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The Role of a Stabilizing Boundary Layer during a Severe/Non-Severe Weather Event

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ABSTRACT

During the evening and overnight hours of 16-17 September 2007, a line of thunderstorms moved across northeastern Colorado and southwest Nebraska. The thunderstorms produced several measured wind gusts in excess of 60 mph in Colorado and extreme southwest Nebraska. The thunderstorms continued moving northeast; however no additional severe winds were reported despite high base velocity radar signatures at 0.5 degrees from the KLNX WSR-88D. The purpose of this case study is to analyze the importance of a mixed surface layer for thunderstorms to produce strong to severe wind gusts at the surface. The 0000 UTC 17 September 2007 KLBF sounding showed a weak inversion around 1800 feet AGL, and LAPS and RUC model soundings showed the inversion strengthening during the remainder of the evening. KLNX WSR-88D and surrounding radars also indicated a rapid expansion of anomalous propagation returns coinciding with the end of the severe wind reports. This case study will look at how super-refraction of the WSR-88D radar beam and resulting anomalous propagation clutter may show the strength of an inversion and, in this case, a correlation to a limited surface severe wind threat.

1. INTRODUCTION

In the 1990s the National Weather Service (NWS) implemented the use of Weather Surveillance Radar - 1988 Doppler (WSR-88D) data to assist NWS meteorologists in analyzing atmospheric phenomena. While the introduction of the WSR-88D is widely known to have greatly improved analysis of storms by meteorologists, there still remain a few limitations. One of the limitations is anomalous propagation (AP) clutter, which includes ground clutter (Chrisman 1995). A process called clutter filtering (Ice 2007; Torres 1999) is used to remove this AP clutter. Clutter filtering is continuing to improve as new technology is developed, especially since the installation of the Open Radar Data Acquisition (ORDA) system in 2006 (Ice 2007; Kessinger 2005). This study will show a possible benefit to NWS warning meteorologists of having AP clutter.

2. BACKGROUND

2a. Boundary Layer

The amount of AP clutter visible on WSR-88D base data depends on the atmospheric conditions within the boundary layer. The boundary layer is defined (Stull 1988) as the part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to the surface forcings with a timescale of about an hour or less. Stull further explains how the boundary layer can become stably stratified whenever the surface is cooler than the air. This stable boundary layer (SBL) often forms at night over land, where it is known as a nocturnal boundary layer (NBL). The depth of the NBL will increase as the height of the nocturnal surface inversion (NSI) increases (André 1981). While the NSI will generally continue to increase throughout the night, Gopalakrishnan et al. (1998) concluded that turbulence in the NBL plays a large factor in the initial development of the height of the NSI. They found that weak wind simulations had a more uniform increase to the NSI through the night, while strong wind simulations had an initial increase to a near-equilibrium point, then a slight increase the remainder of the night.

On rare occasions, a surface inversion can develop from the downdraft of a thunderstorm. In this case, relatively cool air produced by the thunderstorm results in a temperature inversion in the lowest few thousand feet (Battan 1973). The duration of a thunderstorm induced inversion usually is short lived; however, if during the evening or overnight hours, it can transition into the NSI.

2b. Radar Physics

Doppler radar, under standard atmospheric conditions, will send the radio frequency close to a straight line away from the Radar Data Acquisition (RDA) unit, however under differing atmospheric conditions the radar beam will be bent either upward (sub-refraction) or downward (super-refraction; Battan 1973). Standard atmospheric conditions can cause a slight beam bending, typically seen on the lowest scan of the WSR-88D. This beam bending can result in ground clutter visible on the radar image (Fig. 1a), usually limited to within 20 - 30 nautical miles (Chrisman 1995). However, the NSI will cause a radar beam to be super-refracted and additional ground or near ground returns (Fig.1b), commonly referred to as AP clutter, to be visible on the radar image (Battan 1973). The strength and height of the inversion will dictate the extent of the radar beam bending and resulting AP clutter that is visible. Typically the stronger the NSI, the greater the distance from the RDA the AP clutter will be depicted. Figure 2 shows the principle of how the NSI will cause the radar beam to be refracted to the surface.

3. DATA & METHODOLOGY

Most of the data utilized in this case came from the Advanced Weather Interactive Processing System (AWIPS) archiving package, using the Weather Event Simulator (WES) to create images. The archived data analyzed included the National Center for Environmental Prediction's (NCEP) 0000 UTC 12-km North American Model run (not shown), 0000 UTC radiosonde observation (RAOB), hourly Local Analysis and Prediction System (LAPS) model and hourly NCEP Rapid Update Cycle (RUC) model (not shown) analysis data from 0000 UTC to 0500 UTC from 17 September 2007. Only NWS Automated Surface Observing System (ASOS) and Federal Aviation Administration Automated Weather Observing System (AWOS) surface observations were available and analyzed during the event. Finally, additional archived data (day 1 thunderstorm outlooks and severe weather reports) from the Storm Prediction Center's (SPC 2008) website were utilized from 0500 UTC 16 September 2007 to 0200 UTC 17 September 2007.

The area of focus in this study is southwest into central Nebraska. The main cities and observations referenced include: Imperial and an ASOS (KIML) and North Platte and an ASOS (KLBF) in southwest Nebraska, and Thedford and an AWOS (KTIF) in central Nebraska (Fig 3). Thedford is also where the WSR-88D, site KLNX, is located.

4. METEOROLOGICAL CONDITIONS

4a. Upper-Air Analysis

The long-wave pattern during the afternoon of 16 September 2007 was characterized by a long-wave trough positioned along the west coast of the United States and a shallow ridge across the southern Plains (not shown). Southwesterly flow across the High Plains drove a late season short-wave trough across the central Rockies. By 0000 UTC 17 September 2007, a greater than 90-knot 250-hPa jet streak was curving anticyclonically from northern Utah into South Dakota with a strong area of divergence located over northeastern Colorado (Fig. 4a). At 500 hPa a subtle trough was crossing Colorado with a weak vorticity maximum (Fig. 4b). At 700 hPa an area of upward vertical motion was seen over northeastern Colorado (Fig. 4c). Finally, at 850 hPa, a low was located across eastern Colorado (Fig. 4d).

4b. Surface Analysis

Subjective surface analysis from 0000 UTC 17 September 2007 (Fig. 5), included low pressure over east-central Colorado with a stationary boundary extending east across Kansas. A second surface low was located over northwest South Dakota with a trough across the front range of the Rocky Mountains. North of the stationary boundary, temperatures were in the 70s (°F) with dew point temperatures in the lower 60s (°F). South of the boundary, temperatures were in upper 80s (°F) and lower 90s (°F), with dew point temperatures in the upper 40s (°F) to lower 50s (°F). In northeast Colorado, where showers and thunderstorms had occurred, temperatures had fallen into the 60s (°F). South-southwest wind gusts around 25 knots were reported over southwest Kansas, while lighter southeasterly winds less than 10 knots were reported over much of Nebraska.

4c. Sounding Analysis

The 0000 UTC 17 September 2007 RAOB sounding from KLBF showed that the NSI had already developed (Fig. 6a). The inversion height was around 850 hPa or 1800 feet AGL. The observed sounding at Denver, Colorado (KDNR) also showed a developing NSI (Fig. 6b). Other regional soundings from Dodge City, Kansas (KDDC) and Rapid City, South Dakota (KUNR) were still indicative of a well mixed BL (Figs. 6c-d).

The 0000 UTC 17 September 2007 LAPS model analysis sounding was in agreement with the observed RAOB sounding (Fig. 7a), also indicating the NSI at a height around 850 hPa or 1800 feet AGL at KLBF. The hourly LAPS model forecast soundings continued to strengthen the NSI at KLBF through 0200 UTC with a more uniform NBL from 0200 UTC to 0400 UTC, keeping the NSI height at 850 hPa or 1800 feet AGL (Figs. 7a-7e). Initially at KIML the 0000 UTC LAPS model analysis sounding showed the NSI had not yet developed (Fig. 7f). By 0100 UTC the surface had cooled, however the BL surface temperature profile was uniform (Fig. 7g). Finally by 0200 UTC the NSI had developed at a height also around 850 hPa or 1300 feet AGL (Fig. 7h). Similar to KLBF, little change to the NBL occurred at KIML from 0200 UTC through 0400 UTC (Figs. 7h-j). Finally, the LAPS model analysis sounding at KTIF indicated a well mixed BL at 0000 UTC (Fig. 7k). However, by 0100 UTC, the LAPS model forecast sounding was showing the NSI at 850 hPa or 1600 feet AGL (Fig. 7l). The inversion at KTIF strengthened by 0200 UTC with a more uniform NBL (like that observed at KLBF and KIML) from 0200 UTC through 0400 UTC (Figs. 7m-o).

Of the soundings analyzed, LAPS model analysis and RUC model analysis (not shown) were in good agreement developing the NSI around 850 hPa. KLBF developed the NSI first, followed by KTIF and KIML. The NBL showed little change after 0200 UTC.

4d. Thunderstorm Outlook for Nebraska

A line of thunderstorms, associated with the aforementioned short-wave trough, moved across northeast Colorado, from 2100 UTC 16 September 2007 to 0000 UTC 17 September 2007. During this time a total of two severe wind reports were received as the line moved across northeast Colorado. At 2123 UTC 16 September 2007, a storm chaser measured a 58-knot wind gust in Adams County, Colorado. Then at 2345 UTC 16 September 2007, a mesonet observation site in Yuma County, Colorado, measured 55 knots. Additionally, several public reports of blowing dirt and reduced visibilities were received.

Expectations by forecasters were for thunderstorms to continue along the trough as the feature progressed east to northeast across southwest Nebraska into central Nebraska. Thunderstorms were expected to weaken as they moved into southwestern Nebraska, and were expected to remain below severe limits. The day one severe thunderstorm outlook, issued earlier in the afternoon by the Storm Prediction Center (SPC), placed southwestern Nebraska in a general thunderstorm outlook (not shown). Following severe reports in Colorado, the SPC day one severe weather outlook at 0100 UTC 17 September 2007 upgraded southwest Nebraska to a "see text." The SPC uses a "see text" label for areas where a 5 percent probability of severe weather is forecast, but the coverage or the intensity is not expected to be sufficient for a slight risk (SPC 2008). The threat in the written discussion was for a nocturnal low-level jet to develop, increase and sustain convection after sunset.

5. OBSERVATIONS

5a. OVERVIEW OF EVENT

The line of thunderstorms was located in northeast Colorado at 0000 UTC 17 September 2007 (Fig. 8a). By 0100 UTC (Fig. 8b) the line crossed into southwest Nebraska. Over the next 45 minutes, AP clutter expanded significantly across all regional radars (Figs. 9a-d), and was analyzed to be the strengthening NSI. KLNX base reflectivity and base velocity images from 0157 UTC to 0328 UTC show the time progression of the thunderstorms from southwest into central Nebraska (Figs 10a-f). An outflow boundary became visible on both the base reflectivity and base velocity by 0157 UTC (Figs. 10a-b). The outflow boundary continued to be visible on radar, especially on the base velocity imagery, as the storms moved into central Nebraska (Figs. 10c-f). The thunderstorms weakened after 0230 UTC, while the outflow boundary raced further ahead of the thunderstorms.

5b. RADAR/SURFACE REPORTS

As the line of thunderstorms crossed into southwest Nebraska, a couple of strong cells were observed from the KLNX radar. By 0101 UTC 17 September 2007, the highest reflectivity returns of 60 to 65 dBZ were located west of the city of Imperial (Fig. 11a). The co-located highest inbound velocity, analyzed around 60 knots, was at approximately 12,000 feet AGL (Fig. 11b). A few minutes later this line of thunderstorms produced damaging winds in the city of Imperial, with a peak wind gust of 55 knots recorded at KIML at 0116 UTC 17 September 2007.

This would be the last severe wind reported with this line of thunderstorms. Over the next 30 minutes the thunderstorms weakened, as viewed by reflectivity returns (Figs. 11c and 11e). However, highest velocities continued to range from 50 to 60 knots at 10,000 to 12,000 feet AGL (Figs. 11d and 11f). Around 0130 UTC a public report of a 45-knot wind gust was reported southeast of the city of Ogallala. This report was ahead of the line of thunderstorms, and post analysis indicated this to be from the outflow boundary, although the outflow boundary at this time was not visible on radar.

The line of thunderstorms continued to move northeast with an outflow boundary becoming visible on radar just before 0200 UTC (Figs. 10a-b). The thunderstorms continued to weaken through 0300 UTC, with reflectivity values remaining at or below 50 dBZ for the rest of the event (Figs. 12a, 12c, and 12e). The outflow boundary surged ahead of the thunderstorms with the highest velocity values analyzed near the NSI. At 0240 UTC the highest velocities on the leading edge of the boundary (approximately 1500 feet AGL) were still close to 60 knots (Fig. 12b). As the boundary approached the RDA, velocities dropped to around 40 knots, near 500 feet AGL (Fig. 12d). By 0328 UTC (Fig. 12f), the boundary was well past the RDA and velocity values had increased back to around 60 knots. The height of these velocities was again analyzed at 1500 feet AGL.

The only surface reports impacted by the outflow boundary available were the automated observation sites at KLBF and KTIF. Peak winds associated with the outflow boundary at KLBF were only 18 knots (0229 UTC), with a similar result at KTIF, where the peak winds were only 17 knots (0307 UTC). Surprisingly higher wind gust reports were recorded as the line of weakened thunderstorms passed across the automated observation sites. KLBF recorded a peak wind gust of 29 knots at 0331 UTC, while KTIF recorded a peak wind gusts of 38 knots, with the 0410 UTC observation (radar at this time not shown).

6. DISCUSSION

The objective of this case study was to identify if WSR-88D base data and the expansion of AP clutter can be used in real time to assess the development of the NSI. Along with the development of the NSI, this study was to determine the effects the NSI has on the ability of strong thunderstorm winds and thunderstorm outflow boundary winds of reaching the surface. Analyzing regional radar loops, rapid expansion of AP clutter and region wide development of the NSI occurred between 0100 UTC and 0200 UTC 17 September 2007. The development of the NSI was in agreement with model sounding analysis from KIML. An early development of the initial surface inversion from 0000 UTC to 0100 UTC at KTIF may be attributed to the decaying thunderstorm observed on the KLNX radar, which transitioned into the NSI. The earlier development of a surface inversion at KLBF could have been associated with KLBF’s location in the North Platte River valley; however, the storms did not affect this area until after the development of the NSI region wide.

In this case, thunderstorms moved out of northeast Colorado into southwest Nebraska producing severe wind gusts. The line of thunderstorms then produced an outflow boundary as a strong NSI developed. The wind velocity on base velocity radar images were analyzed around 60 knots at only 1800 feet AGL; meanwhile at the surface, automated weather observations surprisingly recorded peak winds less than 20 knots. This case had an interesting result: the thunderstorms, despite weakening while the NSI remained strong, were able to produce stronger winds at the surface, around 30 to 40 knots.

Unfortunately, this case had no surface observations in the path of the storm during the time the outflow boundary and associated strong winds became elevated to the NSI, although, the benefits to such surface observations is unknown. The author would stress that while this case showed a good relationship between the development of a strong NSI and an end to severe winds at the surface, additional research is needed to understand how the transition to elevated winds occurs and how the depth and strength of the NSI may affect the inability of the strong winds to mix to the surface.

7. ACKNOWLEDGEMENTS

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Torres, S. M., 1999: Ground Clutter Canceling with a Regression Filter. *Journal of Atmospheric and Oceanic Technology*., **16**, 1364-1372.

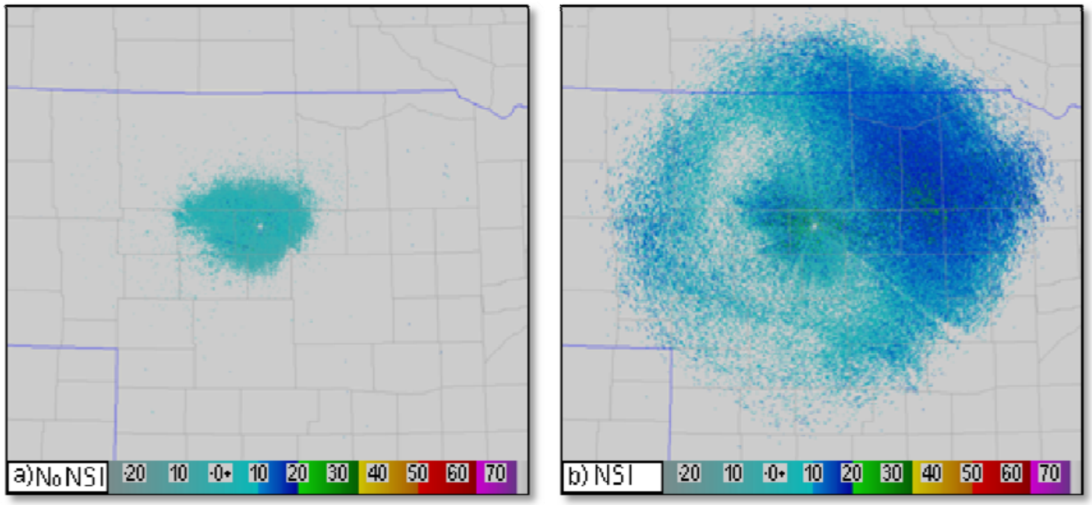

Figure 1. WSR-88D 0.5 degree reflectivity image showing (a) standard atmospheric conditions or no NSI and (b) a strong NSI.

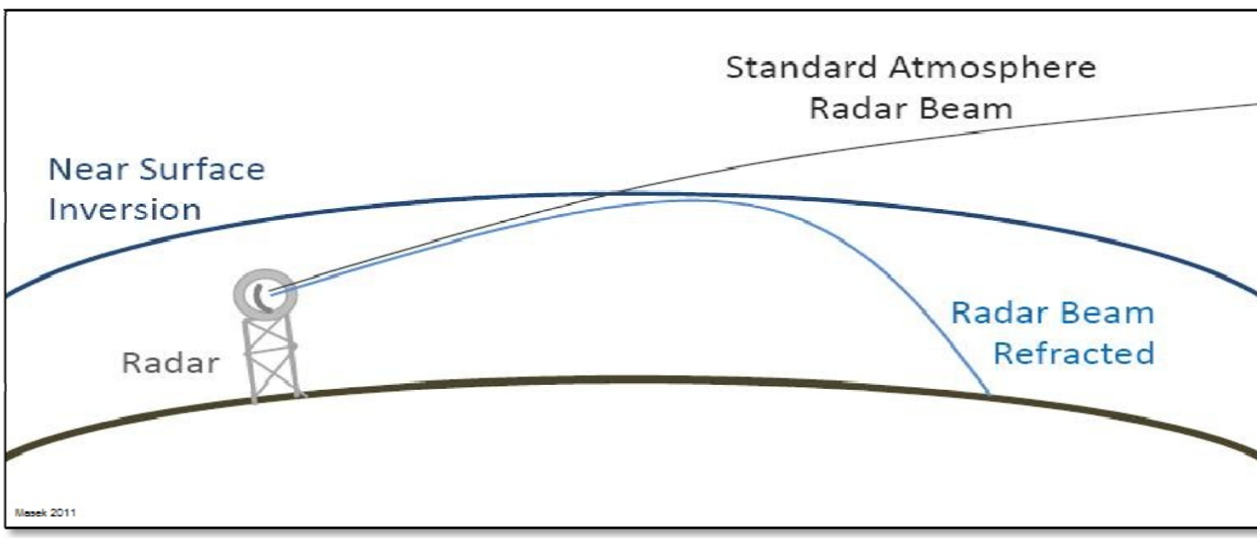

Figure 2. Standard atmosphere radar beam and near surface inversion causing super-refracted radar beam.

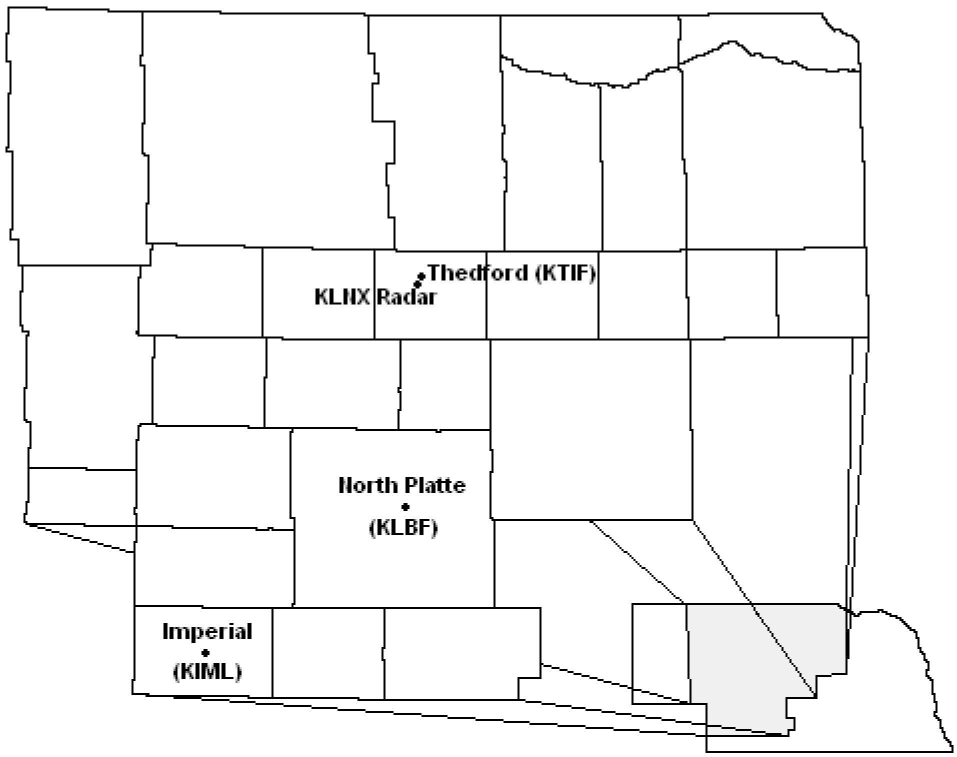

Figure 3. Reference points and radar location within the NWS North Platte Weather Forecast Office coverage warning area.

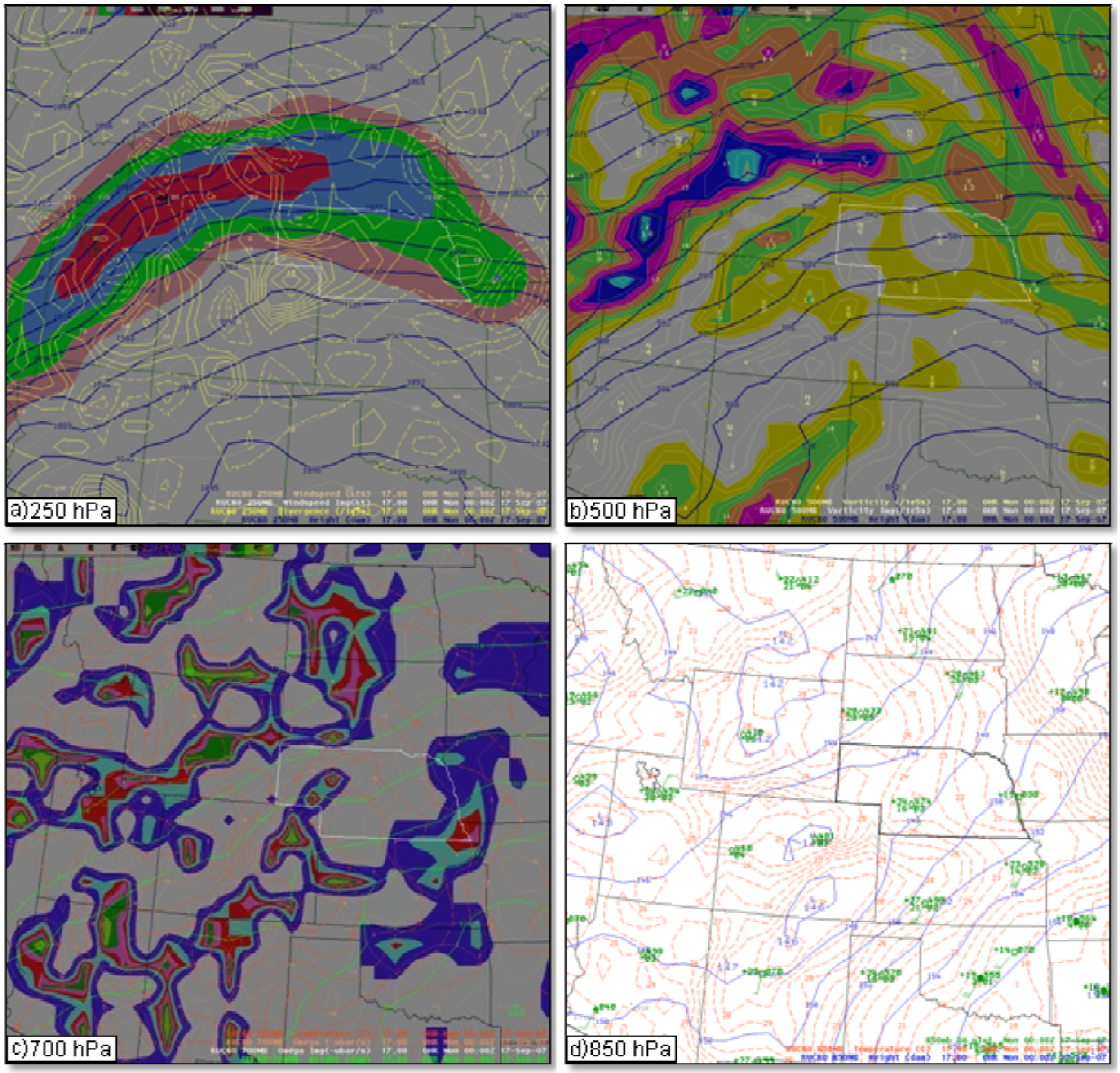

Figure 4. 0000 UTC 17 September 2007 upper-air analysis for (a) 250hPa - windspeed (image; contour interval 10 knots, starting at 60 knots); heights (blue; contour interval 30 m); divergence (yellow; contour interval 1 s^{-1}); (b) 500hPa - vorticity (image; contour interval 2 s^{-1}, starting at 7 s^{-1}); heights (blue; contour interval 30 m); (c) 700hPa - omega (image; contour interval 0.1 Pa s^{-1}, starting at 0 Pa s^{-1}); heights (green; contour interval 20 m); and (d) 850hPa - upper-air plot (green); height (blue; contour interval 20 m); temperature (red; contour interval 1 °C).

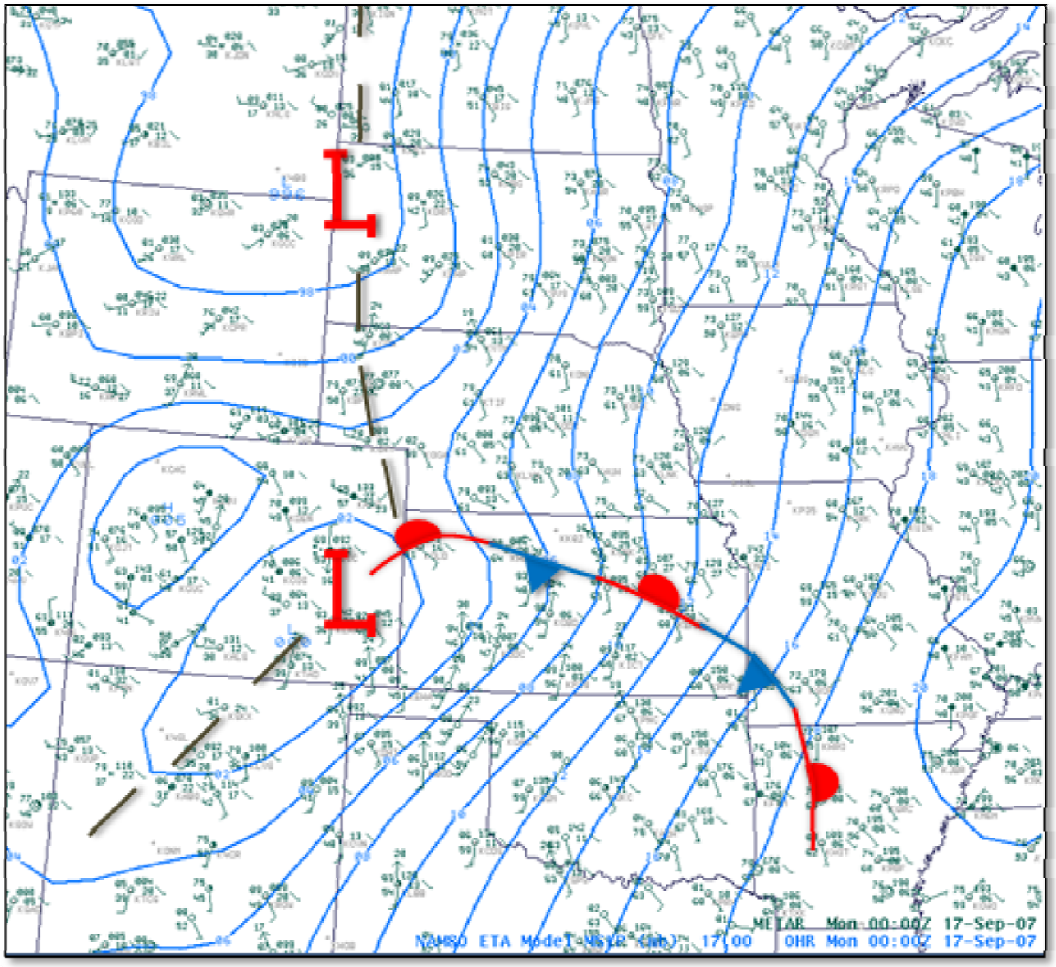

Figure 5. 0000 UTC 17 September 2007 subjective surface analysis (standard convention).

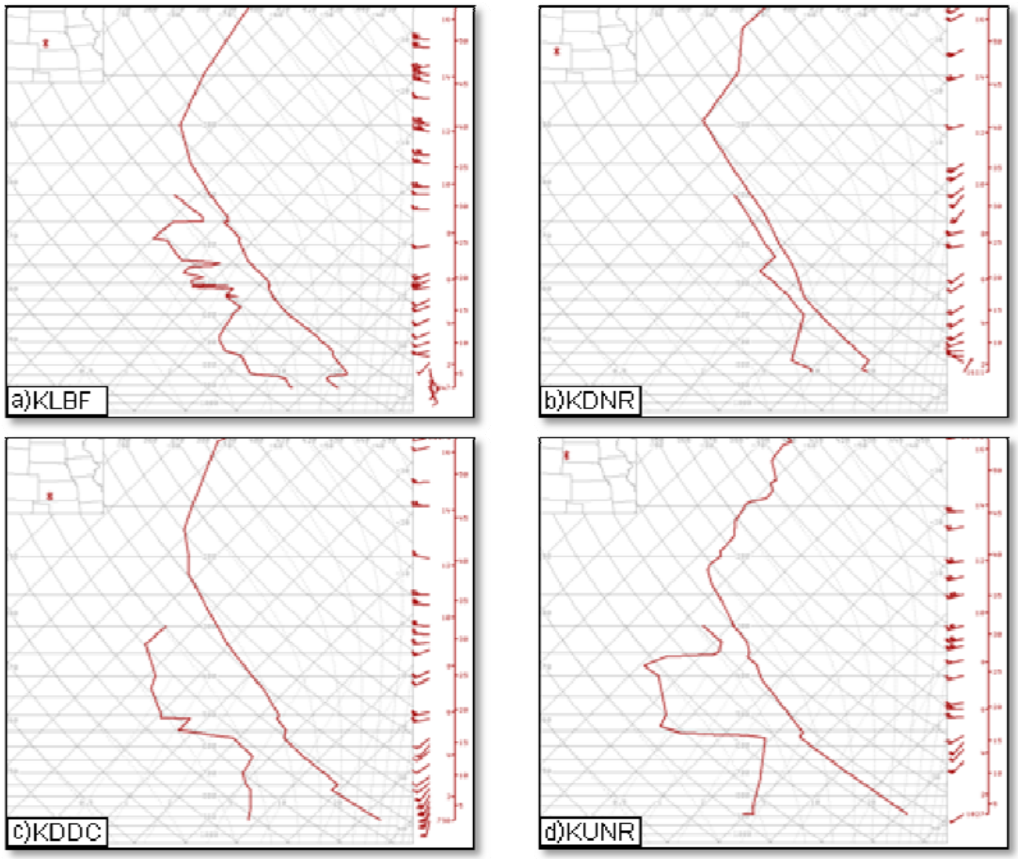

Figure 6. 0000 UTC 17 September 2007 observed RAOB soundings for (a) KLBF, (b) KDNR, (c) KDDC, and (d) KUNR.

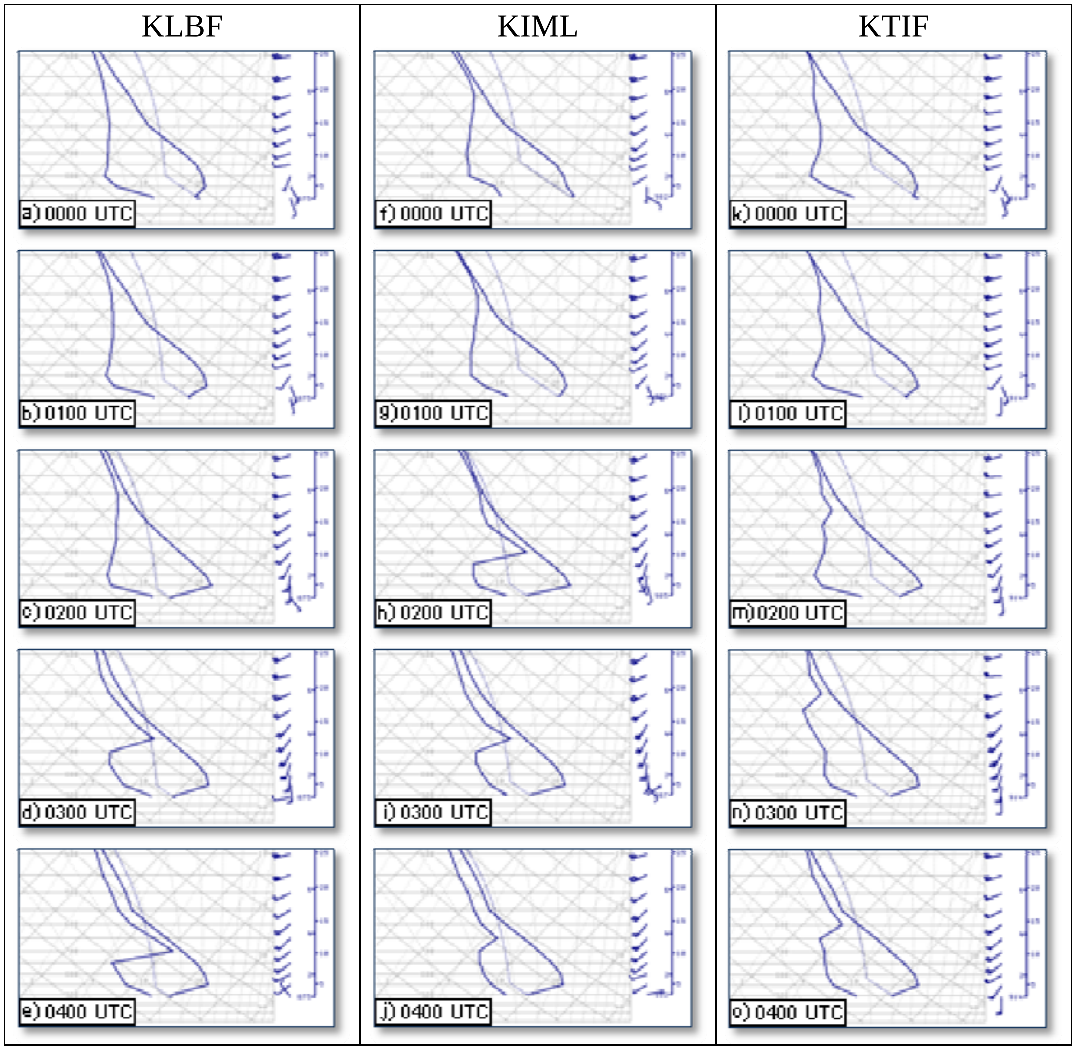

Figure 7. 0000 UTC to 0400 UTC 17 September 2007 lower portion of hourly LAPS model forecast sounding for (a - e) KLBF, (f - j) KIML, and (k - o) KTIF.

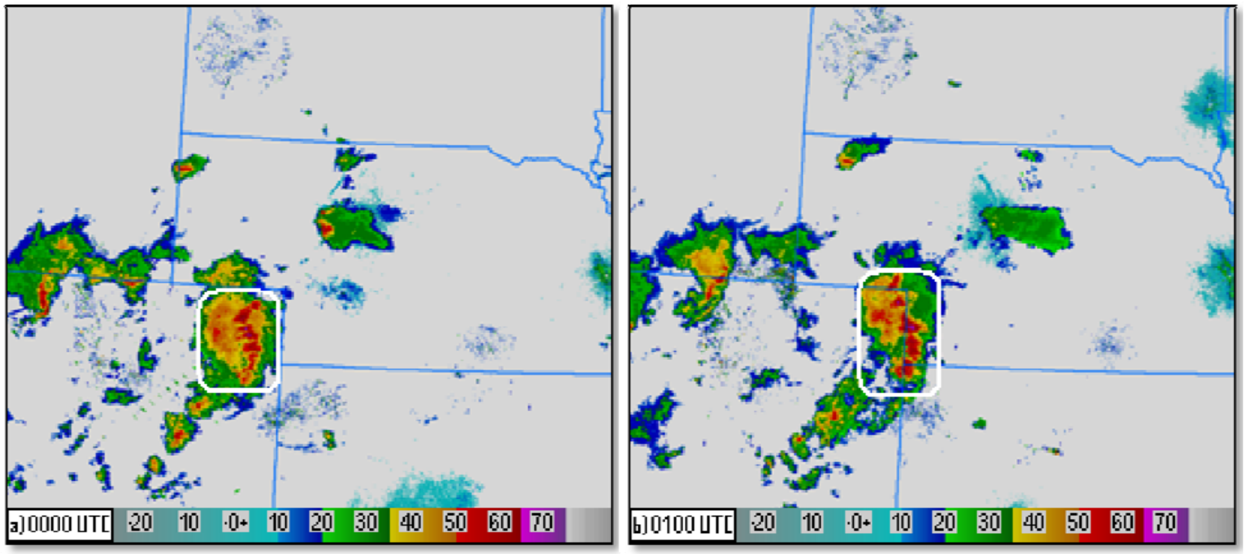

Figure 8. 17 September 2007 regional radar for (a) 0000 UTC and (b) 0100 UTC (line of thunderstorms highlighted in white box).

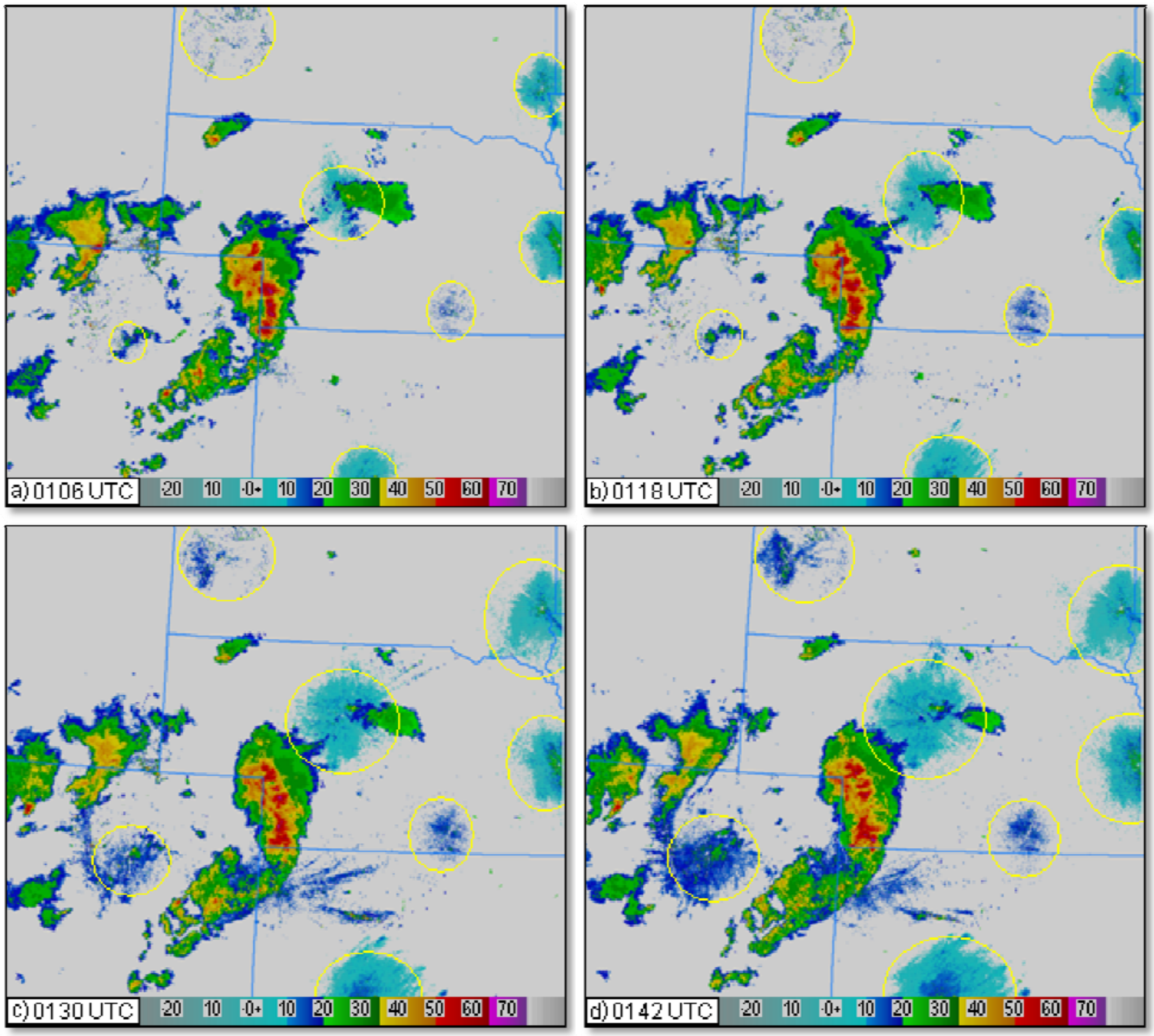

Figure 9. 17 September 2007 regional radar for (a) 0106 UTC, (b) 0118 UTC, (c) 0130 UTC and (d) 0142 UTC (AP clutter highlighted in yellow).

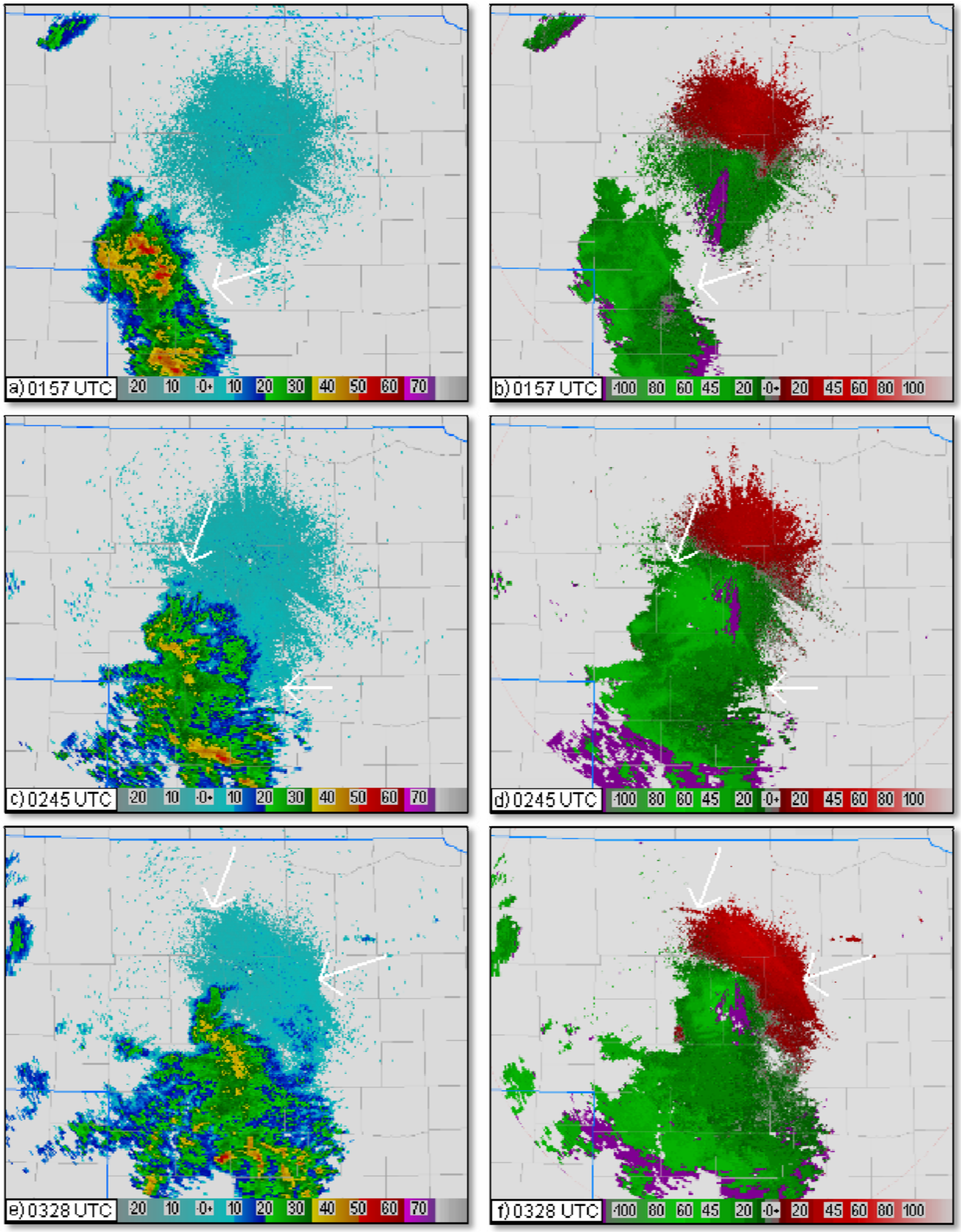

Figure 10. 17 September 2007 KLNX base reflectivity (left) and base velocity (right) for (a-b) 0157 UTC, (c-d) 0245 UTC, and (e-f) 0328 UTC (outflow boundary highlighted by white arrows).

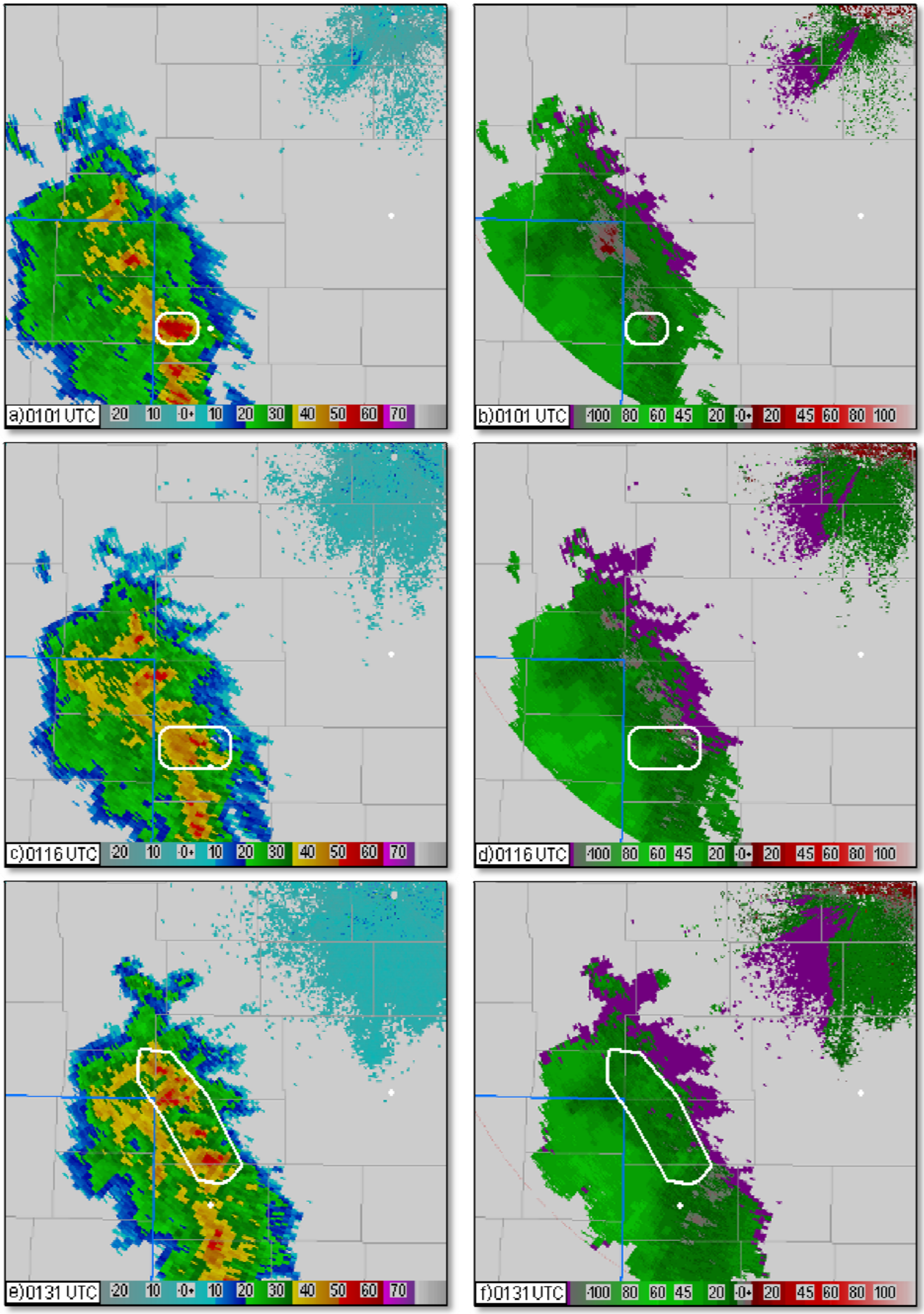

Figure 11. 17 September 2007 KLNX base reflectivity (left) and base velocity (right) for (a-b) 0101 UTC, (c-d) 0116 UTC, and (e-f) 0131 UTC (highest reflectivity returns and highest velocity inbound highlighted with white box).

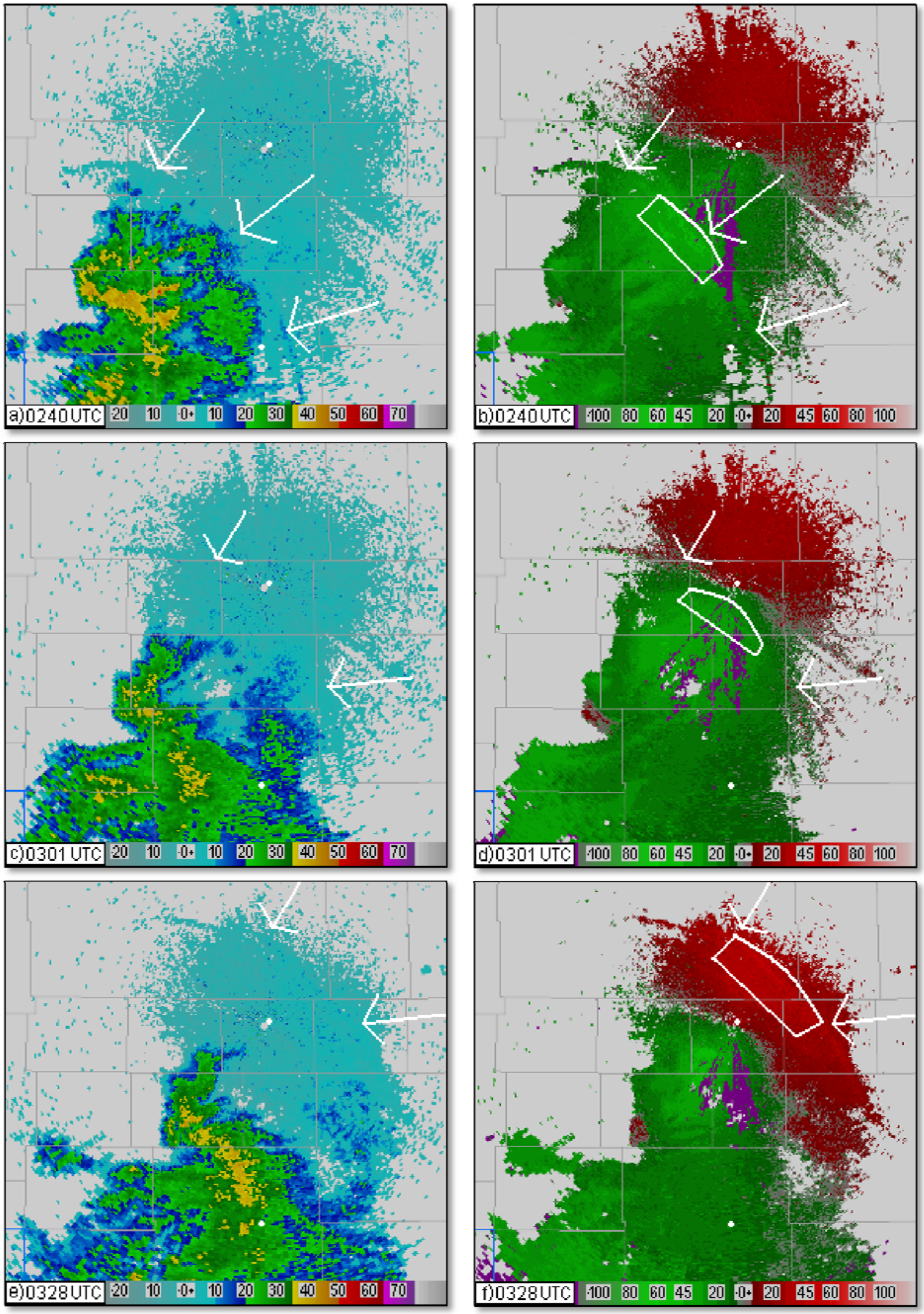

Figure 12. 17 September 2007 KLNX base reflectivity (left) and base velocity (right) for (a-b) 0240 UTC, (c-d) 0301 UTC, and (e-f) 0328 UTC (outflow boundary highlighted by white arrows and high velocity data highlighted in white box).