Boundary-layer Decoupling Affects on Tornadoes

Chris Karstens

ABSTRACT

The North American low-level jet is known to have substantial impacts on the climatology of central and eastern regions of the United States. However, the development of the low-level jet may also have an impact on the low-level shear, which could rapidly alter an environment toward becoming more favorable for producing tornadoes. This study investigates this mechanism's contribution to enhancing low-level shear by analyzing the historical tornado records and through a case study analysis.

1. Introduction

To date, little research has been done to investigate the relationship between frictional decoupling of the planetary boundary layer (PBL) and storm relative helicity (SRH). Both operational and numerical studies have shown that storms developing in environments with large low level shear values have a higher probability for tornadoes (Markowski et al., 1998). Thompson and Edwards (2000) and Miller (2006) show similarity in hodograph structures from proximity soundings near significant tornadoes, with a pronounced kink in the hodograph 1.0 – 1.5 km above ground level (AGL). Meanwhile, Markowski et al. (1998) show large spatial and temporal fluctuations in SRH can exist in the near-storm environment. A common feature among these studies is the analysis of wind shear in the PBL. While there are likely several plausible mechanisms that could result in enhanced shear in this layer, an additional feature to consider is the development of the low level jet, which is likely enhances low-level shear.

From Blackadar (1957), solar heating causes the PBL to be well mixed with subgeostrophic winds, due to the vertical transport of momentum. Approximately one hour prior to sunset, the net upward flux of radiation from the ground reduces to zero. After this time, the nocturnal stable layer forms, decoupling the PBL from surface friction. The residual PBL is then allowed to accelerate toward geostrophic balance though an inertial oscillation, forming the low level jet (Walters 2001). Meanwhile the affects of friction on the nocturnal stable layer is enhanced, increasing the ageostrophic component of the wind near the surface. This results in a substantial increase in low level shear, which could rapidly alter an environment toward becoming more favorable for producing tornadoes.

This study analyzes the historical tornado records to see if a notable increase in the number of reports occurs beginning one hour prior to sunset, corresponding to the time when the decoupling boundary layer could be enhancing the low-level shear. In addition, both observed and model soundings are analyzed for evidence of frictional decoupling and it's affect on low-level shear.

2. Methodology

The two types of analyses are broken into separate subcategories, including analysis of the historical tornado records and analysis of atmospheric profiles for evidence of enhanced low-level shear due to frictional decoupling of the PBL.

2.1 Analysis of Tornado Records

The historical tornado records contain a list of specific attributes pertaining to each report. Among them include the time and date of the report, given in Central Standard Time (CST), and the touchdown location (latitude and longitude). The sunset time for each report was determined using this information. In addition, the sunset time is used to normalize the reports, with reports occurring before sunset are labeled -12 to 0 hours, and reports after sunset 0 to 12 hours.

Finally, the normalized reports are used to construct a distribution for the cumulative data set. Graphical Information System (GIS) display software is used to represent the normalized information in CWA polygons. This was done for potential operational utility, and to supplement the distributions.

2.2 Analysis of Atmospheric Profiles

The February 5, 2008 tornado outbreak is analyzed in greater detail to investigate what, if any role frictional decoupling played in enhancing low level shear.

With an outbreak of severe weather expected on Feb. 5, weather service offices within the regions of highest anticipated risk launched 18 UTC radiosondes to supplement forecast guidance. This is used along with the normal 00 UTC radiosondes to analyze how the atmosphere changed leading up to the event.

Finally, hourly soundings from the RUC and NAM models are analyzed using BUFKIT. To analyze the decoupling boundary layer, vertical profiles of temperature and dew point are addressed. To analyze low-level shear, hodographs in the lowest 3-km are used.

3. Results

The results have been broken into two subcategories, including results from analysis of tornado records and from analysis from observed and models proximity soundings.

3.1 Tornado Records

Figure 1 shows no apparent increase in the number of reports beginning one hour prior to sunset in a majority of the County Warning Areas (CWA). In fact, the opposite trend is apparent, with most CWAs showing a decrease in the number of tornado reports. This is supported by Figure 2a, which indicates that the number of tornado reports decreases as the sun is beginning to set. Additionally, the peak in reports is apparent in the three hour period prior to frictional decoupling. This suggests that the occurrence of tornadoes is more commonly associated with the late afternoon hours, when solar insolation is maximized, rather than being directly related to decoupling of the PBL, when low level shear might substantially increase.

While a majority of tornadoes appear to occur between one and five hours before sunset, Figure 2a shows a fair number of tornadoes occurring both before and after this time. Thus, there are other mechanisms in addition to peak solar heating that can possibly explain the occurrence of tornadoes. This provides some justification for looking into the frictional decoupling mechanism a bit further.

3.2 Atmospheric Profiles

To further investigate the role of decoupling of the PBL, the Super Tuesday outbreak on February 5, 2008 is analyzed in greater detail, when 131 preliminary tornadoes were reported in the south-central U.S. Figure 2b shows a majority of these reports occurred between one hour prior and four hours past sunset, a much different distribution of the reports than in figure 2a.

Synoptically, this event was characterized by a typical setup for a severe weather outbreak. A deep trough was present in the south central U. S., with diffluent southwesterly flow ahead of the trough. At the surface, a warm and humid airmass was present in the warm sector, with a strong cold front approaching from the west. The convective cells responsible for a majority of the reports initiated in the warm sector shortly before 18 UTC, and remained disjointed from the front throughout their lifetime. As indicated in figure 2b, all storms on this day did not begin producing tornadoes until 23 UTC.

While the 18 UTC hodographs in figure 3a and 3b exhibit a good amount of speed shear, there is relatively small directional shear. Based on the storm motion vector, the 0-3 km storm relative helicities (SRH) are 259 m^2s^{-2} and 272 m^2s^{-2} respectively. While this SRH value is typical of tornadic environments, it is largely the result of speed shear. The 00 UTC hodograph in figure 3c shows a substantial amount of speed and directional shear developed, while the storm motion vector veered slightly. The 0-3 km SRH also increased to 426 m^2s^{-2}. It is evident that the low level wind profiles in this region changed during this time period.

To investigate this change, the 21 UTC RUC sounding in Figure 4 is used to depict the evolution of the lowest 1km skew-T and 0-3 km hodograph for Nashville, TN. This location was chosen for a few reasons. First, Nashville is an official radiosonde launch location. This observed sounding could be used to compare the model sounding. Secondly, a supercell with a history of producing tornadoes passed directly over this location. Finally, Nashville resided in the warm sector throughout the duration of the event.

At 21 UTC, the temperature profile shows the boundary layer is dry adiabatic, or well mixed, and is supported by BUFKIT's momentum transfer algorithm. The hodograph at this time displays similarities to the hodographs in Figures 3a and 3b. Then, at 22 UTC the boundary layer is shown to be decoupled from the surface, while sunset for Nashville on this date is 2317 UTC. Winds near the surface have backed, and winds in the decoupled layer have increased.

This same pattern is evident at 23 UTC and 00 UTC. The shape of the hodograph in Figure 4d resembles the observed hodograph in Figure 3c.

Supporting evidence that the decoupling boundary layer in this case resulted in enhanced low level shear arises from a key assumption in the Blackadar (1957) analytical solution to the low level jet. The assumption is that the pressure gradient force (PGF) remains constant in time. If this is assumed, then the geostrophic wind will also remain constant. For the February 5th outbreak, a majority of the tornado reports came from storms that resided in the warm sector, where low level flow remained nearly constant in time from the south. As the boundary layer decouples, the inertial oscillation begins toward geostrophic balance, resulting in a substantial amount of veering between 0.5 to 1-km above the surface (Fig. 4). Meanwhile, the surface winds back with time, the result of enhancing the affects of friction within the newly formed nocturnal surface layer. The end result is a rapid increase in both speed and directional shear close to the ground, which appears to correspond well with the implications of Figure 4.

Interestingly, both of these hodographs are identical to the sickle shape noted by Thompson and Edwards (2000) and Miller (2006). While it is difficult to ascertain that a decoupling boundary layer will result in a sickle shaped hodograph, it appears there is supportive evidence that the low level shear, and resulting SRH, can be substantially increased.

4. Conclusions

Analysis of the historical tornado records indicate that no apparent increase in the number of reports coincides with the time when the boundary layer decouples from the surface. The opposite trend is noted, with peak solar heating appearing to play a more significant roll. While the affects from a decoupling boundary layer do not explain the occurrence of most tornadoes, there are a sufficient number of reports that occur during the time when the boundary layer decouples to warrant further investigation.

The reports from the outbreak on February 5, 2008 occur during the time when the affects of the decoupling boundary layer could be enhancing the low-level shear. Investigation of observed and model soundings, within the regions of highest risk, show supporting evidence that boundary layer decoupling can rapidly enhance low-level shear. Studies like Markowski et al. (1998) have shown that a relationship exists between environments with large low-level shear and significant tornadoes. Thus, the affects of the decoupling boundary layer may result in a higher tornado potential. This might be particularly true for storms in the warm sector, where the Blackadar (1957) analytical solution to the low-level jet is valid.

Additionally, evolution of the hodograph structure resembles the sickle-shape as noted by previous authors. While I found this interesting, there is not enough evidence to suggest this is the direct result of boundary layer decoupling.

5. References

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6. Figures

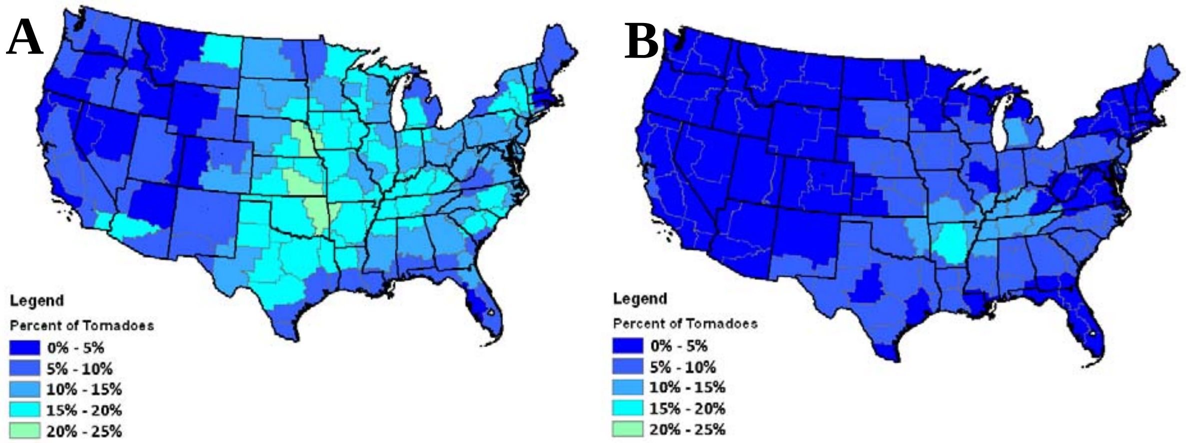

Figure 1. Percentage of all tornado reports for each CWA occurring in the A) two hours prior and B) two hours after frictional decoupling.

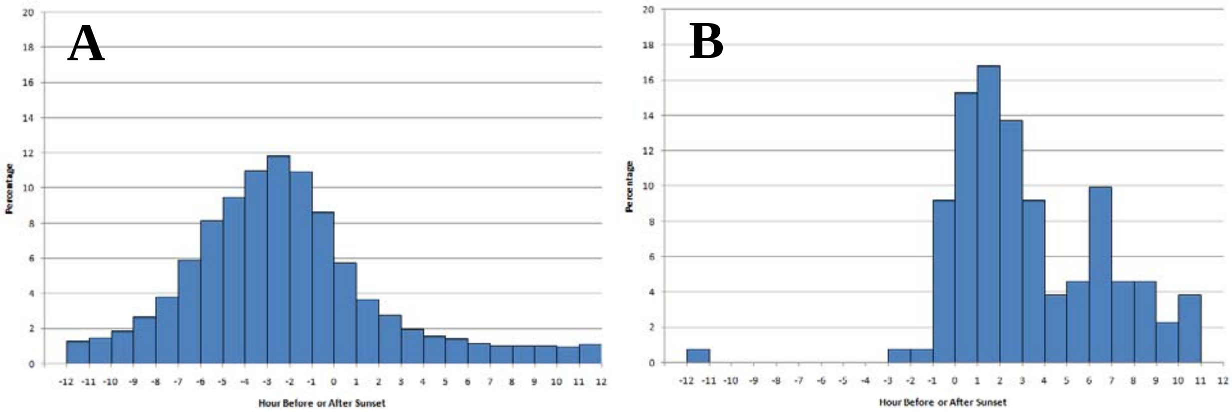

Figure 2. Normalized distribution of A) official tornado reports (1950-2006) and B) preliminary tornado reports from February 5, 2008.

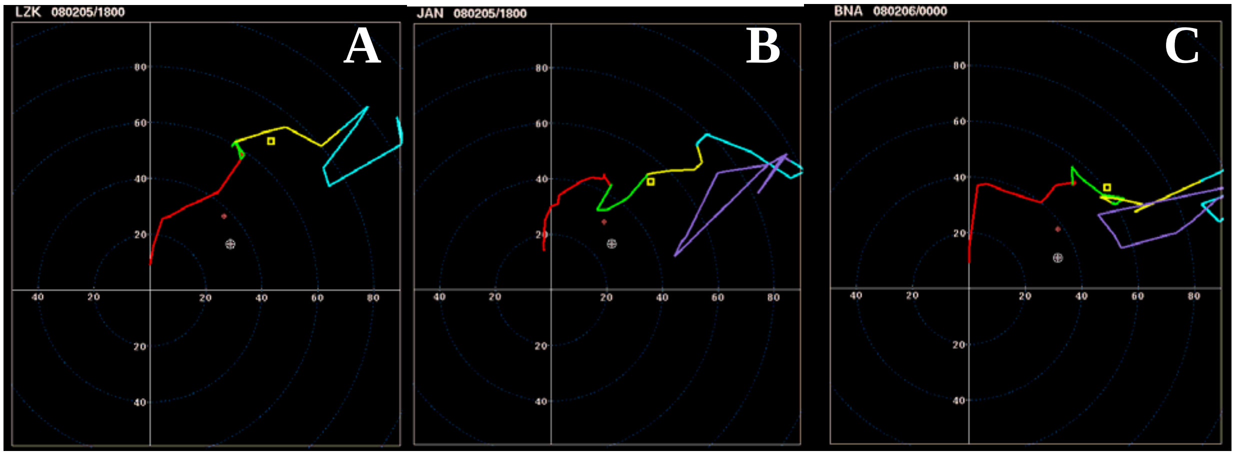

Figure 3. February 5, 2008 18 UTC observed sounding for A) Little Rock, AR and B) Jackson, MS, and C) February 6, 2008 00 UTC observed sounding for Nashville, TN.

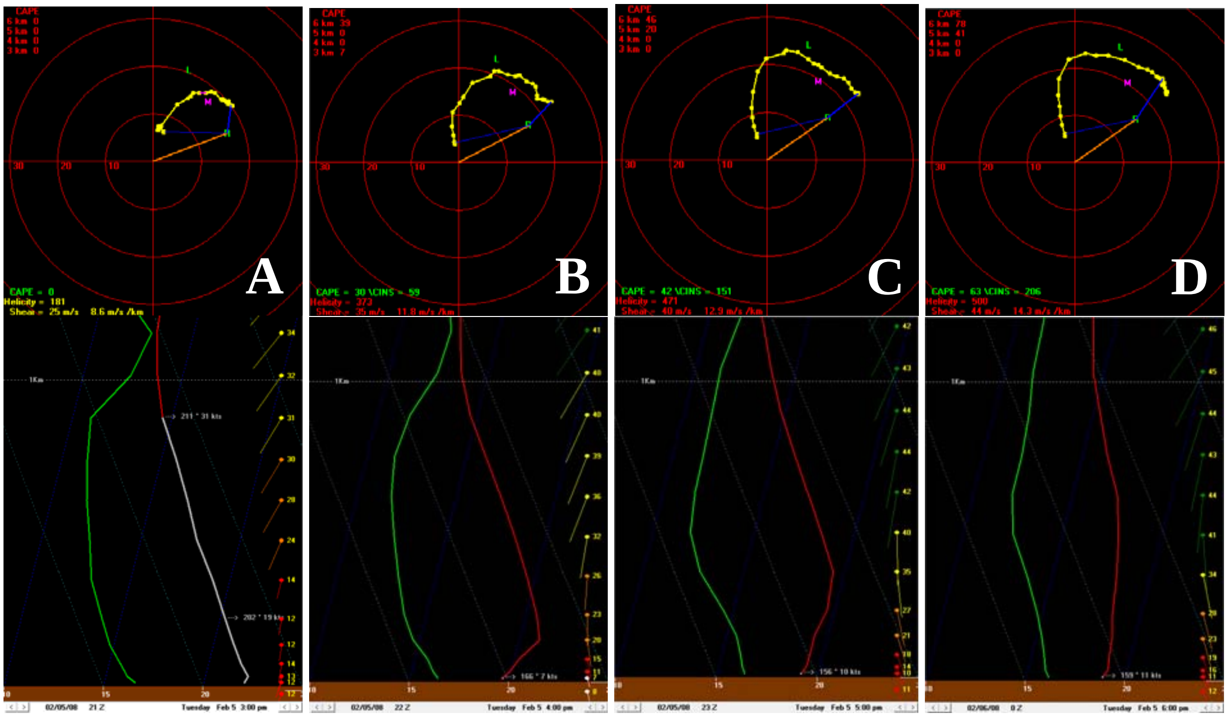

Figure 4. Feb. 5, 2008 21 UTC RUC 0-3 km hodograph and lowest 1km sounding for Nashville, TN valid A) 21z, B) 22Z, C) 23Z, and D) 00UTC.