CRARP 27-03

Terrain Influences on Severe Convective Storms Along the Pine Ridge from East Central Wyoming to Northwest Nebraska

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1. Introduction

Severe convective weather in the warm season is a common occurrence in the high plains. The storms in the high plains are produced primarily by synoptic and mesoscale features which have been described by Doswell (1980) and Maddox et al (1981). In addition to the weather parameters involved in producing severe convective weather, local terrain can also be a factor. The effects of the large scale Rocky Mountains on development of severe thunderstorms are well known. Since the early to mid 1980s, small scale terrain has been shown to have an effect on the development of severe convective weather, primarily revealed by the PROFS (Pratte and Clark, 1983) mesoscale network in northeast Colorado at that time. Most of the recent studies have concentrated on the small scale terrain in eastern Colorado. However, Benjamin et al (1986) ran a mesoscale model with a 20 km grid spacing over the central high plains from northern New Mexico to southern Wyoming using a homogenous southerly flow from data on 25 July 1983. From that numerical study, a cyclonic turning of the boundary layer winds was observed to the north of the Palmer Divide as well as to the north of the Raton Mesa and the Cheyenne Ridge.

This paper examines the effects of the Pine Ridge in northwest Nebraska, extreme east central Wyoming and extreme southwest South Dakota on severe thunderstorm development, and the possibility of a Pine Ridge circulation. First, the climatology of severe weather in the region is examined, which suggests a concentration of severe weather to the north of the Pine Ridge. A mesoscale model is then used to examine how the topography affects horizontally homogeneous flow in a way that may favor convective initiation and/or intensification in this region. Finally, a case study with the aid of a full physics mesoscale model illustrates a typical example of convective intensification possibly due to enhanced cyclonic vorticity in the vicinity of the Pine Ridge.

2. Terrain

The terrain of the high plains from northern New Mexico to central Wyoming and northwest Nebraska is generally downward sloping gradually to the east, with several west to east oriented ridges extending from the Rocky Mountains.

Figure 1 shows the area of study including the main west to east oriented ridges. Most previous studies have dealt with the Palmer Divide in east central Colorado. In similar fashion, the Pine Ridge extends from the northern Laramie range in east central Wyoming to northwest Nebraska (Figure 2).

The Pine Ridge is bordered on the south by the North Platte River valley and on the north by the Oglala grasslands of southwest South Dakota. The elevation of the Pine Ridge ranges from 4000 feet MSL to 5280 feet MSL, which is from several hundred to over a thousand feet higher than the terrain to the north or south. The Black Hills in western South Dakota are a large terrain feature starting about 60 miles to the north of the Pine Ridge. Figure 3 shows state and county boundaries.

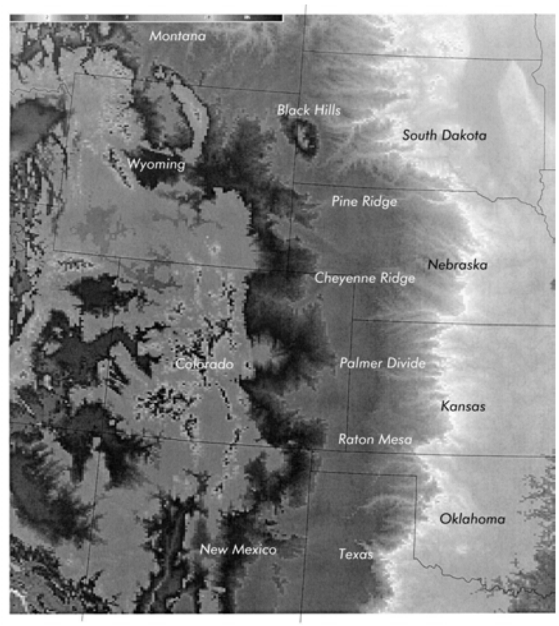

Figure 1 Topography of the western high plains

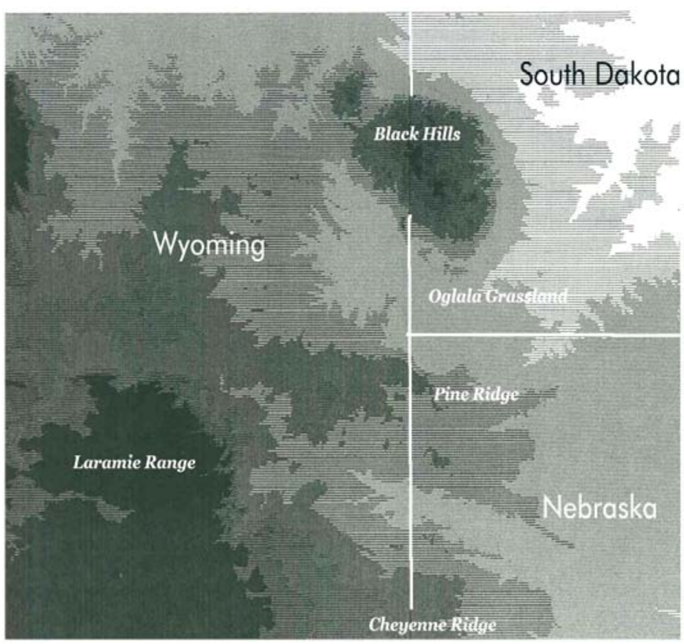

Figure 2 Topographic relief of area of study.

3. Climatology of Severe Weather in Northwest Nebraska

The area of study in northwest Nebraska and adjacent areas averages one third to one half of the summer days with thunderstorms Kessler (1982). Of those 5 to 10 % produce severe weather. As is the case with the entire high plains, the most active months for thunderstorms are May and June. They occur primarily from mid afternoon through late evening. Per Doswell (1980), the typical severe weather pattern is one with low level east wind flow, an unstable environment, low level moisture (dew points of 50F or more), a low level theta e ridge axis over the area and an approaching upstream shortwave trough. The greatest occurrence of severe weather takes place with northwest wind flow aloft and a southeast or east boundary layer wind flow after the passage of a cold front. Northwest Nebraska and nearby areas on some days appear to be favored for the development of severe convective storms and this paper will attempt to offer a partial explanation. Some of the more notable severe weather events in that area include the 5 inch diameter hail in Crawford on 15 July 1993 and the flash flood on the White River on 10 May 1991.

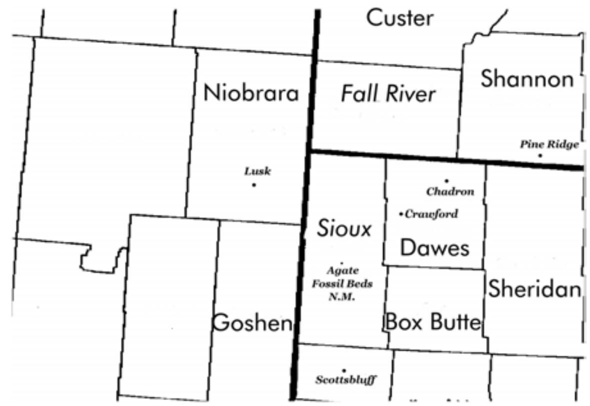

Figure 3 Geopolitical Boundaries for the study area.

4. Discussion and Hypothesis

In addition to the favorable synoptic variables for severe convection, terrain can aid storm development and provide surface forcing. The Pine Ridge in the study area and the Black Hills to the north both alter the boundary layer winds and possibly enhance convection in some areas. With the introduction of the PROFS mesonet in northeast Colorado in the early 1980's, low level wind circulations began to be observed. Szoke et al (1984) linked a low level wind flow in the Denver area with tornadoes in June of 1981. Wolczak and Glendening (1988) termed this low level circulation the Denver Cyclonic Vorticity Zone or DCVZ. Since that time, a number of studies have taken place in northeast Colorado relating the low level wind circulations at least in part to the area’s terrain. A cyclone of similar nature may form in the lee of the Pine Ridge.

The Denver Cyclone is defined by Wolczak and Glendening as a frequently observed, stationary, terrain induced mesoscale gyre located near the Denver metropolitan area which is often associated with the formation of severe weather. More specifically, the cyclonic low level wind flow in northeast Colorado is primarily caused by a southerly low level wind at ridge top level (around 800 mb) coming over the west to east oriented Palmer Divide in east central Colorado. The proximity of much higher elevation terrain to the west of this area also enhances the low level circulation.

Szoke and Augustine (1990) verified that indeed, many severe weather events in the Denver area occur with the Denver Cyclone. In fact, their study revealed that thunderstorms occur on 95% of the days when the Denver Cyclonic Vorticity Zone is present. The DCVZ provides a source of low level vertical velocity according to the study.

The effects associated with the Palmer Divide have been the most documented. Similar west to east oriented terrain exist in the central high plains. These include the Cheyenne Ridge and the Pine Ridge (Figure 2).

Our hypothesis is then that these ridges also produce a similar effect in southerly low level wind flow situations in the summer, with the corresponding increase in severe convective storms.

We realize that population density and locations of highways have large role in the ground truth detection of any severe weather (Hales 1985). This was a factor in the area of study and is discussed in the next section. However, in our area of study, there appears to be enough theoretical and observational information, as well as numerical studies, that support the possibility of a Pine Ridge circulation.

5. Examination of Plots of Severe Weather

To identify if there indeed is a concentration of severe convective storms in northwest Nebraska, and in adjacent areas of extreme east central Wyoming and extreme southwest South Dakota (Figure 3), Storm Data was examined from 1962-1991. The severe events are defined by the standard National Weather Service criteria for severe storms: three quarter inch diameter hail or larger, wind gusts to 58 mph or more, tornadoes and heavy rain resulting in flash flooding. The severe weather was then matched to low level flow direction and strength. Most of the events in the study area were associated with an east or south wind. All of the severe weather events in southerly flow (220 to 140) were then plotted in categories of wind strength. These categories were weak (10 kts or less), moderate (11-25 kts) and strong(>25 kts).

To obtain the locations of severe reports, the National Severe Storms Forecast Center database was accessed using the personal computer program SVRPLOT (Hart, 1993).

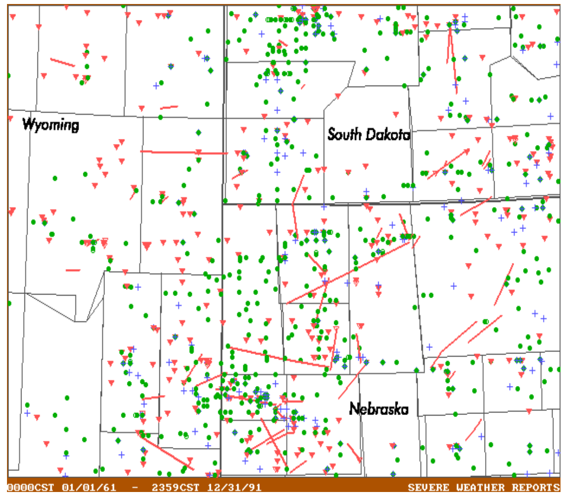

Figure 4. Locations of all severe reports for the period 1962 to 1991.

Figure 4 shows all severe weather reports over the northwestern Nebraska panhandle, southwest South Dakota and eastern Wyoming for the period 1962-1991. It is obvious from casual inspection of Figure 4 that population density had a role in the location of event reports. However, a slight, but perceptible, enhancement can be seen along and near the Pine Ridge.

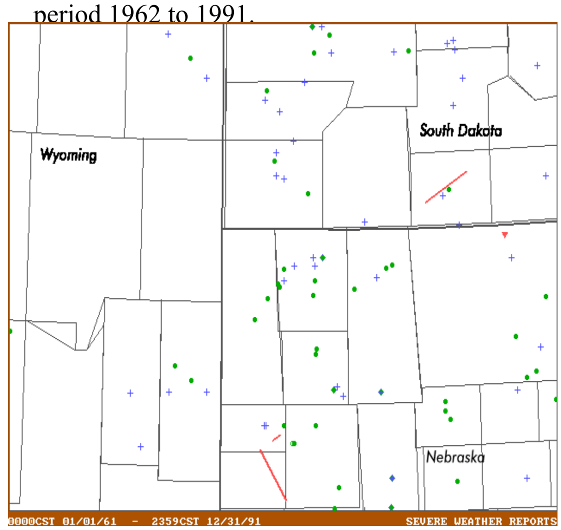

Figure 5. Locations of strong wind gusts, large hail and significant tornadoes for the period 1962 to 1991.

Figure 5 shows the location of reported wind gusts in excess of 65 knots, hail 3 inches in diameter or greater, or F3 tornadoes. A stripe of reports from central Sioux county to southern Dawes and Sheridan counties is along and near the Pine Ridge. The decreased number of severe reports surrounding this stripe lends credence to the idea that the Pine Ridge has some role in increasing the strength of severe convection. It is not clear if the secondary maximum in the number of reports meeting these criteria in southwest South Dakota is a function of the Pine Ridge or the Black Hills.

The next step was to see if there are certain atmospheric flow patterns which favored severe convection over the Pine Ridge. There were 334 separate calendar days in the period from 1962-1991 in which severe convection was reported along or near the Pine Ridge. All of the severe reports for the Dawes, Sheridan and northern Sioux counties of Nebraska were examined. Reports from Niobrara and northern Goshen counties in Wyoming as well as Fall River and Shannon counties in South Dakota were also examined, although we were more inclined to discard reports which clearly occurred well away from the ridge.

If there were three or more severe reports in a calendar day and they occurred in any of the counties along or near the Pine Ridge, surface and upper air patterns for that day were studied (NCDC 1994). If hail of 3 inches or greater in diameter was reported, the case was studied even if there were fewer than 3 reports that day. Sixty of the 334 days met these criteria.

A day was discarded from further review if it appeared that a surface front or a front aloft was in the area and appeared to be a major contributor to initiating and supporting convection. In limiting strong synoptic scale forcing, the effects of the ridge on convection itself could better be determined. A total of 37 days remained.

Types of wind flow from the surface to 700 mb was determined by using the global historical fields CD (Dept of Navy/DOC 1994) and the Radiosonde Data of North America CD (NCDC 1994, 1997) for each event. Low level wind flow was roughly in the layer from the surface to 850 mb, while mid-level flow was taken to be 700 mb.

Low level wind flow was then categorized as easterly, northerly or southerly. No westerly severe events occurred. Southerly wind flow was broken down into weak (10 knots or less), moderate (11-25 knots), or strong (greater than 25 knots). The choice of defining weak, moderate or strong flow thresholds was largely arbitrary, though the choice yielded roughly a normal distribution of severe reports.

Eighty three percent of the severe reports were associated with southerly flow (defined as winds from 220 to 140), while northerly flow and easterly flow accounted for the remaining 17 percent.

Figures 6-8 show locations of severe reports on a high resolution topographic map corresponding to light southerly flow, moderate southerly flow, and strong southerly flow.

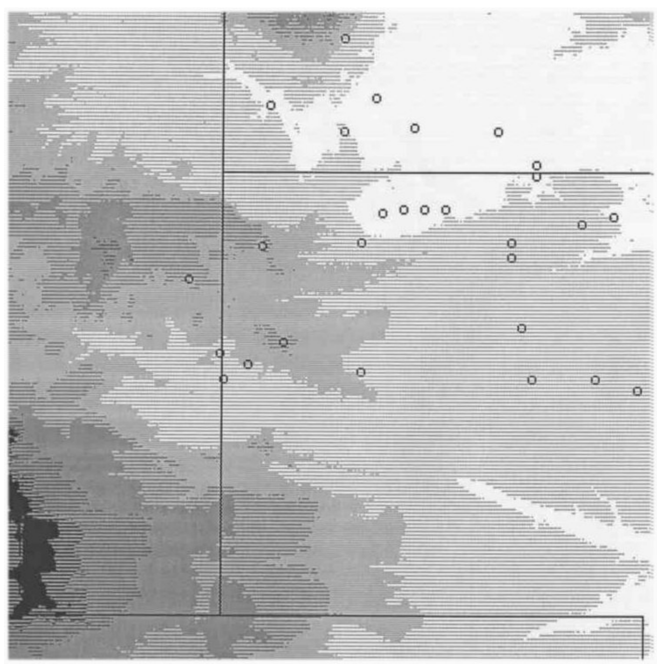

Figure 6. Plot of severe reports in the area of study from 1962-1991 with weak southerly boundary layer wind flow.

Note there is a tendency for severe weather to occur close to the ridge when southerly flow was light and that severe weather occurs further to the north (downstream) of the ridge as low level flow increased. This is consistent with the idea that convection formed over the ridge, but gets displaced farther downstream before the severe weather begins to occur. It also leaves open the possibility that a circulation forms in the vicinity of the Pine Ridge when a southerly flow blows across the Pine Ridge, and that alternatively the severe weather develops along the associated convergence zone, in a manner similar to the DCVZ.

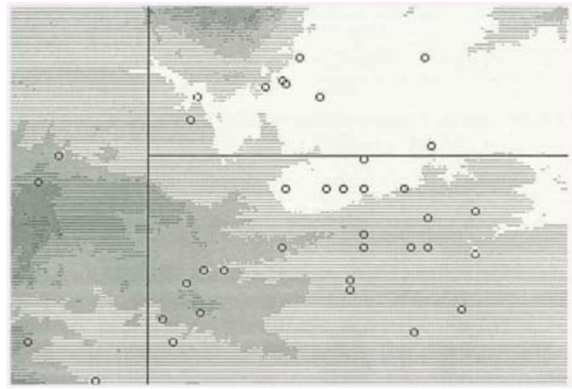

Figure 7. Plot of severe reports in the area of study from 1962-1991 with moderate southerly boundary layer wind flow.

6. RAMS Simulations with Homogeneous Southerly Flow

In order to examine whether and how the Pine Ridge might produce a low-level circulation akin to the DCVZ, a number of idealized simulations were performed on version 4.29 of the Colorado State University Regional Atmospheric Modeling System (RAMS; Pielke et al., 1992). Three two-way interactive nested grids were used: parent, intermediate, and fine grids. All were centered on the eastern Wyoming border, and square domains of 2400, 840, and 410 km on a side, respectively, and had grid spacings of 80, 20, and 5 km, respectively. Vertical grid spacing on all grids stretched from 150m at the surface to 1000m aloft, with the model top at about 17km. With this setup, the total domain was large enough so that lateral and top boundary effects did not affect the area of interest in low levels, and the finest grid could resolve mesoscale features down to about a 20 km wavelength. Topography on the finest grid is shown in Figure 9.

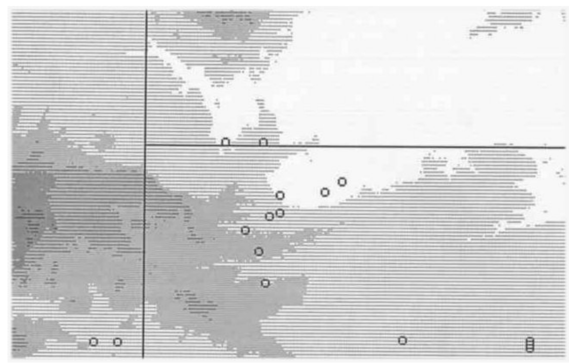

Figure 8. Plot of severe reports in area of study with strong south southerly flow.

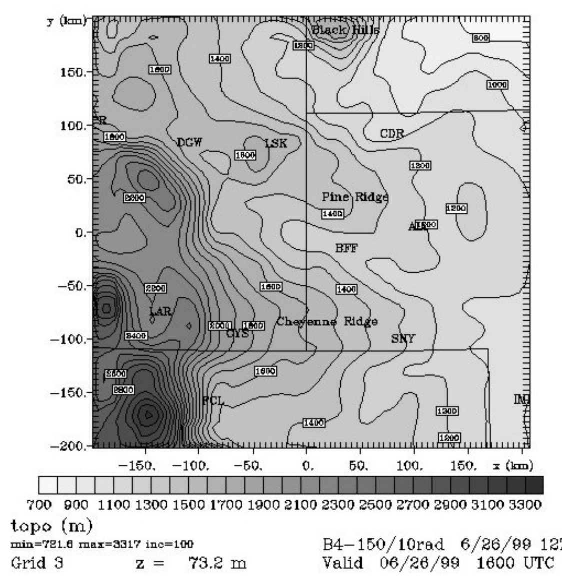

Figure 9. Topography of Study Area in the RAMS model

The model temperature field was initialized horizontally homogeneously based on a typical summertime morning sounding at North Platte, Nebraska on a day that severe convection later developed (1200 UTC 26 June 1999). It featured a very stable surface-based layer up to 800 mb and a near neutral layer above that up to 550 mb. The water vapor field was also initialized horizontally homogeneous from the same sounding, although no condensation was allowed in the simulations. Thus, effects were on buoyancy and radiation only. Soil moisture and temperature were initialized horizontally uniform in an 8 layer soil model based on observations at the same time at Nunn, Colorado, and the LEAF-2 surface/vegetation parameterization (Walko et al. 2000) was used.

Simulations were performed for a number of horizontally homogeneous wind field specifications, including uniform flow from either 180, 150 or 120-deg, at 5, 10 or 15 m/s. Runs with increasingly complex physics were made, with the most insightful being those that included coriolis force and a diurnal heating cycle with short and longwave radiation. Several runs with the same uniform flows at low levels veering to westerly aloft showed no strong effects in low levels due to shear. Therefore we restrict our discussion to the runs with uniform flow, coriolis, and radiation. With horizontally homogeneous initialization and coriolis, the initial pressure field is assumed to be in geostrophic balance with the initial wind field, and coriolis and pressure gradient forces are computed from ageostrophic wind and pressure deviations from the initial fields.

The simulations began at 12 UTC (05 LT), about 40 minutes after sunrise on 26 June at Pine Ridge. In these runs, the initial wind speed is quickly reduced by surface friction at low levels, becoming subgeostrophic and deviating slightly to the left. At the same time, surface heating induces an easterly upslope component to develop, leading to further leftward deviation from the southerly or southeasterly flow. For instance, 2h into the run with flow from 180-deg at 10 m/s (180/10 run), Fig. 10 shows streamlines generally deviating by 20-30-deg to the left, with speeds reduced by several meters per second.

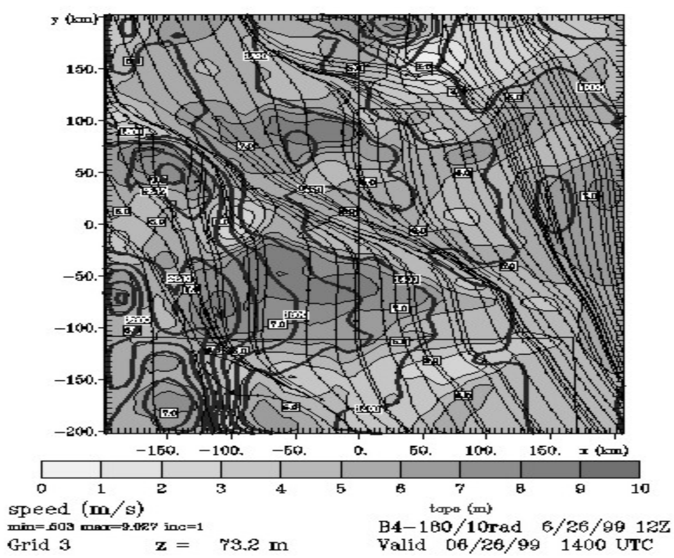

Figure 10. 1400 UTC plot of streamlines from 1200 UTC RAMS run.

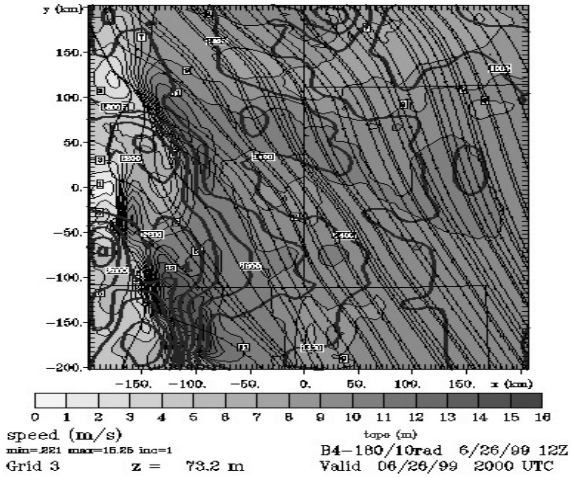

Figure 11. 2000 UTC plot of surface streamlines from 1200 UTC RAMS run.

There is greater speed reduction to the north of both the Pine and Cheyenne Ridges than on the ridges, along with a cyclonic turning of the winds more toward the west. This is because the stable layer is shallower over the ridges and mixes out faster due to surface heating, whereas the stable layer is deeper over the valleys between the ridges and remains capped longer by an elevated stable layer. As a result, turbulent mixing transports more of the relatively undisturbed momentum from aloft to the surface over the ridges, while the upslope component persists longer in the valleys.

As heating continues to erode the overlying stable layer over the valleys, the upslope component is reduced there and the flow becomes more uniform over the plains. However, reduced wind speed persists in the lee of the Pine Ridge, as shown 8h (early afternoon) into the 180/10 run

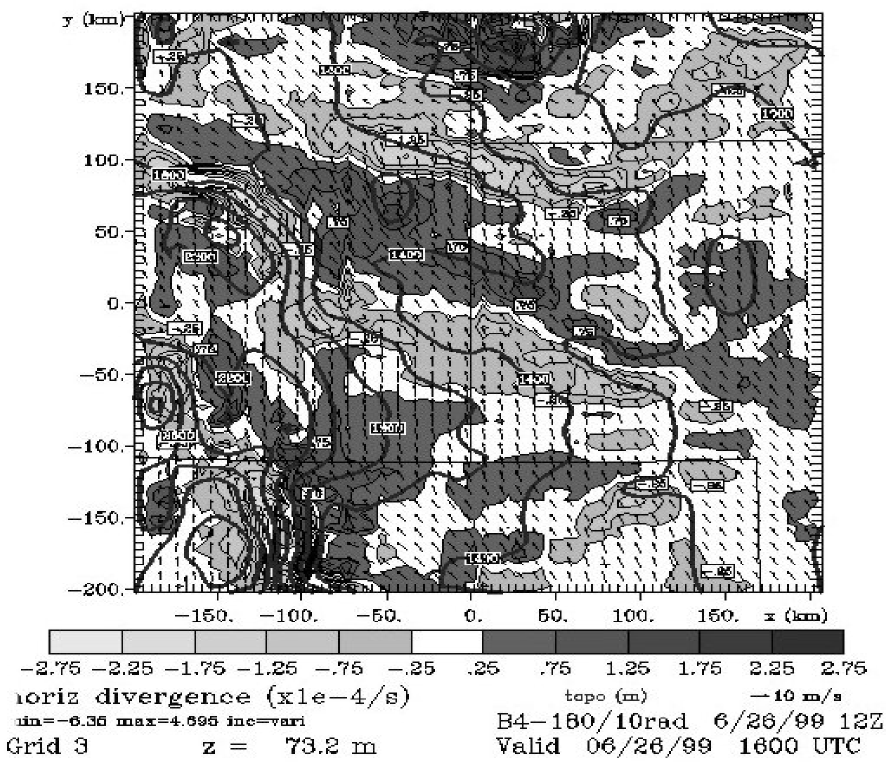

Figure 12 1600UTC plot of surface divergence from 1200 UTC RAMS run over study area.

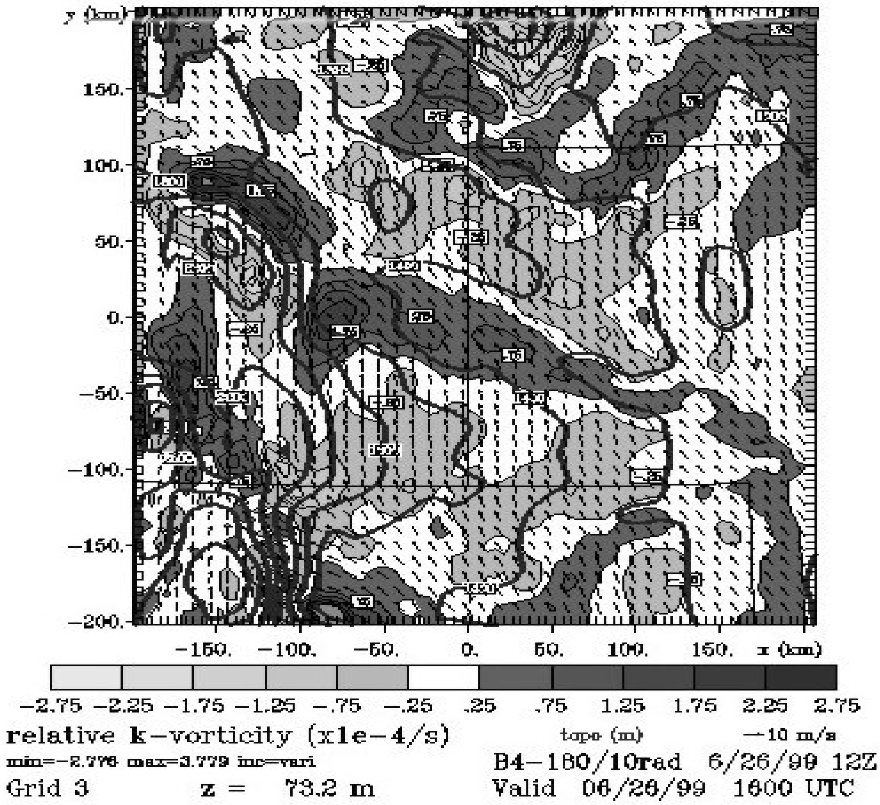

Figure 13 1600 UTC plot of surface vorticity from 1200 UTC RAMS run.

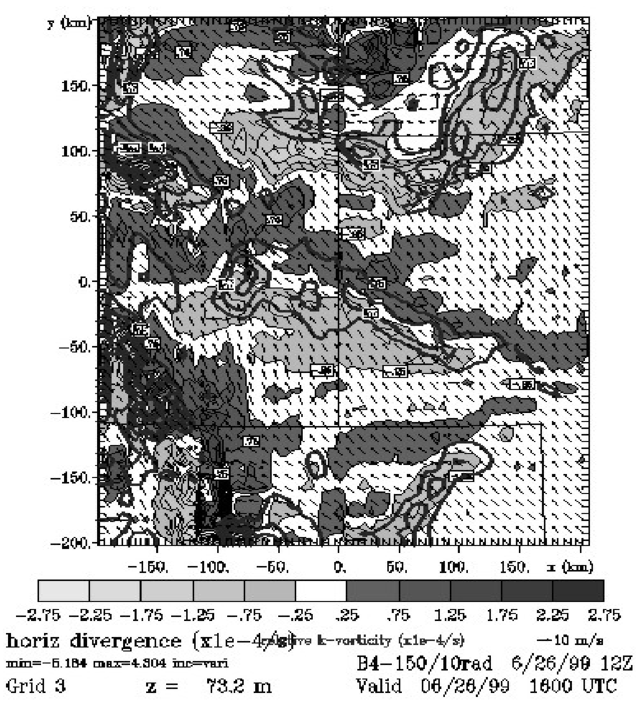

Figure 14 1600 UTC plot of surface horizontal divergence from 1200 UTC RAMS run.

Figure 14 1600 UTC plot of divergence and positive

As a result, a persistent low-level convergence zone develops in the lee of the Pine Ridge, as shown 4h into the 180/10 run in Figure 12.

The convergence in this region is stronger than that in the lee of the Cheyenne Ridge, due primarily to a local northeasterly upslope component in the former region that more strongly opposes the specified flow. A cyclonic vorticity zone as seen in the same region (Fig. 13), with a slight downstream shift from the convergence axis.
Results from runs with flows from other combinations of direction and speed were quite similar in producing convergence and cyclonic vorticity zones on the northern flank of Pine Ridge.

For instance, in Figure 14, the divergence and positive vorticity patterns 4h into the 150/10 run are very similar to those seen in Figs. 12 and 13. In general, convergence and cyclonic vorticity maxima appear to increase with the southerly component of the specified flow, although their locations vary slightly in the various runs.

However, all runs produced an axis of convergence along the northern flank of Pine Ridge from north of Douglas and Lusk, Wyoming (DGW and LSK in Fig. 1), east-southeastward to around Chadron, Nebraska (CDR), and turning northeastward into South Dakota (Figs. 10, 11 and 12). All runs similarly had an axis of cyclonic vorticity parallel to and shifted slightly downstream (north) from the convergence axis (Figs. 10 and 11). The convergence maxima are similar in magnitude to those analyzed in the DCVZ on days with tornadic thunderstorms, while the Pine Ridge vorticity maxima are about half the magnitude of the DCVZ vorticity maxima. (Szoke et al. 1984; Szoke and Brady, 1989).

Thus it appears that a zone of convergence and cyclonic vorticity along the north flank of the Pine Ridge could act to initiate and/or intensify convection on days with southerly to southeasterly flow in a manner that has been documented with the DCVZ.

7. Case Study of the May 29-30 1998 Event

In the late afternoon of May 29, 1998, thunderstorms initiated along the northern portion of the Laramie Range in south central and southeast Converse County. These storms gradually became more intense as they moved to the east-northeast through southern and eastern Niobrara County and finally into the northwest Nebraska panhandle. Several of those storms became severe by 02 UTC in the northwest Nebraska panhandle and extreme southwest South Dakota and remained severe until the early morning hours of May 30, 1998. During the event, southerly boundary layer wind flow to 30 knots was present, making the event possibly caused or aided by the Pine Ridge circulation.

During the time that severe weather was occurring, most of the events were hail. In those areas, hail size ranged from three quarters of an inch to two and three quarters of an inch near the town of Pine Ridge, SD. Storms moved off to the northeast, with continued development on the west portions in northwest Nebraska until around 06 UTC. A brief description of the synoptic data will be given along with WSR-88D Archive 4 data from the radar near Rapid City, SD (KUDX). In addition, the operational RAMS forecast model was run for this event several months later for this case study, and will be discussed.

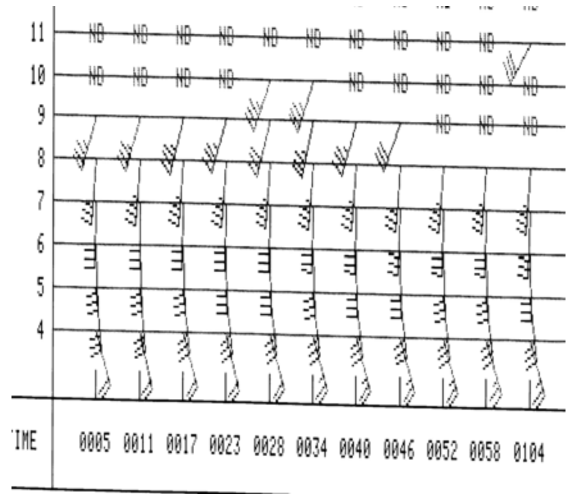

Figure 15 KUDX VAD wind profile from 0005 UTC until 0104 UTC on May 30, 1998 read from left to right.

Briefly, southwest flow at 700 mb and above was over the high plains during the afternoon and evening of May 29, 1998 (including the Pine Ridge study area). A shortwave trough within that wind flow aloft was located from central Wyoming to north central Colorado at 00 UTC on May 30, 1998 (not shown) and moved east of the study area by 09 UTC. During that same time, surface low pressure was over southeast Montana with a low pressure trough extending into extreme eastern Wyoming (not shown). Surface dew points in western Nebraska were around 10C during the afternoon and evening.

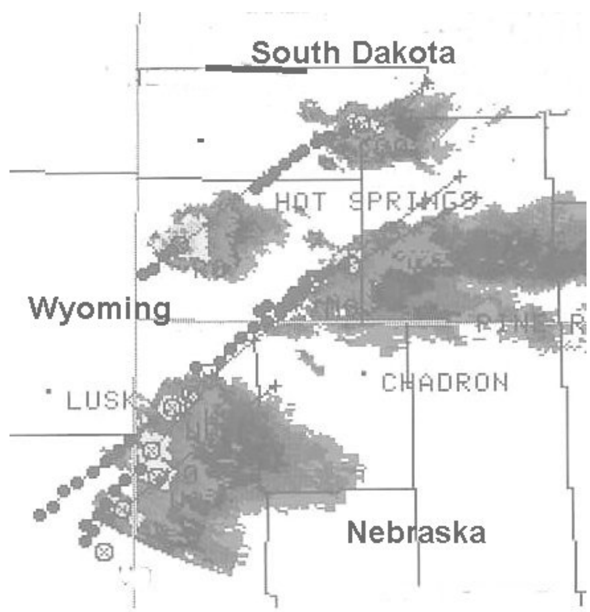

Figure 16 KUDX 0.5 degree Base Reflectivity at 02 UTC.

Archive 4 88D radar data was obtained for the event from the radar site near Rapid City, SD (about 60 miles from the Pine Ridge).

The VAD wind profile from KUDX (Rapid City) the early evening of May 30, 1998 indicated winds at the lowest gate from 160 at 20 kts (Figure 15), with the winds increasing in the early evening. At the 850 mb level, the VAD wind profile had winds from the south. By 06 UTC, the winds were from the south (180) at the surface and up through the 850 mb level at speeds of 30 kts (not shown). Winds between 700 mb and 500 mb were from the west-southwest at 35 kts during the evening. Two separate areas of severe convection had developed by 02 UTC (one near the southeast edge of the Black Hills and the other over the northwest Nebraska panhandle) as seen in Figure 16.

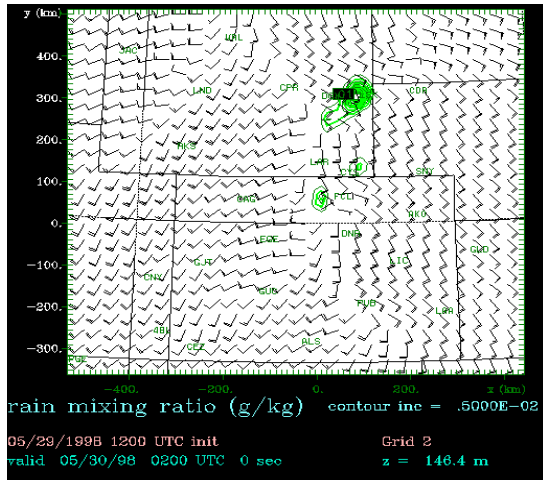

Figure 17 RAMS forecast valid 02 UTC on May 30, 1998.

Between 0215 UTC and 0305 UTC, three-quarter to one inch diameter hail fell at Agate Fossil Beds National Monument. In the southwest corner of South Dakota, the city of Edgemont recorded two and one-half inch diameter hail at 0215 UTC. Backbuilding of the storms took place between 03 UTC and 06 UTC mainly over Sioux and Dawes counties in northwest Nebraska.

The RAMS simulation for this case study utilized the realtime operational version of RAMS in use at the time (Nachamkin et al. 1999), initialized at 12 UTC 29 May 1998. It featured a nested 12 km regional grid and used a single-moment bulk microphysics scheme. The simulation depicted well the intense thunderstorms (Figure 17), but by 02 UTC had the storms still in Niobrara County, Wyoming, a little further west than observed. Note the turning of the boundary layer winds to more easterly at this time to the north of the Pine Ridge on the RAMS output. This cyclonic curvature of the boundary layer winds to the north of the Pine Ridge from RAMS existed during the entire evening of May 29, 1998. By 03 UTC, the RAMS had the severe thunderstorms extending from extreme southwest South Dakota to northern Sioux County and back into Niobrara County (not shown).

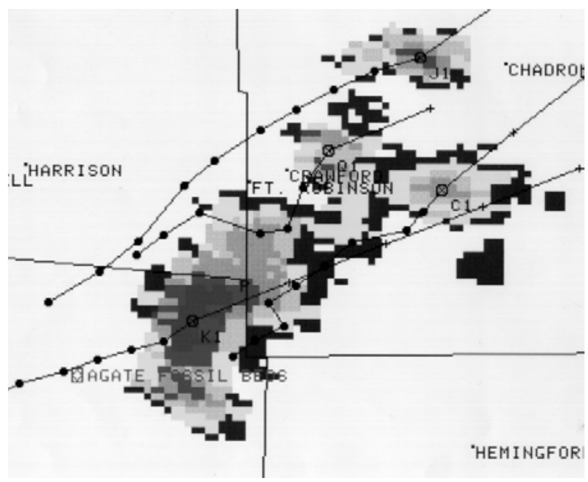

Figure 18 KUDX 0.5 degree Base Reflectivity from 04 UTC.

By 04 UTC, the severe thunderstorms in southwest South Dakota had moved northeast and were about 30 miles to the north of Pine Ridge, SD. The severe storms in northwest Nebraska at that time were located over east central Sioux County and western Dawes County (Figure 18).

By 0412 UTC, the strongest part of the activity in northwest Nebraska was in the southwest corner of Dawes County and had taken on a more bowed shape (not shown). This severe cell moved almost straight east, to the right of the mean flow and general movement. At 0442 UTC, that cell was in south central Dawes County, with another severe storm moving just to the north of Crawford and Fort Robinson, which may have formed on an outflow boundary from the cell to its southeast (Figure 19).

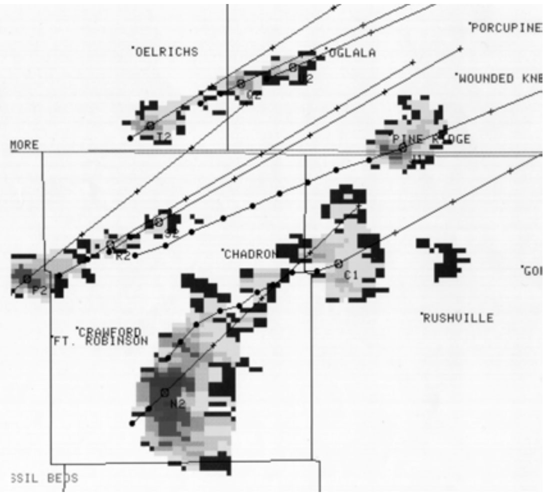

Figure 19 KUDX 0.5 degree Base Reflectivity from 0442 UTC.

No reports of severe weather were received after 04 UTC in the northern Nebraska panhandle. RAMS data valid at 04 UTC (Figure 20) depicted the severe thunderstorms from north of Chadron (in South Dakota) to eastern Niobrara County (not shown), continuing to be a bit further west than observed.

All of the activity shifted slowly to the east and by 0522 UTC, the strongest cells were in extreme east central Dawes County (to the southeast of Chadron) and about 10 miles north of Crawford (Figure 21). Twenty minutes later, severe storms existed in north central and northeast Dawes County (not shown).

Finally, at 0645 UTC, the severe storms had moved into southern Shannon County, SD (not shown). RAMS for 06 UTC had all of the severe thunderstorm activity to the north of Chadron, in southwest South Dakota (not shown). The thunderstorms produced severe weather in southwest South Dakota after this time, with one inch diameter hail at Oglala at 07 UTC and two and three quarter inch diameter hail, five miles north of Pine Rdige at 0715 UTC.

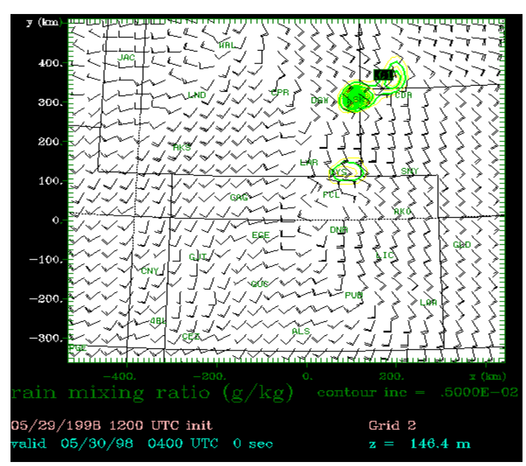

Figure 20 RAMS forecast valid 04 UTC.on May 30, 1998.

This case study was an example of a Pine Ridge circulation, aiding in the development and movement of severe convection. The RAMS model run for 12 UTC May 29, 1998 did very well at depicting the location of the severe convection during the entire event as well as the cyclonic turning of the boundary layer winds to the north of the Pine Ridge. Synoptic scale models for both 12 UTC May 29, 1998 and 00 UTC May 30, 1998 had a much broader and less detailed QPF forecast for the evening.

8. Conclusion

Reports of severe weather over the Pine Ridge show some increase in the number of reports as well as a tendency for larger hail, stronger winds and occurrence of tornadoes than surrounding areas. This suggests that the Pine Ridge has an effect on the initiation and strength of convection over and near the ridge. Knowing that flow across the Palmer Divide has been shown to result in a mesocyclone (and has been correlated with a large percentage of the severe weather in and around metropolitan Denver), it seemed possible that such a circulation could be initiated by southerly flow across the Pine Ridge.

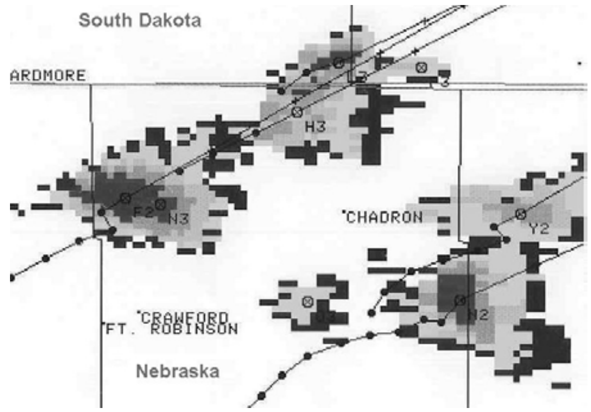

Figure 21 KUDX 0.5 degree Base Reflectivity at 0522 UTC.

A simple application of the RAMS model with southerly flow over the ridge and a typical summertime temperature profile revealed a zone of convergence and positive vorticity to the north of the ridge that is somewhat analogous to the Denver circulation. When supplied with the data from 12 UTC on the morning of May 29th, the RAMS model developed a cyclonic circulation over the ridge during the day and did an acceptable job in the position and strength of afternoon and evening convection.

9. Acknowlegements

The authors would like to thank Mr. David Copley SOO at WFO Cheyenne and Ms. Valerie Scheele for their efforts in reviewing the document and their assistance with the graphics.

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