968 OBSERVATIONAL ANALYSIS OF A SURFACE-BASED BOW ECHO TRANSITIONING TO ELEVATED CONVECTION OVER COMPLEX TERRAIN

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1. INTRODUCTION

Thunderstorms are a common occurrence across much of North America. In the central United States, storms often develop in the afternoon over elevated terrain of the Rocky Mountains and move east over the Plains during the overnight hours (e.g., Carbone et al. 2002). This nocturnal convection is responsible for the majority of growing season rain in the Great Plains (Wallace 1975, Fritch et al. 1986) and thus an important part of the local hydrologic cycle. The afternoon storms are generally assumed to be "surface-based", fueled by conditionally unstable air that has been warmed by contact with the Earth's surface (e.g., Parker 2008, French and Parker 2010). As night falls, and the near-surface boundary layer stabilizes owing to radiational cooling, this source of potentially unstable air is removed, and nocturnal storms have long been assumed to be "elevated", sustained by a layer of conditionally unstable air that is above the surface and not modified by radiational cooling. Such storms are believed to be sustained by gravity waves, or bores (e.g., Parker 2008, French and Parker 2010) or frontal overrunning (Trier and Parsons 1993) rather than surface-based cold pools, however the role of these processes remain an active area of research (Geerts et al. 2016).

The processes governing the evolution of afternoon, surface-based convection to nighttime, elevated convection, in particular, are not well understood. Idealized model simulations by Parker (2008) and French and Parker (2010) demonstrated that simulated storms can undergo a substantial amount of environmental cooling before ceasing to ingest near-surface parcels. Once this occurs, forcing for convective updrafts evolved from a cold pool (density current) to a bore that propagated through the simulated stable layer. Such bores have been observed in the vicinity of nighttime convective systems in a number of observational studies (e.g. Haghi et al. 2017; Haghi et al. 2019, Parsons et al. 2019). More recently, observations from the Plains Elevated Convection at Night (PECAN, Geerts et al. 2016) field project have found that a number of observed nighttime convective systems appeared to remain surface based well after dark (Hitchcock et al. 2019). This suggests that the evolution of daytime-to-nocturnal storms may be more variable than originally thought and deserves further study.

The present study seeks to continue to address this issue by examining a case of a bow echo that evolved into elevated convection while traversing the Black Hills of western South Dakota on 11-12 July 2017. In this particular case, the surface-based-to-elevated convection transition appeared to coincide with the storms' motion off of the elevated terrain of the Black Hills onto the surrounding plains. It is hypothesized that the storm rapidly encountering a deeper nighttime stable layer over the plains may have facilitated the evolution in this case.

2. METHODOLOGY

Archived radar reflectivity factor and Doppler velocity data from the Rapid City, South Dakota WSR-88D (KUDX) were analyzed using the GRLevel 2 Analyst software to create a detailed timeline of storm evolution. This included documenting changes to storm structure in relation to the underlying topography as well as the evolving pre-storm environment. The evolving near-storm environment was analyzed using a combination of the 0000 UTC, 12 July 2017 rawinsonde observation from Rapid City, South Dakota (KUNR), surface observations from multiple Automated Surface Observing (ASOS) stations in the region, and soundings generated from Rapid Refresh (RAP, Benjamin et al 2016) model analysis fields. The RAP model analyses were also used to characterize the synoptic- and mesoscale environment for this case.

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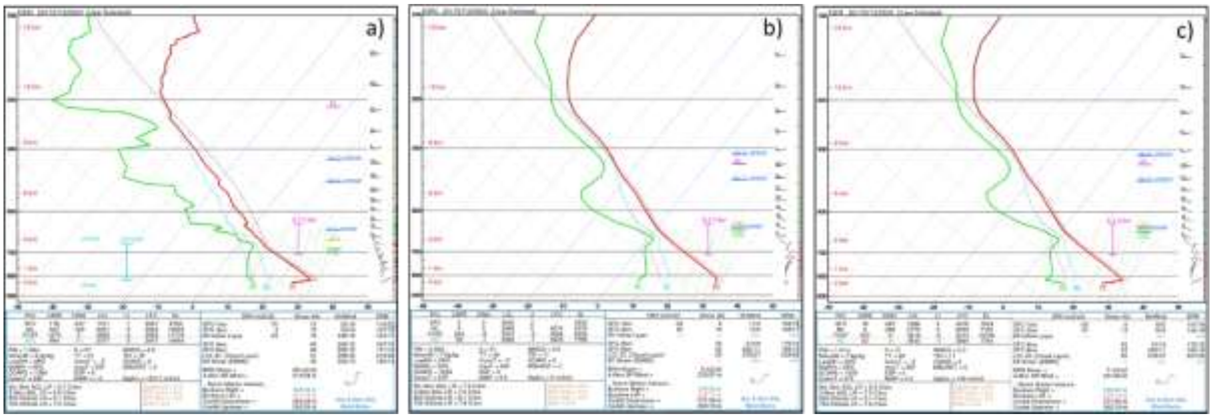

Figure 1 Example soundings: a) KUNR 00 UTC observed sounding modified with KIEN 05 UTC surface observation, b) RAP model sounding for KIEN at 05 UTC, c) hybrid of RAP sounding from (b) modified with 05 UTC KIEN surface observations.

Several methods were employed to estimate how the static stability profile evolved overnight during this event. Initially, the KUNR 0000 UTC sounding was modified to match individual surface stations at several locations along the storm path. Figure 1a shows an example of this using the 05 UTC surface observation from Pine Ridge. A strong surface inversion was present, which seemed likely in this event, however assuming static conditions above the surface for upwards of 6 hours after the sounding released is likely unrealistic. To address this issue, RAP analysis soundings were created for the locations of the surface stations along the storms' path, with the expectation that they would better capture the evolving environment. While these did capture changes to the mid- and upper levels, surface temperatures were generally too warm, and surface dew point temperatures too dry compared to observed surface stations (Figure 1b). This would have an effect of likely under-representing the strength of the nocturnal inversion, while also reducing most-unstable parcel convective available potential energy (CAPE) due to the reduced dew points. Ultimately, a hybrid approach was taken whereby the RAP profiles were combined with observed surface temperature and dew point values to create hybrid model/observed soundings along the path of the storm (Figure 1c). These hybrid soundings represent a reasonable compromise between tracking the evolving environment through the lower troposphere while accurately reflecting near-surface conditions. The locations of the surface stations used for these soundings are shown in figure 2.

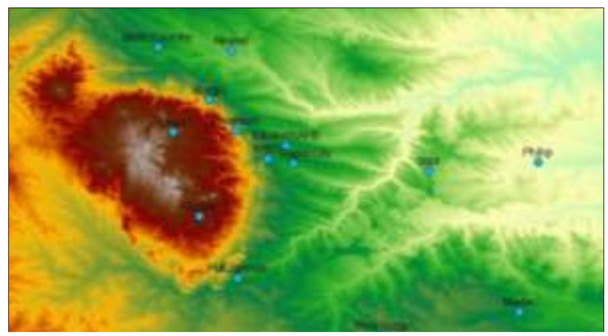

Figure 2: digital elevation map of the Black Hills depicting location of ASOS surface stations.

3. RESULTS

3.1 *Synoptic Setting and Radar Timeline, 11-12 July 2017*

The storm in question began in southeastern Montana in the late afternoon of 11 July 2017. Analysis of RAP surface and upper air charts for that day at 2100 UTC (approximately three hours before the storm was spawned) did not suggest strong large-scale forcing. The study area was under a region of largely zonal upper-level flow at the northern periphery of an upper level ridge (Figure 3).

A compact 80-85kt jet streak over central Montana may have aided in the development of the initial storms in this case, as convection initiation occurred in the vicinity of the right entrance region of the jet, however upper level forcing appeared limited. In the lower troposphere, a strong moisture gradient was evident across the eastern Dakotas,

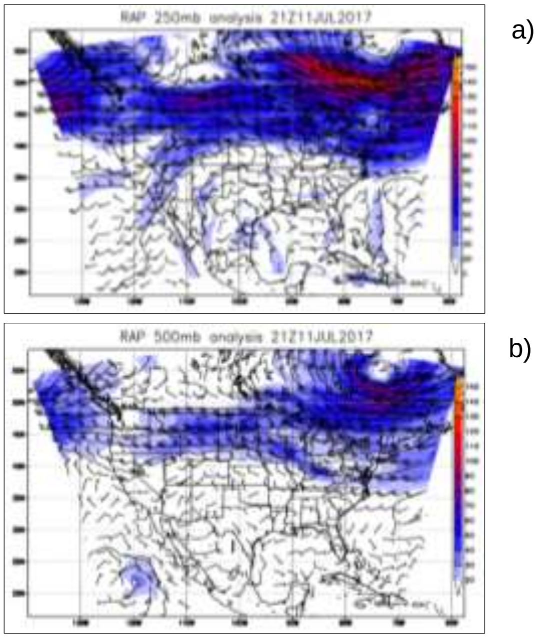

Figure 3 RAP upper air charts, 2100 UTC on 11 July 2017: a) 250mb and b) 500mb charts both show mostly zonal flow and weak forcing.

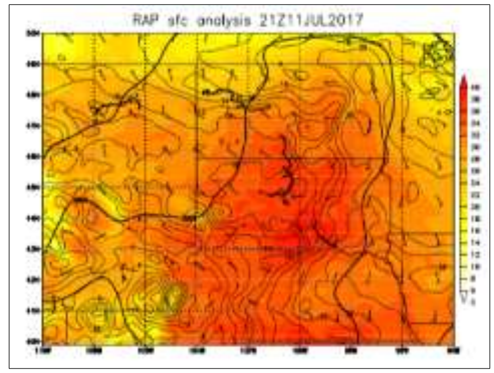

Figure 4 RAP surface chart 2100 UTC 11 July 2017: Dark contours represent pressure in millibars, dashed contours dewpoint in °C, shading temperature in °C.

Figure 5: KUNR sounding 00 UTC, 12 July 2017

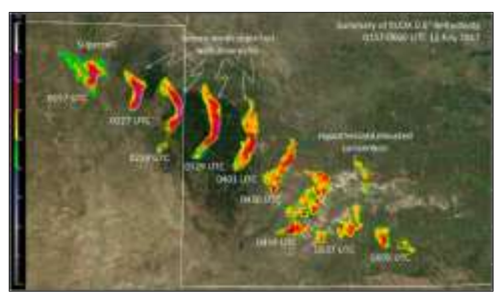

Figure 6: topographic map of the Black Hills of SD illustrating storm path.

with a region of locally higher dew points extending from southeastern Montana into the Nebraska panhandle. The storm of interest appears to have developed on the northern periphery of this region of a locally enhanced dew points and travelled along the diffuse dewpoint gradient through the overnight hours (Figure 4). The 00 UTC KUNR sounding sampled a deep, well-mixed boundary layer and contained approximately 800 J/kg of surface-based CAPE (Figure 5).

Figure 6 shows a radar progression of the event, with radar reflectivity plotted at key times. By 0157 UTC, 12 July 2017, the storm had strengthened into a supercell and had been severe warned by the National Weather Service in Rapid City, South Dakota. By 0259 UTC the storm began to ascend the western Black Hills and had evolved into a compact bow echo (Fujita 1978, Przybylinski 1995). Radar reflectivity at the strongest part of the bow was 70 dBz. The storm maintained its bow echo organization as it passed over the central Black Hills, producing severe-criteria wind gusts and hail. As the bow echo crossed the eastern slopes of the Black Hills and emerged onto the surrounding Plains, 0401 UTC, there was a marked decrease in reflectivity. As it moved over the Plains it continued to diminish in intensity and started to devolve into a loosely organized cluster of cells between 0430-0600 UTC. At this point it is hypothesized that the storm had transitioned completely to elevated convection.

3.2 ***Hypothesized surface-based to elevated convection transition***

Shortly after the storm moved onto the plains, beginning at 0428 UTC, a series of radar fine lines accelerated ahead of the storm, and new convective cells developed following their passage south and east of the original convection (Figure 7e). The presence of a series of fine lines rather than a single line is suggestive of an undular bore moving ahead of the convective system (Parsons et al. 2019). In addition to radar fine lines, examination of surface stations near the foothills of the Black Hills suggested the passage of a density current, indicated by a sharp decrease in temperature with a sharp spike in pressure (Haghi et al. 2017, Haghi et al. 2019, Parsons et al. 2019). Surface stations farther out on the plains, aligned closely with the radar fine lines, showed a slight but temporary increase in temperature at the same time showing a sharp increase in pressure consistent with an undular bore (Haghi et al. 2017, Haghi et al. 2019, Parsons et al. 2019). The system continued progressing eastward into the overnight hours as a cluster of cells.

Analysis of the modified RAP soundings ahead of the storm indicated that as the above evolution was taking place the storm was encountering an increasingly stable boundary layer. As illustrated in Figures 7a-7e as the bow echo was moving across the Black Hills, there non-negligible surface-based CAPE, and the developing inversion was comparatively weak (surface temperatures at Custer, SD in the mid-upper 70s Fahrenheit). However, as the storm emerged onto the plains, SBCAPE dropped to near 0 J/kg with SBCIN values < -650 J/kg, and a much more pronounced inversion was present, suggesting a very strong stable layer. The depth of the stable layer appears to be tied to the variation in terrain height. A series of hybrid soundings created just prior to the bow echo reaching the peak of the Black Hills (approximately 03 UTC, Figure 8) shows the stable layer was considerably deeper and stronger over the plains (KRAP and KIEN) compared with over the Hills (KCUT). Thus, as the bow echo moved off of the Black Hills it very quickly encountered a deep, strong near-surface stable layer. This would appear to be conducive to the rapid evolution from surface-based to elevated convection hypothesized, as well as with the triggering of the bore noted in the radar data.

4. SUMMARY AND FUTURE WORK

The thunderstorm that occurred over eastern Montana and Wyoming on the evening of 11 July 2017 developed in a marginal supercell and bow echo environment in the absence of strong synoptic or mesoscale forcing. Despite that, the storm evolved into a supercell, and then into a bow echo as it progressed eastward, producing heavy rain and hail reports. It intensified as it ascended the western Black Hills, reaching a peak radar reflectivity of 70 dBz. As it crossed onto the Plains it began to weaken and radar indicated a gust front, likely initially a density current, accelerating away from the storm. A series of radar fine lines followed that suggest the density current encountered the SBL and induced an undular bore, which initiated elevated convection. The storm progressed eastward as a convective cluster of storms. The stability of the environment east of the storm as indicated by multiple surface stations and RAP model soundings suggested an increasingly stable boundary layer throughout the night.

Given the timing of the observed decrease in reflectivity and loss of cohesion, aligned with the surface station data, it is hypothesized that the movement of the bow echo off the elevated terrain of the Black Hills assisted in the transition from surface-based to elevated convection. One likely scenario is that as the cold pool descended the lee side of the Hills it was accelerated by gravity. East of the Hills, over the Great Plains, a strong stable boundary layer had developed during the night. As the cold pool encountered the SBL it generated a bore that initiated elevated convection in the unstable layer immediately above it.

The next phase of this study will involve running simulations using the Weather Research and Forecasting (WRF) and/or Cloud Model 1 (CM1) models to examine cold pool properties and more directly test the hypothesis that the underlying topography affected the evolution to elevated convection. In particular, this will seek to examine how possible thinning of the cold pool over the Black Hills may have influenced the rapid transition to elevated convection over the Plains.

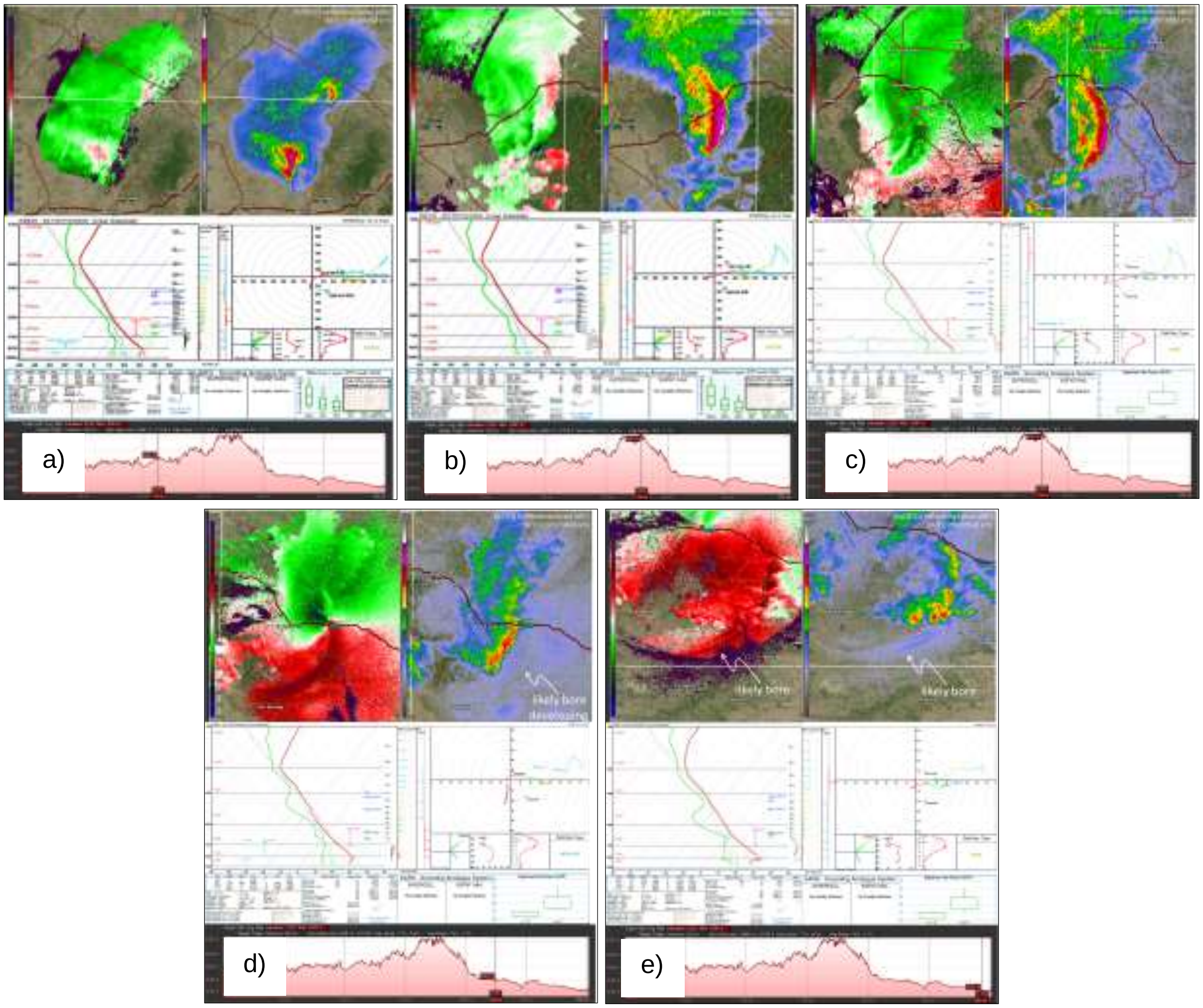

Figure 7 radar timeline with hybrid sounding from the surface station nearest to storm and associated elevation profile, 12 July 2017: a) supercell, b) storm ascending the Black Hills, c) mature bow echo, d) suspected bore development, e) radar fine lines that could indicate a bore.

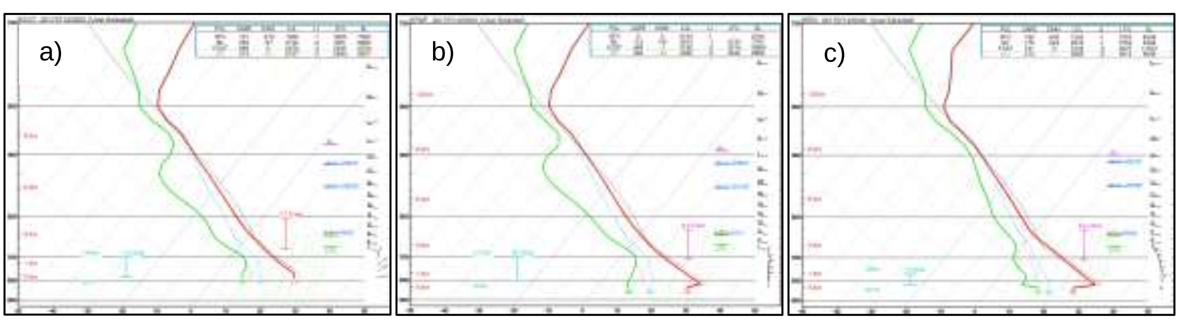

Figure 8 0300 UTC Hybrid soundings: a) Custer, SD (elev. 1707 m), surface-based CAPE of 101 J/kg, surface-based CIN of -219 J/kg, most unstable CAPE of 314 J/kg, most unstable CIN of -69 J/kg. b) Rapid City, SD (elev. 976 m), surface-based CAPE and CIN of 0 J/kg, most unstable CAPE of 265 J/kg, most unstable CIN of -46 J/kg. c) Pine Ridge, SD (elev. 1016 m), surface-based CAPE of 189 J/kg, surface-based CIN of -640 J/kg, most unstable CAPE of 214 J/kg, most unstable CIN of -127 J/kg

Acknowledgements

Archived radar data and RAP model analyses were retrieved from archives maintained by NCEI. Archived surface and upper air observations were accessed from archives maintained by MesoWest and the University of Wyoming, respectively. Sounding data were analyzed using the SHARPpy sounding analysis package. Elevation profiles created using Google Earth Pro.

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