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A Comparison of Two Cold Fronts—Effects of the Planetary Boundary Layer on the Mesoscale

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ABSTRACT

Two cold fronts passed through central Oklahoma in late 2006, one on 29 November and the other on 7 December. Meteorograms for Norman, OK, show the two frontal passages had very different characteristics. The late November event was a textbook example, with the windshift and rapid temperature drop very close together in time. On the other hand, the early December event was unusual, showing a temperature *rise* after cold frontal passage. The reasons for this behavior in the December case are shown to be associated with the time of day and the ambient conditions in the planetary boundary layer at the time of the frontal passage. Shear-induced turbulence within the nocturnal boundary layer is likely responsible for the seemingly paradoxical initial temperature rise following passage of the cold front.

1. Introduction

Cold frontal passages through the "featureless" central plains of the United States occur every few days, in part because there are no major orographic barriers between the Gulf of Mexico and the North Pole. Seasonal changes alter the frequency of cold frontal passage (see Hutchinson and Bluestein 1998), but it might be assumed that the lack of major orography in the plains would simplify greatly the structure and evolution of fronts and how they affect the character of frontal passages. However, this is not necessarily the case.

Recently, Schultz (2004, 2005) reviewed cold fronts with and without a variety of *prefrontal* features, discussing several different mechanisms that can alter the character of the frontal passage by the presence of structures that precede the front itself. A cold front can be distinguished from any prefrontal structures by using the classical definition of a cold front (e.g., Petterssen 1956, Ch. 11) as a first-order density discontinuity (which, in turn, implies a steep gradient in temperature or potential temperature). These prefrontal structures (also discussed by Sanders and Doswell 1995) are not considered to be true fronts by the classical definition. Such features complicate how the passage of a cold front is seen at any given location, but if we consider only the "true" front, as manifested by a strong thermal gradient, and ignore the possibly complex features that can precede the intrusion of a synoptic-scale cold air mass, it might seem to the unwary that all such frontal passages through the central and southern plains should look similar.

However, even in those plains, true cold frontal passages are *not* always more or less the same. We believe that various aspects of the planetary boundary layer (PBL) in advance of a cold front can have a large impact on the character of frontal passage.

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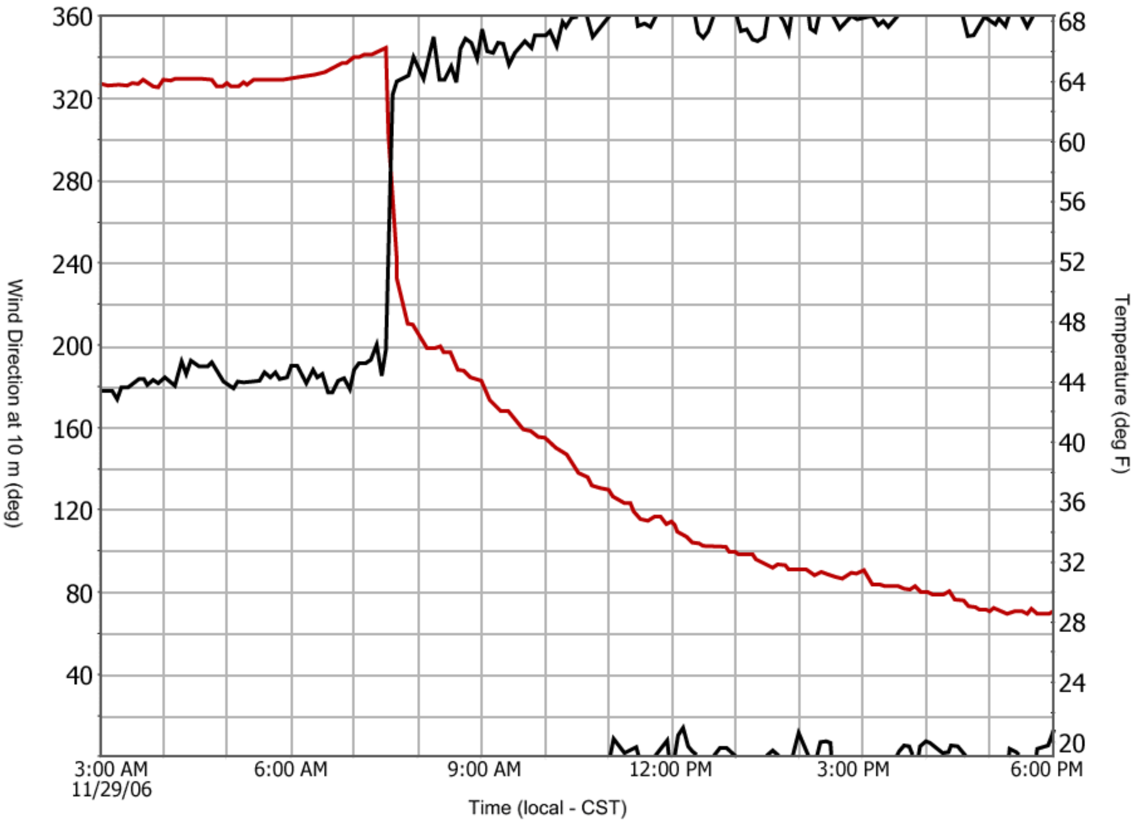


Figure 1. Meteorogram for Norman, OK, mesonet site, showing wind direction at 10 m (black) and temperature at 1.5 m (ºF, red) for the 9-h period from 03 Central Standard Time (CST, or 09 UTC) on 29 November to 18 CST (00 UTC on 30 November). Use of local time makes the time of day evident.

In this paper, we compare two very different cold frontal passages through Oklahoma in late 2006, one in late November and the other in early December. In section 2, we present the evidence that reveals the contrasting surface manifestations of the frontal passages. Section 3 then discusses these observations and offers an explanation for the very different behavior of the two fronts, in terms of the antecedent conditions within the PBL. In section 4, we conclude by considering the implications of these observations for how to use surface observations to diagnose physical processes that are of relevance to forecasting the weather, including severe weather.

2. Observations

a. The frontal passage of 29 November 2006

The first frontal passage is exemplified by the Oklahoma Mesonet (see McPherson et al. 2007) meteorogram for Norman, OK, that includes the frontal passage (Fig. 1). The days preceding the intrusion of this polar airmass were a period of persistently above-average temperatures and the front represented the first major intrusion of polar air of the late fall/early winter season. Snowfalls in central Oklahoma followed the frontal passage, so this event could be seen as marking the transition to winter in central Oklahoma.

As shown in the data, the precipitous fall in temperature following frontal passage was virtually coincident with the wind shift. Therefore, this frontal passage corresponds well to the prototypical cold frontal passage discussed in the literature. Its eventual intrusion into the southern plains was anticipated for several days, and it followed a more or less classical evolution for a plains cold frontal passage, plunging equatorward most rapidly along the relatively steeply sloped High Plains to the lee of the Rocky Mountain Front Ranges (Fig 2). The close proximity of the windshift and the temperature decrease persisted after the front passed Norman, as shown in Fig. 3. In Fig. 3, the objective analysis of the temperature has spread out the thermal gradient over a relatively wide zone, but inspection of several stations reveals that the close coincidence of the abrupt temperature decrease with the wind shift was typical throughout the passage of the front through Oklahoma.

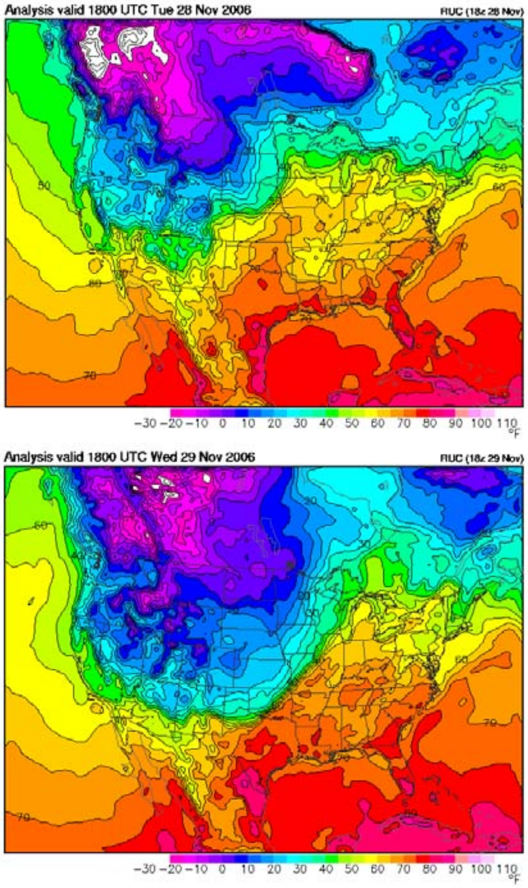


Figure 2. Rapid Update Cycle (RUC) model initial temperature (ºF) analyses at 1800 UTC on (top) 28 November and (bottom) 29 November.

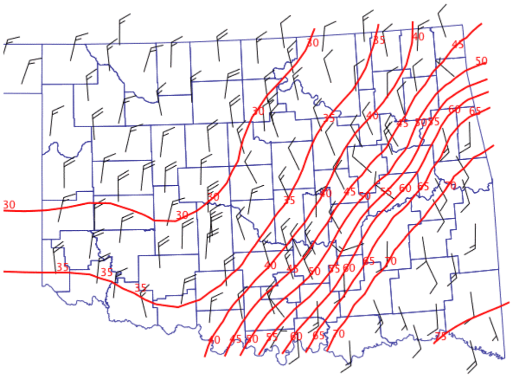


Figure 3. Oklahoma Mesonet wind (wind barbs are conventional, in knots) and temperature [ºF, red contours at 5°F (2.8 ºC) intervals] data for 14 CST (20 UTC) on 30 November 2006.

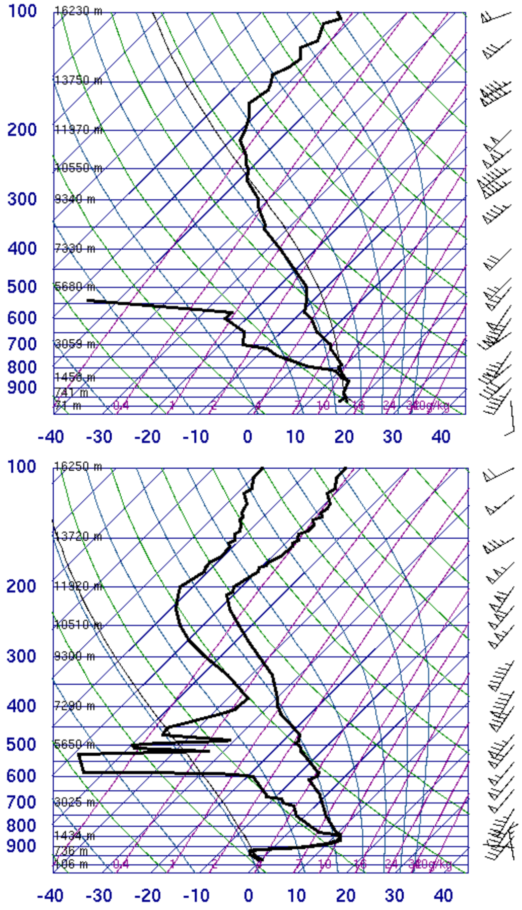
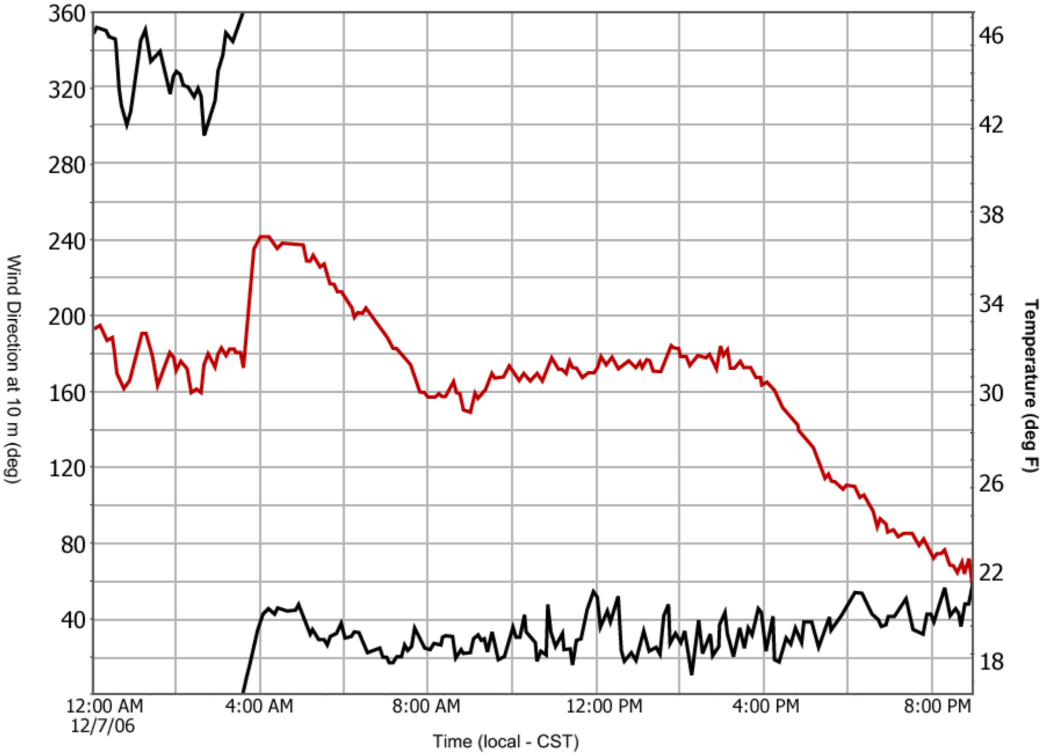


Figure 4. Skew-*T*, log *p* plots of temperature and dewpoint soundings for Norman, OK at (top) 12 UTC and (bottom) 21 UTC on 29 November 2006. Wind barbs are conventional. A moist adiabat associated with the surface parcel is indicated on both soundings.

Despite the front passing through Norman in the morning (cf Fig. 1), the 12 UTC sounding at Norman (Fig. 4, top), taken prior to frontal passage, exhibits no particularly strong surface-based stable layer and has surface-based convective available potential energy (CAPE) of nearly 1000 J kg^{-1}, with an equilibrium level (EL) at about 260 hPa. A special sounding at 21 UTC (Fig. 4, bottom), taken after frontal passage, reveals the shallow nature of the post-frontal cold air and the intensity of the frontal inversion. This event was characterized by a few thunderstorms in the wintry post-frontal precipitation. The airmass above the shallow cold airmass was moist and unstable enough to support thunderstorms—a parcel lifted from 850 hPa has CAPE of more than 500 J kg^{-1} with an EL higher than 350 hPa—whereas there clearly is no surface-based CAPE at all.



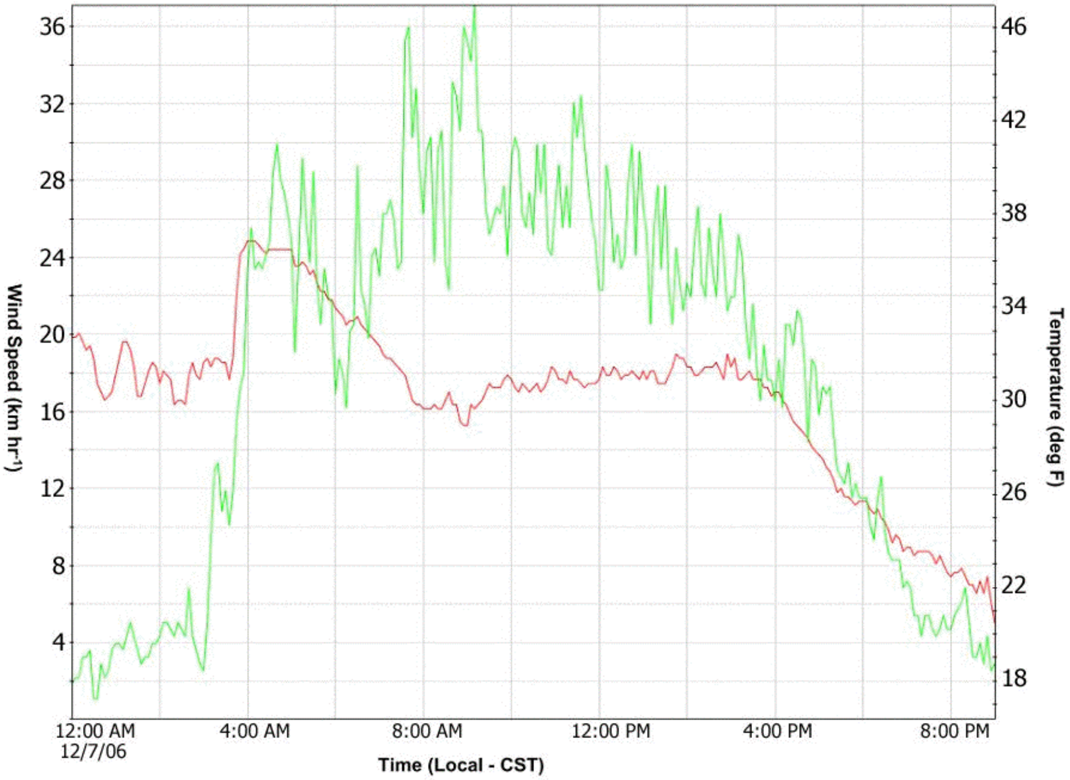


Figure 5. Top: Meteorogram from the Norman Mesonet site (as in Fig. 1), for the period from 00 CST (06 UTC) on 7 December 2006, to 21 CST (03 UTC on 8 December). Bottom: As with Fig. 5 (top), except showing windspeed (green, in km hr^{-1}) and temperature (red, in °F).

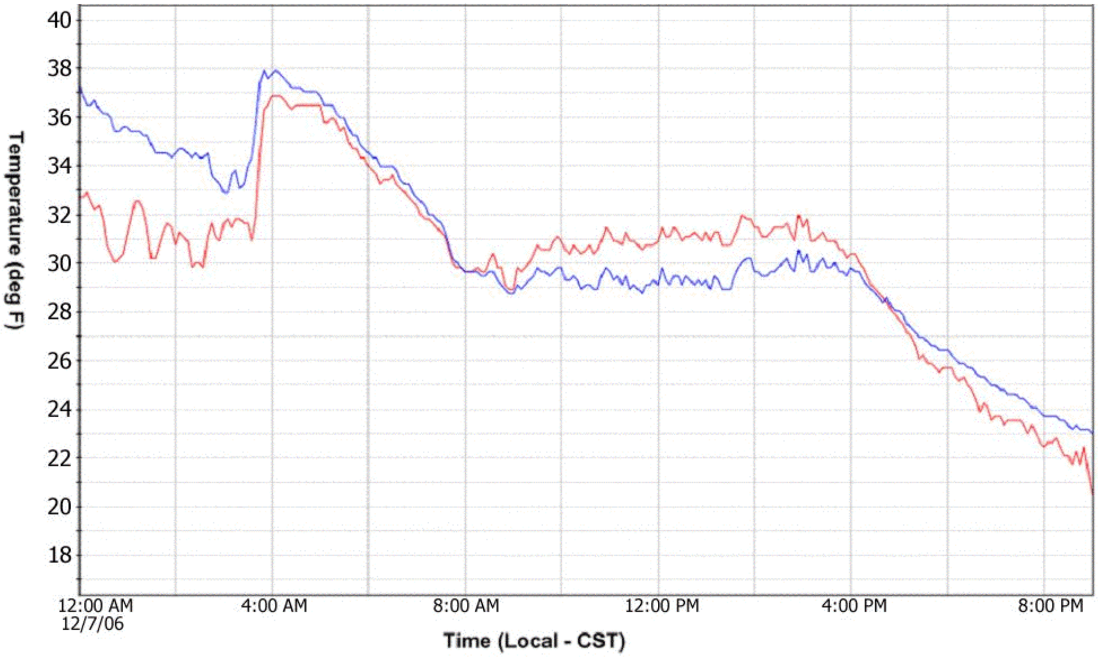


Figure 6. As in Fig. 5 (top), except for temperature (ºF) at 1.5 m (red) and at 9 m (blue).

b. The frontal passage of 7 December 2006

Several days after the previous case, another cold front pushed through central Oklahoma, with the frontal passage occurring in the pre-dawn hours of 7 December 2006. As the meteorogram for Norman shows, this cold frontal passage at about 0330 CST (0930 UTC) was remarkable in that it was accompanied by a marked temperature *rise* of short duration (about 10 min) followed by slowly decreasing temperatures, eventually to values below those in the pre-frontal airmass (Fig. 5, top). This case is an example of a phenomenon described by Sanders and Kessler (1999), of abrupt temperature rises after passage of apparent cold fronts. They noted this was primarily a nocturnal phenomenon and associated with minor orographic features, consistent with this case.

Preceding the frontal passage, Fig. 6 shows that a strong surface-based inversion had developed overnight, as the windspeeds near the surface had become nearly calm before the frontal passage, consistent with the case presented by Sanders and Kessler. As the front approached, the near-surface winds began to increase just prior to the abrupt temperature increase (Fig. 5, bottom). Shortly after this, the winds became strong and gusty and the temperature began a relatively slow fall, which was interrupted by the diurnal heating (as shown in Fig. 6 by a positive lapse rate between 1.5 and 9 m during the day), then fell considerably during the next night. The surface conditions following this frontal passage were notably different from those in the previous case (Fig. 7). Winds ahead of the front were not predominantly poleward and were quite weak. A “pool” of warm air was present behind the transition zone where windspeeds increased rapidly. Following the axis of this pool of relatively warm surface temperatures, temperatures decreased steadily, but the gradient was substantially less than in the previous example, consistent with the meteorograms of Fig. 5.

To help understand this case, consider the surface analysis for the afternoon preceding passage of the front through central Oklahoma (Fig. 8). Surface winds at this time were mostly northerly as far south as central Texas, behind a relatively weak front connected to a deep occluded cyclone well to the northeast. The front under consideration here, the leading edge of an Arctic airmass, was moving through Nebraska at this time, following relatively close behind an earlier, weaker frontal passage through Oklahoma.

It might have been anticipated that this Arctic front would also behave more or less typically, ignoring any complications associated with the absence of much poleward surface flow ahead of it. As already shown, however, events proved otherwise.

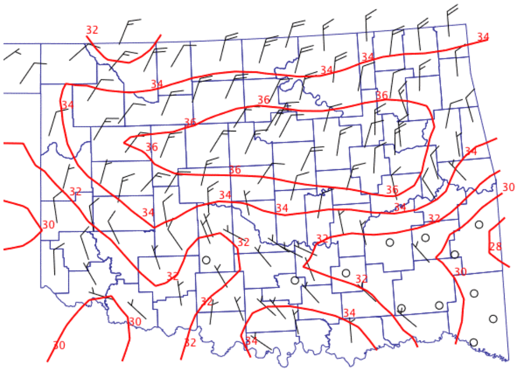


Figure 7. As in Fig. 3, except at 0330 CST on 7 Dec. 2006, with the isotherm interval changed to 2°F (1.1 ºC).

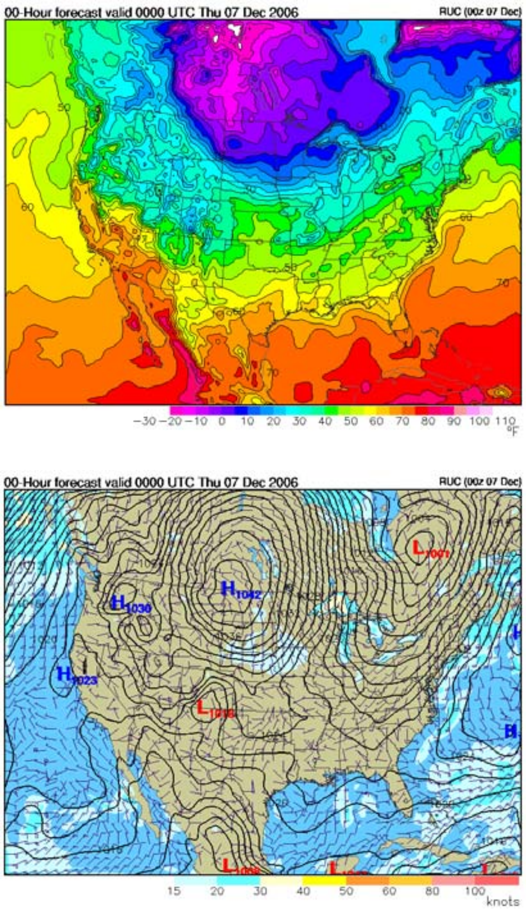


Figure 8. (top) As in Fig. 2 except for 00 UTC on 7 December 2006; (bottom) wind barbs and sea level pressure (hPa) contours.

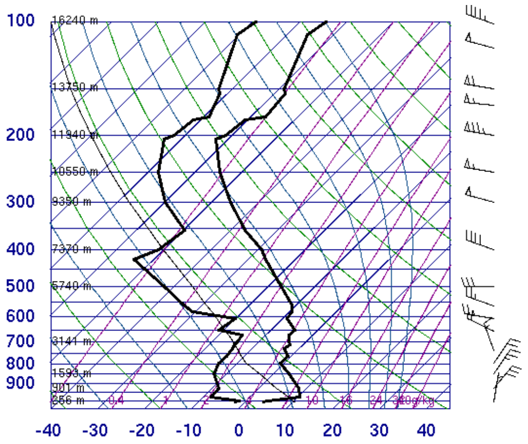


Figure 9. As in Fig. 4, except for Dallas-Fort Worth at 12 UTC on 7 December 2006.

The front moved through Norman before the morning 12 UTC sounding on 7 December, so to see the character of the pre-frontal situation, consider the sounding at Dallas-Fort Worth (Fig 9). In this case, there was a strong surface-based nocturnal inversion, likely similar to the character of the airmass ahead of the front as it passed through Norman early in the morning. The inversion might have been somewhat stronger in central Oklahoma prior to frontal passage, given the observed strong inversion in the lowest 10 m (cf. Fig. 6).

Mesoscale variability of radiational cooling across central Oklahoma was reflected by marked differences in the response of near-surface temperatures to the frontal passage at nearby surface sites. At Washington (located 20 km south of Norman), the frontal passage had little impact on the near-surface temperature (Fig. 10). But at the Crosstimber Micronet[1] site CR18 (25 km southeast of Norman; see Fig. 11) where stronger radiational cooling occurred overnight, the temperature increased by a remarkable 8.3 ºC (15°F). The Washington site is open grassland, even more so than the Norman site, whereas the Micronet site is at a lower elevation and in a forested area (although the immediate vicinity of the site is grassy), so is relatively sheltered from the wind. After frontal passage, spatial temperature variability decreased.

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[1] This is a small network of surface stations instrumented comparably to those of the Oklahoma Mesonet, operated privately by the second author (Haugland 2006)

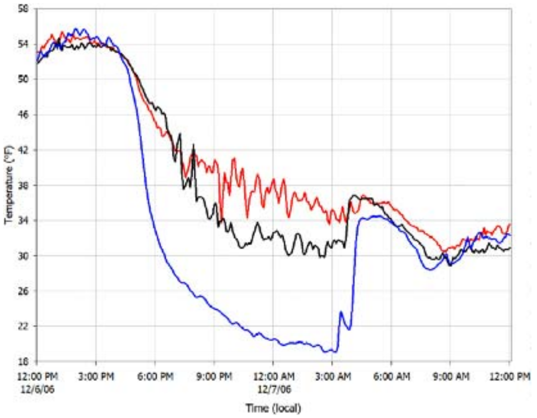

Figure 10. Temperature at Norman (°F; black) and Washington (red) Mesonet sites, as well as the Crosstimber Micronet site CR18 (blue), all at 1.5 m.

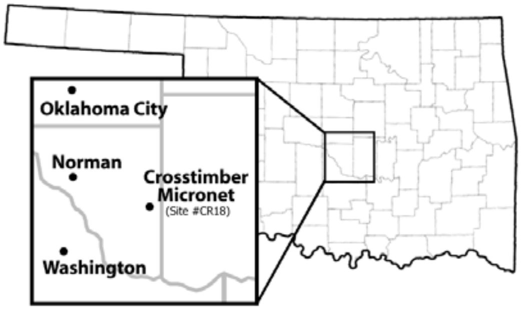

Figure 11. Location of the observing sites in Fig. 10.

3. Interpretation of the observations

The two cases together make it clear that frontal passages through Oklahoma are not always simple and certainly can vary in character. In the first case, the frontal passage was similar to a prototypical cold front, with the wind shift and temperature decrease occurring nearly simultaneously. There were no complicating features ahead of the front that might confuse an analyst about where to locate the front. The relatively narrow transition zone and near-colocation of the wind shift with the leading edge of the abrupt temperature decrease were persistent features of this front.

On the other hand, the second case was very different from the prototypical frontal passage. During the afternoon, as the arctic air was moving equatorward, the airflow at the surface ahead of the front was not poleward. A previous frontal passage still was affecting the low-level airflow in advance of the arctic air mass, although by nighttime, the surface winds had become mostly light and variable, whereas winds became strong and gusty behind the front. The most remarkable feature during the nocturnal passage of the front through Oklahoma is that it was accompanied by a temperature *increase* at many locations, rather than a temperature decrease. This is evidently the result of the timing of the frontal passage, occurring after the establishment of a strong surface-based inversion at many of the sites. The increased wind speeds after frontal passage produced shear-induced turbulent mixing that resulted in warm air from above the surface being mixed downward. As the front continued to move equatorward, the Arctic airmass intrusion eventually resulted in a temperature fall to values well below that of the prefrontal airmass.

The second case provides expanded documentation of a phenomenon noted by Sanders and Kessler (1999). In their study, they did not have Oklahoma Mesonet maps and meteorograms to provide mesoscale details. Our data corroborate their proposed mixing mechanism by which cold frontal passages can result in temperature *increases* after frontal passage when a prefrontal inversion is present. Not all sites in Oklahoma exhibited this behavior, however, owing to variability in such factors as elevation and vegetative cover. These can introduce horizontal variability that might be taken for observation errors, but are in fact accurate observations that reflect how exposure factors influence atmospheric structure in the PBL (see Hunt et al. 2007 for another example).

This second case raises the issue of where an analyst should locate a front and how it should be classified. If a dogmatic adherence to locating a cold front at the leading edge of the transition zone with steadily falling temperatures behind the front is followed, the front would be analyzed well poleward of the initial onset of strong winds. This feature—the initial onset of strong winds—had been associated with steadily falling temperatures during frontal passage the day before (during daylight hours) the front entered Oklahoma. It is the presence of a surface-based nocturnal inversion that produced the phenomenon of initially rising post-frontal temperatures, followed by a more or less steady temperature fall. In our interpretation of the case, the "cold front" still should be located in this leading transition zone, despite the paradox of temporarily rising temperatures behind the initial boundary. This odd feature does not signal a permanent change in the character of the front, but simply reflects the changing structure of the boundary layer and its mesoscale variations during the diurnal cycle.

Note that Christensen (1935) documented a frontal passage in the plains that was characterized by rising temperatures behind the apparent cold front. That case (on 26 October 1933) was evidently one that occurred during the day, and provided an alternative mechanism for such an event: differential diabatic heating across the front. When the region ahead of the front remains cloudy and perhaps rainy, it can happen that if the air behind the front is clear, diurnal heating can produce the seeming paradox of warming behind a cold front. Although not documented herein, we have seen cases similar to that presented by Christensen.

4. Discussion and Conclusions

The preceding interpretation of the observations serves to illustrate an important aspect of the boundary layer as it interacts with synoptic-scale processes. In the boundary layer, extremely strong vertical gradients can be created during the diurnal cycle that may interact with features on the synoptic scale to produce mesoscale structures that might seem unusual or even paradoxical, as in our second case of frontal passage. Even on the plains, modest elevation and vegetative cover variations can combine with these occasionally intense vertical gradients to produce strong horizontal variability in the surface observations or unusual behavior of fronts.

Moreover, there are many other sources of mesoscale variability on the plains; examples include soil type variation, soil moisture variation, as well as the presence of large bodies of water, human structures, and localized anthropogenic modification of all these characteristics. The exposure of a particular observation site to these diverse factors can play an important role in the observations it produces. Mesoscale atmospheric structures generally are poorly sampled by most existing surface observation networks—the Oklahoma Mesonet provides a glimpse into the complex processes that make interpretation of surface observations challenging.

Sanders (1999) proposed an approach to classifying surface boundaries, defining a threshold for considering a thermal gradient to qualify as a true front, as well introducing the term “baroclinic trough” to describe front-like structures that don’t meet the threshold. Our view of these features emphasizes trying to understand the physical processes producing the observations rather than to classify the event. The thermal gradient observed at the surface associated with fronts can be strongly affected by various processes within the planetary boundary layer. The magnitude of the thermal gradient is only part of what we see as a more complex range of possibilities than described in the classification scheme proposed in Sanders (1999). The precise character of a frontal passage can vary substantially in space and time. Therefore, we support strongly the recommendations in Sanders (1999) and Sanders and Doswell (1999) that rather than discussing what name to give some feature, we should allow an *analysis* of surface temperature (or, preferably, potential temperature) to tell its own story. The physical process associated with the observations is what matters. A similar recommendation can be made for the analysis of other variables observed at the surface: dewpoint (or, preferably, mixing ratio), wind velocity, pressure, and so forth.

Classification of physical processes via conceptual models is an important element in meteorological diagnosis. Whether the goal of a diagnosis is for forecasting or research, the perception of what physical processes are underway is always important. It *matters* whether or not a surface boundary is a barotropic pressure trough or windshift, a warm front, a cold front, an occluded front, or a dryline.[2] But classification systems (or “taxonomies”) are imposed by humans, whereas the atmosphere always produces more diverse behavior than is described within our inevitably simplified taxonomies, leading to seemingly incessant discussions about what names to use (for example, see Doswell 1991) and where in some classification scheme a particular event seems to fit. It is our belief that such debates are only useful insofar as they lead to physical understanding of the phenomena of interest.

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[2] A discussion of this topic can be found at: http://www.flame.org/~cdoswell/conceptual/conceptual.html

Acknowledgments: The authors are grateful to our formal reviewers for their valuable suggestions regarding the manuscript. We also thank those who have developed and maintained the websites from which the most of the figures presented herein were obtained—notably, the National Center for Atmospheric Research / Research Applications Laboratory [http://www.rap.ucar.edu/weather/—Figures 2 and 7] and Greg Thompson, in particular, as well as the University of Wyoming [http://weather.uwyo.edu/upperair/—Figures. 4 and 8], and the Oklahoma Mesonet [http://www.mesonet.org/—Figs 1, 3, 5 and 6]. Data were provided by the Oklahoma Mesonet, funded by the Oklahoma State Regents for Higher Education.

REFERENCES

Christensen, A. H., 1935: Analysis of a warm "cold front". *Mon. Wea. Rev.*, **63**, 9.

Doswell, C. A. III, 1991: Comments on "Mesoscale convective patterns of the southern High Plains." *Bull. Amer. Meteor. Soc.*, **72**, 389–390.

Haugland, M. J., 2006: The Crosstimber Micronet: An automated microscale surface observation network. Preprints, *10th Symp. On Observing and Assimilation Systems*, Atlanta, GA, Amer. Meteor. Soc.

Hunt, E. D, J. B. Basara and C. R. Morgan, 2007: Significant inversions and rapid in situ cooling at a well-sited Oklahoma Mesonet station. *J. Appl. Meteor. Clim.*, **46**, 353–367.

Hutchinson, T. A., and H. B. Bluestein, 1998: Prefrontal wind-shift lines in the plains of the United States. *Mon. Wea. Rev.*, **126**, 141–166.

McPherson, R. A., et al., 2007: Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. *J. Atmos. Oceanic Technol.*, **24**, 301–321.

Petterssen, S., 1956: *Weather Analysis and Forecasting. Vol. 1, Motion and Motion Systems*. 2d ed., McGraw-Hill, 428 pp.

Sanders, F., 1999: A proposed method of surface map analysis. *Mon. Wea. Rev.*, **127**, 945–955.

______, and C. A. Doswell III, 1995: The case for detailed surface analysis. *Bull. Amer. Meteor. Soc.*, **76**. 505–521.

______, and E. Kessler, 1999: Frontal analysis in the light of abrupt temperature changes in a shallow valley. *Mon. Wea. Rev.*, **127**, 1125–1133.

Schultz, D. M., 2004: Cold fronts with and without prefrontal wind shifts in the Central United States. *Mon. Wea. Rev.*, **132**, 2040–2053.

______, 2005: A review of cold fronts with prefrontal troughs and wind shifts. *Mon. Wea. Rev.*, **133**, 2449–2472.

REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

REVIEWER A (Peter C. Banacos):

Initial Review:

Recommendation: Accept with Minor Revisions.

Summary: This paper is pretty standard fare, using basic analysis methods to demonstrate that not all cold frontal passages are alike using two examples in the southern Great Plains. The interpretation of the temperature trends is right on, so my brief suggestions are aimed mainly at improving a few figures and putting the paper in the broader context of what exactly classifies as a front, with some consideration given to including the term "baroclinic trough" for the 7 December case.

Major Comments:

1.) I believe it is fair to ask whether the 7 December event is really a system we would regard as a "cold front". It is not accompanied by much of a temperature gradient (temperatures falls 4-6 ^{o}F after brief post-frontal rise period), the surface wind shift is much more gradual than the 29 November case based on the Oklahoma Mesonet observations, and there is a relative maximum in temperature along the wind shift. Additionally, there was presumably little sensible weather of consequence in the frontal zone (since there is no documentation of any), whereas the first case was associated with elevated thunderstorms in the frontal zone.

It's fair to ask, but that's a fair question in many "classification" discussions. I have no doubt it is a cold front – albeit not so dramatic as the earlier case. The character of the frontal passage in Norman is somewhat misleading – after the temperature decrease began, the daily heating cycle began to mitigate the continuing temperature fall, as hopefully should be evident in the revised manuscript. The following evening, temperatures resumed their decline.

All in all, this case appears to be in line with what Fred Sanders was attempting to define as a "baroclinic trough" (June 1999, MWR, and August 2005 WAF). Sanders and Kessler (1999) urged calling a similar nocturnal episode over the same geographic region a "trof", so it seems somewhat of an omission not to do so here.

Perhaps it does. A discussion of the 99 Sanders paper cited here has been added. However, the omission of proposed new terminology like "baroclinic trough" or "trof" is intentional. We're not trying to classify this event as this or that, but rather are trying to illustrate the complicated physical processes that result in the observations.

I believe the reader would gain additional appreciation for the challenges of classifying these structures (irrespective of the pre-frontal trough issue) if some brief acknowledgment was given to the "baroclinic trough" nomenclature and these other references. This also has forecast application since the conceptual model for a baroclinic trough differs from that of a real front. This discussion would likely fit best in Section 3 of your paper.

See the preceding comment.

2.) There are some inconsistencies in the data analysis for the two cases. In particular, it would be nice to see a sea-level pressure analysis (similar to Fig. 7) for the 29 November case, and also at the time of the Mesonet wind/temperature plot shown in Fig. 6 (time not included on Figure) for the second case. This would help to compare and contrast the events in terms of the sea-level pressure field, and how it relates to the wind and temperature fields.

Adding comparable figures is not a trivial task, since we're using the NCAR/RAP maps, which aren't easily available more than a few days after the event. They can be obtained, but only at the convenience of the site manager, who's a busy man. We don't see a large amount of value in comparing sea-level pressure fields.

3.) The temporal details included in the meteorograms are the centerpiece of this paper, in my opinion. Thus, the lack of readability of these figures (specifically the axis labels in Figs. 1, 5) is disappointing. It should be permissible to enlarge the figures themselves to span both text columns for improved readability.

Done.

4.) I understand the authors' desired point that frontal structures and analysis in the central and southern plains is not as straightforward as one might presume given the relatively flat topography. However, is the "featureless" plains description necessary no less than *three times* in the introduction? Besides the redundancy, it's been demonstrated that the westward sloping terrain plays a role in the faster cold front movement southward across the high plains relative to points further east (the authors themselves allude to this in section 2a). I'd prefer to see the topography described for what it *is* rather than what it is not – i.e., the terrain is not of negligible impact on frontal characteristics, and frontal movement in particular. The intended point can probably be made more succinctly.

In our effort to make a point, we may have over-emphasized this widespread misconception of the plains. Text revised.

5.) A "county-scale" map indicating the relative locations of the Meteorogram sites referenced toward the end of Section 2b of the paper might be helpful for those unfamiliar with the local geography.

A good suggestion. A locator map has been added.

6.) It appears there is some CAPE for a parcel lifted from near 850mb on the 21z Norman sounding on 29 November 2006. The last sentence of Section 2a states that the atmosphere was "apparently unstable enough to support thunderstorms". It might be worthwhile to include a quick quantification of the instability on the sounding since you have the data (e.g., "CAPE was X J/kg for a parcel originating from 850mb.", or wherever the most unstable parcel level is exactly).

We don't believe that "exact" values are very important, but we've followed this suggestion to highlight the elevated nature of the thunderstorms.

7.) Page 4, Section 2b, paragraph 2: The specific description of temporal events in paragraph 2 fails to mention the rise in temperatures, stating only that "Shortly after frontal passage, the winds became strong and gusty while the temperatures continued to fall". It would be better to state the duration of the temperature rise after the frontal passage before the trend reversed.

Done.

8.) Temperature is given in degrees Fahrenheit throughout the text and in the figures. At the very least, the mention of the "15 ^{o}F" temperature rise in the last paragraph of Section 2b could also be listed in degrees Celsius. Otherwise, it is perhaps more of an editorial issue in terms of whether or not this is acceptable.

I'll leave that to the editor's discretion. I would hope that most readers can convert between them, but will add parenthetical Celsius values if the editor wishes.

[*Editor's Note:* EJSSM, being a formal journal, requires that metric units are prioritized in the text; but equivalent English units *may* be used in figures and placed in parentheses in the text body for work that is operationally (U.S.) oriented.]

[Minor comments omitted…]

REVIEWER B (James Johnson):

Initial Review:

Recommendation: Accept with Minor Revisions.

General Comments: The authors have provided an excellent manuscript. Their data and diagnosis of the same make it clear that while the so called classical definition of a cold front as a first-order density discontinuity apparently holds true for all cold fronts, the manifestation of that density discontinuity can be (and in this reviewer's experience very often is) far less evident in the associated gradients analyzed from observational data sets. Their two cases, while certainly not providing an unequivocal proof, adequately demonstrate the case they have made and clearly identify the apparent cause of the anomalous behavior of warming in the wake of cold frontal passage.

Reviewer Recommendation: This manuscript is ready for publication once the authors have addressed the matter of applicability (substantive) and the problem with figures 1. and 5. (technical). I do not necessarily need to see the paper again providing the authors respond to these comments.

Substantive Comments: There is little to quibble over with the substance of this paper as the authors have done a good job of supporting their observations and conclusions with well accepted science. I can really offer only two suggestions which may serve to improve the manuscript.

There is some question concerning applicability of this paper to this particular journal. Although cold fronts are frequently associated with severe storms (both on the synoptic scale and on the convective scale), it is not immediately obvious to this reviewer where that association lies with respect to the cases presented and the premise offered by the authors. In order for this excellent study to be germane to the Electronic Journal of Severe Storms Meteorology (EJSSM), some discussion of the impact of the author's findings with respect to severe storms would be welcome even if only of a speculative nature. Though I certainly abhor idle speculation in the name of science, I believe there is enough substance to the author's case to support at least some conjecture.

Some discussion of the convection in the first case has been added. However, I think the mandate regarding subject matter for EJSSM is sufficiently broad that we prefer not to engage in this exercise just to make sure the connection to "severe storms" is made more evident.

Also, I suggest to the authors that they include a reference in the introduction section for the classical definition of a front as being a first-order density discontinuity. While this may be obvious to some, this reviewer's experience is that many operational forecasters have great difficulty in identifying frontal discontinuities in the observational data during analysis.

Done.

[Minor comments omitted…]

REVIEWER C (Bill Eckrich):

Initial Review:

Recommendation: Accept with Minor Revisions.

The paper was well-written, informative and presented in an easy-to-follow progression. I began to draw conclusions about the second front based on the data presented and those conclusions were confirmed as I read on. Excellent use of all the figures, especially those from the Oklahoma Mesonet. You made good use of this data to show the effects of the second front relative to the the conditions at each location and how each location's conditions were, in turn, relative to its physical location (elevation, vegetation, etc.) As an operational meteorologist, this paper gave me renewed insight into how a cold front can act given the conditions presented.

[Minor comment omitted…]

Aside from that, I found the paper to be acceptable with sound scientific facts and principles and well-written.

Thank you.