

# ***HIGH-RESOLUTION RAWINSONDE OBSERVATIONS OF THE COLD SECTOR PRECIPITATION REGIONS IN TRANSIENT MID-LATITUDE EXTRATROPICAL CYCLONES***

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## ***Abstract***

Precipitation in the cold sector of mid-latitude, extratropical cyclones has come under scrutiny recently, especially banded rain and snow that occurs poleward, and often upstream (“wraparound precipitation”), of the surface cyclone center (usually called the “northwest quadrant”). The Profiling of Winter Storms (PLOWs) project was conducted during the winter months of early 2009, and again during the 2009-2010 winter season, to gather data on such storms. During this time, data from 138 high-resolution radiosonde flights were collected to establish, in part, the static stability conditions in which wraparound precipitation occurred. Of chief interest in this paper is the prevalence of conditions conducive to upright convection in the sampled storms. Indeed, all but one of the 17 sampled storms presented upright convection (verified by radar) in the wraparound region, so the static stability values reported herein are likely underestimates due, in part, to the unique path of each radiosonde balloon. Of the 17 storms that were sampled, 12 (71%) captured at least one sounding with elevated convective available potential energy (CAPE), while of the 138 individual soundings, only 52 (38%) had elevated CAPE. We may thus conclude that the majority of sampled cyclones revealed elevated CAPE, but it was often short-lived. Those soundings also revealed that the most unstable CAPE values appear about 3 hours prior to the onset of wraparound precipitation, but still had a median value of  $77 \text{ J kg}^{-1}$  at the time of onset.

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## 1. Introduction

The Profiling of Winter Storms (PLOWS) project was conducted during the first few months of 2009, and again during the winter of 2009-2010, with the objective of understanding better the precipitation substructures in the northwest and warm frontal quadrants of continental extratropical cyclones. Among the topics to be addressed in the course of the PLOWS study are determining the instabilities and types of mesoscale forcing (e.g., moist symmetric instability, moist frontogenesis, gravity waves, and elevated upright convection) that control the generation and evolution of precipitation substructures. To that end, the University of Missouri participated in PLOWS through its Collection and Analysis of Upper Air Sounding Data (CAUSD) subproject, using a radiosonde system to gather high-resolution vertical sounding profile data (both spatial and temporal) on the targeted extratropical cyclones. Specifically, the subject of elevated upright convection is addressed with this analysis; other instability modes are not addressed in this paper. Over the last two decades, studies have suggested a spectrum of energy scenarios for the atmosphere that harbors upright elevated convection. The results from these studies range from ample available energy for upright convection in the warm season (Rochette and Moore 1996; Moore et al. 1998), to lesser amounts in the cold season (Moore et al. 1998; Market et al. 2006), to cases where, due most likely to sampling errors, no energy was present at all (Colman 1990; Market et al. 2006). The occurrence of potential instability is common in these cases and portends layer lifting to the point where the atmosphere becomes unstable to a convective-scale disturbance in that layer (Sherwood 2000). In this brief contribution, we examine the data as they pertain to the convective-scale perturbations.

Herein, we examine the aggregate data that were collected during these radiosonde flights and what they reveal about the static stability of the atmosphere sampled in the northwest and warm frontal quadrants of continental extratropical cyclones. We pay particular attention to those parameters that indicated the likelihood of upright convection. In section 2, we examine the methods of data collection and analysis. In section 3, the data are analyzed, and in section 4, conclusions from those analyses are offered.

## 2. Data and Method

During the months of February and March 2009, and again between November 2009 and March 2010, radiosonde data were collected on multiple storm systems that traversed the central United States (Table 1). As noted

previously, the project focused on precipitation in the cold sector of mid-latitude, extratropical cyclones that occurs poleward and usually upstream (“wraparound precipitation”) of the surface cyclone center. This is the region of an extratropical cyclone (especially post-occlusion) that harbors the trough of warm air aloft, also known by the acronym *trowal* (Martin 1999); nine of the 12 PLOWS Intense Observing Periods (IOP) with robust wraparound precipitation signatures (storms denoted with asterisks in Table 1) were associated with occluded cyclones. Serial radiosonde ascents were flown from fixed locations every 2 or 3 hours to sample the target region of each cyclone. The data were quality controlled at the National Center for Atmospheric Research prior to analysis. A total of 148 of these ascents were examined for this paper, of which 10 were unused because they were lost, incomplete, or contained deep layers whose accuracy was suspect. Therefore, we had a collection of 138 ascents that were usable.

Data were collected on pressure, temperature, humidity, wind speed and direction from each radiosonde ascent and plotted on skew- $T$  log  $p$  diagrams for analysis of standard variables associated with large vertical parcel displacements (e.g., convection). Following Rochette et al. (1999), each level in the profile was evaluated by lifting the parcel representative of that level in the lowest 400 mb of the ascent in a search for the most unstable lifting parcel level (LPL). From that level, the lifting condensation level (LCL), level of free convection (LFC) and equilibrium level (EL) for the most unstable parcel were determined. The convective available potential energy (CAPE) and the convective inhibition (CIN) were also calculated for the most unstable parcel, also following Rochette et al. (1999).

For each event, many radiosonde ascents were initiated before the wraparound precipitation began/arrived at the surface launch site. We have separated ascents from each storm into groups of radiosondes flown before wraparound precipitation began/arrived, and after that time. This approach allows for a deeper understanding of the timing of stability changes in each of these storms. Yet, it is important to remember that each profile is dependent upon the path of the radiosonde balloon, some of which ascended through regions of precipitation; in convective regions, derived metrics (e.g., CAPE) may have been reduced.

## 3. Analysis

We examine convective parameters in several different ways. First, we examine the aggregate results from those soundings with CAPE, particularly elevated CAPE. We then look at the time tendency of elevated CAPE with respect to the location of the radiosonde ascent within the

IOP	Location	Date	Platform	Elevated CAPE	Wraparound Sampled
1	Joliet, IL	11 Feb 09	UMO	Yes*	Yes
2	Devalan, WI	18 Feb 09	UMO	No	Yes
3	Tomah, WI	26 Feb 09	NCAR	No	No
4	Davenport, IA	08 Mar 09	NCAR	Yes*	Yes
5	Manteno, IL	28 Mar 09	UMO	Yes*	Yes
7	Odessa, MO	16 Nov 09	UMO	Yes*	Yes
8	Ames, IA	24 Nov 09	UMO	Yes*	Yes
9	Amo, IN	02 Dec 09	UMO	Yes*	Yes
10	Clinton, IA	08 Dec 09	UMO	Yes*	Yes
13	Moulton, AL	17 Jan 10	UMO	Yes*	Yes
14	Whitewater, WI	24 Jan 10	UMO	Yes*	Yes
15	Vienna, IL	29 Jan 10	NCAR	No	No
17	Franklin, IN	05 Feb 10	NCAR	No*	Yes
18	Ft. Atkinson, WI	09 Feb 10	NCAR	No	Yes
19	Evansville, IN	15 Feb 10	NCAR	Yes*	Yes
21	Atlanta, IL	22 Feb 10	UMO	Yes*	Yes
24	Story City, IA	09 Mar 10	NCAR	Yes	No

**Table 1.** A listing of the number of the PLOWS Intense Observing Period (IOP), location (city, state), date of the collected data, observing platform (UMO=University of Missouri radiosonde system; NCAR=the National Center for Atmospheric Research Mobile radiosonde system), presence of elevated CAPE (Yes / No; asterisks denote those storm systems which had a robust wraparound signature), and whether the wraparound region of a cyclone was sampled (Yes / No).

sampled extratropical cyclone. Through these analyses, we reveal the likelihood of elevated convection and how long those episodes last.

### 3.1 Aggregate results

We focus this analysis on the identification of those storms that were prone to upright convection resulting from the release of elevated conditional instability. Such environments are simple to diagnose, and their identification sets the stage for a more robust analysis (to appear in future papers) of the processes at work in generating banded precipitation. Similar work has been done previously (Market et al. 2006) for analyzing and comparing the stability regimes in thundering and non-thundering cold sector snow events, but the data samples used there were substantially smaller.

Of the 138 radiosonde ascents in the PLOWS dataset that were usable, 81 (59%) revealed no CAPE for vertical parcel displacements. However, of the 17 storms that were sampled, 12 (71%) had at least one sounding with elevated convective available potential energy (CAPE). This distribution scatters a relatively small number of ascents over a relatively large number of cyclones. Therefore, the conditions suitable for upright convection

manifest themselves in a majority of storm systems, although those conditions may not last very long.

Indeed, 57 of the 138 usable sounding ascents revealed CAPE somewhere in the profile, including several that were based in the planetary boundary layer (PBL). Specifically, 5 of those 57 ascents with CAPE had no temperature inversion, indicating that the most unstable parcels originated from within the PBL. Therefore, the remaining 52 (38%) ascents that revealed CAPE, were harboring elevated CAPE representative of parcels above a temperature inversion and insulated from PBL processes.

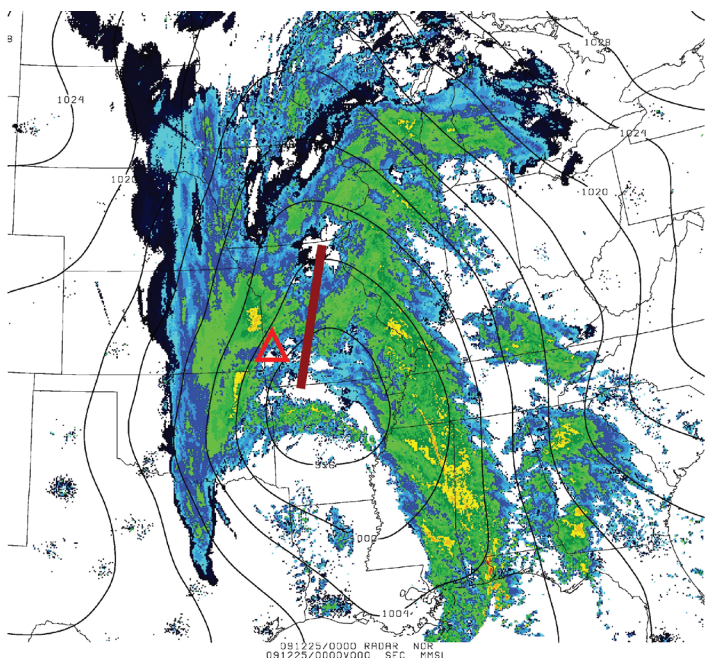
The pertinent values for the 52 ascents through layers conducive to elevated convection are summarized in Table 2. The most unstable parcel often originates, nearly saturated, around the 750-mb level (about 2250 m MSL), with an LCL a few tens of meters above that level, and an LFC a few tens of meters above the LCL. As such, convective inhibition values are often only a few J kg<sup>-1</sup>, if calculable at all. The median EL is 222 mb (about 2500 m) further above the LFC, and with a median most unstable CAPE of only 57 J kg<sup>-1</sup>, we have thus identified a layer where upright convection is likely, albeit often weak.

	Min	Max	Mean $\pm$ SD	Median
LCL (hPa)	557	930	755 $\pm$ 103	752
LFC (hPa)	551	936	752 $\pm$ 103	751
EL (hPa)	124	935	525 $\pm$ 154	530
CAPE (J kg <sup>-1</sup> )	1	1000	127 $\pm$ 176	57

**Table 2.** Descriptive statistics (N = 52) for radiosonde ascents that exhibited elevated convective available potential energy and were collected in the wraparound precipitation area northwest of transient, mid-latitude cyclone systems. Minimum, maximum, mean (and standard deviation), and median data are listed for the parcel with the most unstable lifting condensation level (LCL; expressed in hPa), level of free convection (LFC; expressed in hPa), equilibrium level (EL; expressed in hPa), and convective available potential energy (CAPE; J kg<sup>-1</sup>).

### 3.2 Time tendencies

An effort was made to distinguish those radiosonde ascents that were collected in the wraparound precipitation region of the target cyclones, as opposed to those ascents collected elsewhere over the cold sector (e.g., in warm frontal precipitation northeast of the surface cyclone). An example of this distinction is shown in Fig. 1. As shown in Table 1, 14 cyclones had their wraparound precipitation regions sampled. Of those, 12 of the target cyclones had a well-defined wraparound signature. Most

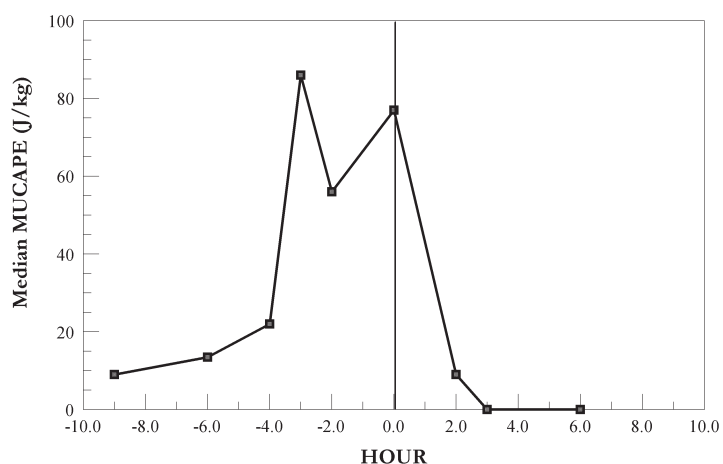


**Fig. 1.** Example analysis of a well-developed, transient, mid-latitude cyclone with a well-defined wraparound precipitation region to the left / west of the heavy dark red line, valid at 0000 UTC 25 December 2009. Red triangle depicts typical storm-relative location of PLOWS equipment. Analyses are for a storm not sampled during PLOWS / CAUSD, and are meant for illustration only. The background image is radar reflectivity, and sea level pressure contours (every 4 hPa; black, solid) are from initial fields of the Rapid Update Cycle model.

of these featured the surface cyclone center to the southeast of the radiosonde launch site. Those that did not were situated in an extratropical cyclone that had already begun to occlude. In ensuing analyses we refer to the time when wraparound precipitation begins at the launch site as  $t=0$ . Thus,  $t = -6$  hours is 6 hours *before* wraparound precipitation starts, and  $t = +6$  hours is 6 hours *after* wraparound precipitation starts.

Figure 2 is a plot of the most unstable CAPE (J kg<sup>-1</sup>) as a function of time, centered on the period of transition to wraparound precipitation. This analysis reveals a long tail of elevated CAPE leading up to the time of transition to wraparound precipitation (the solid vertical line in the middle of Fig. 2). These values escalate rapidly around 3 hours prior to the transition and remain relatively high (50-90 J kg<sup>-1</sup>) until  $t = 0$  hours (when the most unstable CAPE still had a median value of 77 J kg<sup>-1</sup>), after which time the values drop dramatically, becoming zero by  $t = +3$  hours.

This analysis reveals that, for those systems that harbor elevated CAPE, non-zero values may exist for as long as 9 hours (if not longer) before the transition to wraparound precipitation. Beginning around 3 hours prior to the transition time, CAPE values increase by a factor of four, in response to warming and moistening near the base and/or cooling and drying near the top of the conditionally unstable layer, most likely in response to the presence of the trowal air stream (Martin 1999). These data suggest that by three hours after the transition, convective overturning and/or system translation have eliminated or are in the process of eliminating the elevated CAPE in most events.



**Fig 2.** A plot of the median most unstable convective available potential energy (MUCAPE; J kg<sup>-1</sup>), based upon the most unstable parcel in a given thermodynamic profile, versus time (hours). The abscissa is broken into the period prior to the onset of wraparound precipitation (times < 0) and the period after wraparound precipitation. Median values are only shown for those times when  $\geq 5$  values were available.



## 4. Conclusions

Analyses were presented of data from 138 radiosonde ascents through 17 winter storms over the central United States from the winters of 2008-2009 and 2009-2010. Of the 138 individual ascents, only 52 (38%) possessed elevated CAPE, which might seem to suggest that the environment conducive to elevated, upright convection is not that common. However, of the 17 storms that were sampled, a majority of them (71%) had at least one radiosonde ascent with elevated convective available potential energy (CAPE). Thus, the 52 ascents that possessed elevated CAPE were distributed fairly broadly across 12 of the 17 sampled storms. We may thus conclude that the majority of sampled cyclones revealed elevated CAPE, although it may have been short-lived.

Statistical analysis of the LCL, LFC, EL, and CAPE of the most unstable parcel in each of the 52 ascents with elevated CAPE were also offered. Those values reveal a typical elevated layer in the mid-troposphere as nearly saturated, with a median base at around 750 hPa, a depth of 2-3 km, and a CAPE value of  $57 \text{ J kg}^{-1}$ , which translates into a theoretical maximum vertical velocity of  $10.6 \text{ m s}^{-1}$ . These values tend to maximize at the time of, and during the several hours prior to, the transition to wraparound precipitation north and west of the surface cyclone center.

These findings are important to the operational community, as they serve to highlight that the majority of transient, mid-latitude, extratropical cyclones possess an environment conducive to elevated upright convection. That environment is transient and often short-lived (at least from an Eulerian perspective), but it can support significant vertical motions over the cold sector of winter storms. This is a frequency much higher than many had previously thought. Moreover, given the existence of radar-verified elevated upright convection in 16 of the 17 storms, it is clear that this rawinsonde dataset alone, while important and useful, fails to account for all possible instability scenarios.

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