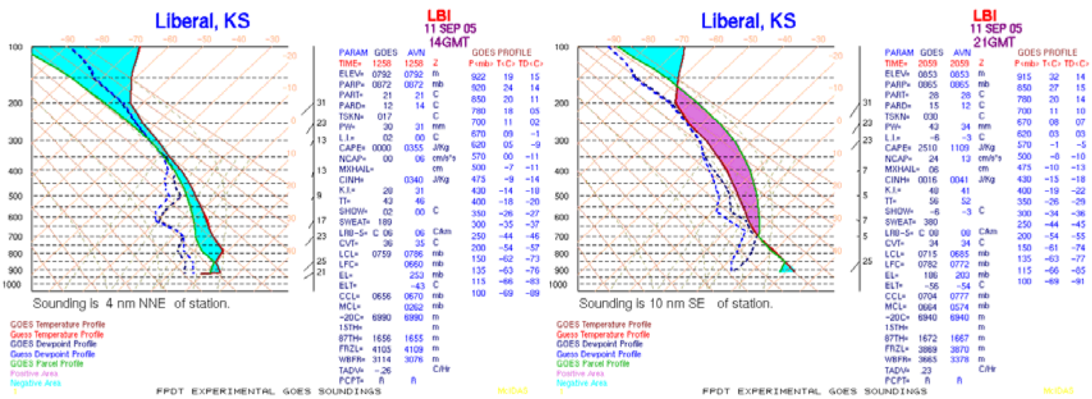

Figure 2. GOES soundings at 1400 UTC (left) and 2100 UTC (right) 11 September 2005 at Liberal, Kansas. Sounding on right displays "inverted-v" profile.

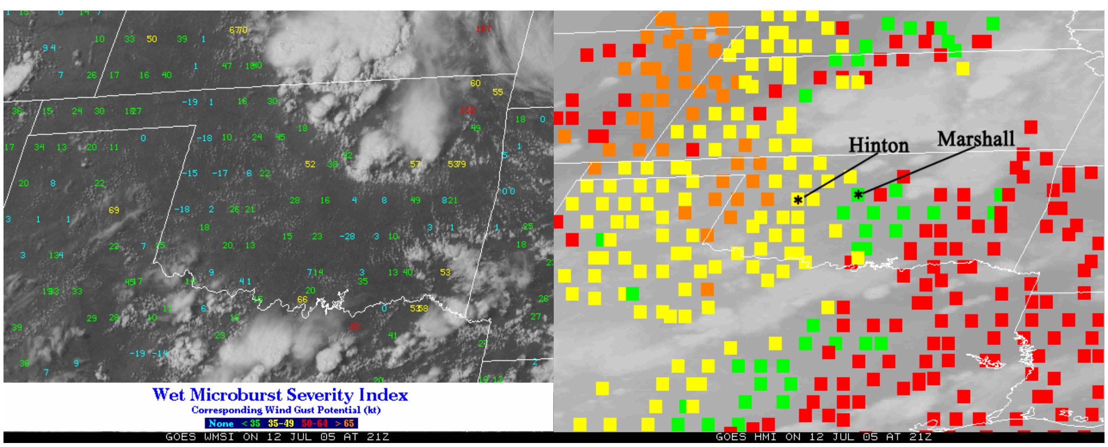

Figure 3. GOES WMSI (left) and HMI (right) images at 2100 UTC 12 July 2005.

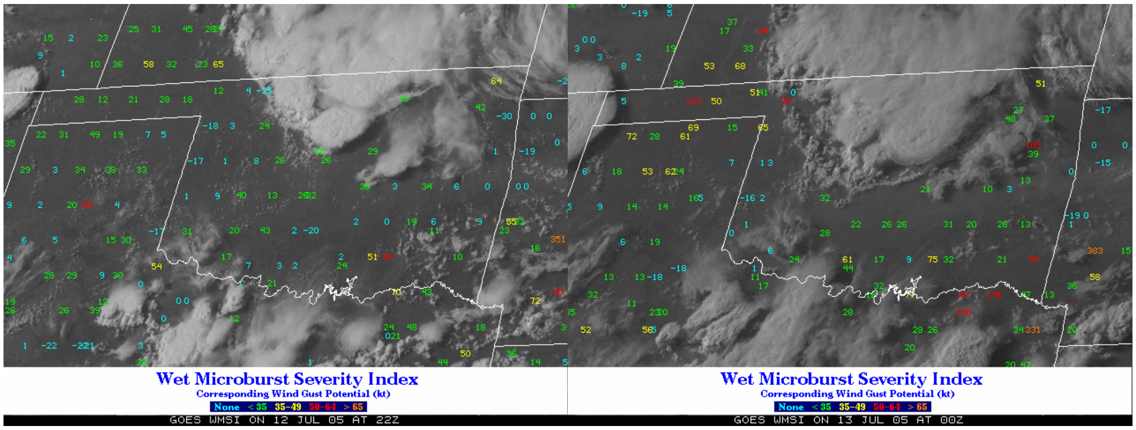

Figure 4. GOES WMSI images at 2200 UTC 12 July 2005 (left) and 0000 UTC 13 July 2005 (right).

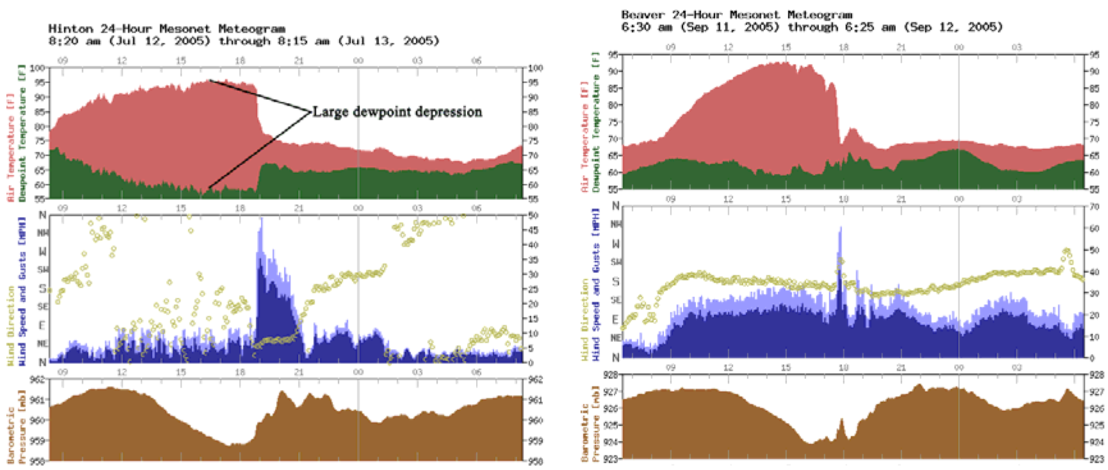

Figure 5. Meteograms from Hinton (left) and Beaver, Oklahoma (right) mesonet stations (courtesy of the Oklahoma Climatological Survey).

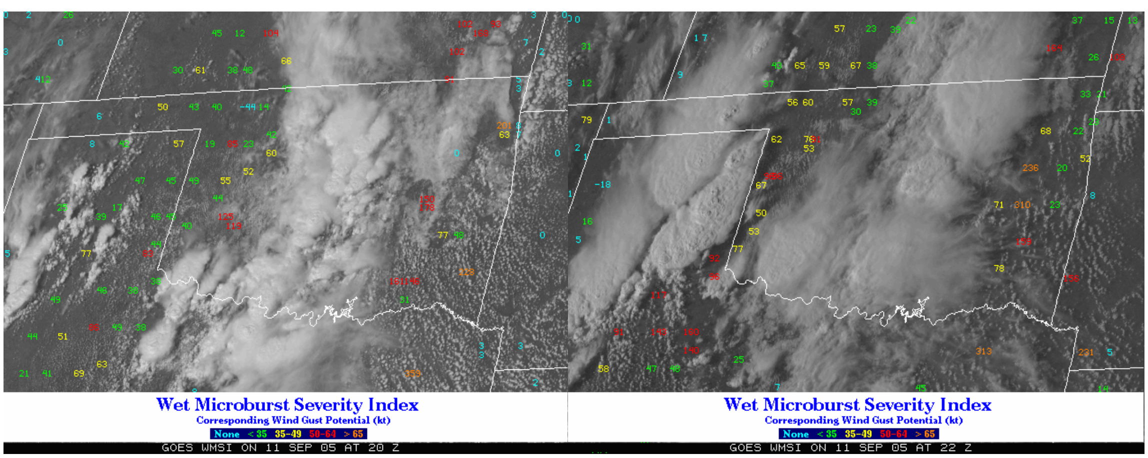

Figure 6. GOES WMSI images at 2000 UTC (left) and 2200 UTC (right) 11 September 2005.