TRANSITION OF CONVECTION FROM THE MOUNTAINS TO THE PLAINS ALONG
THE COLORADO FRONT RANGE AS DETECTED BY TDWR

A Thesis in
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by
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ABSTRACT

The relationship between primary convection over the mountains and secondary convection over the plains is examined along the Front Range of northeastern Colorado. Data collected from the Federal Aviation Administration Terminal Doppler Weather Radar indicate that thunderstorms over mountainous terrain typically produce plains thunderstorms by one of three mechanisms, or transition modes: initiation along convergent outflows, propagation along existing convergence lines, and propagation behind well-developed cold pools. Analysis of sounding data indicates which temperature and wind profiles favor each mode. The results of this study have the potential to be used operationally in short-term forecasting.
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Chapter 1

Introduction

Warm-season convection in northeastern Colorado has been studied quite extensively since the 1970s. It is a topic of importance to the population of the Denver area, and particularly to aviation interests throughout the region (Rhodes, 1992). New operational instrumentation systems such as mesonetworks (Beran and Little 1979; Wilson et al., 1988) and Doppler radar (Wilson et al., 1988; Lang, et al., 2004) have provided new perspectives as well as ever more detailed observations. In the present study we examine the advantages of using the Federal Aviation Administration Terminal Doppler Weather Radar (TDWR) (Turnbull, et al., 1989) to observe, analyze, and predict warm-season convection in the region.

Karr and Wooten (1976) were among the first to study the cycle of summer convection in this area. They observed in radar imagery a consistent diurnal cycle of thunderstorms which were first detected over the mountains in the late morning, then over the plains in the afternoon.

Toth and Johnson (1985) used the Prototype Regional Observing and Forecasting Service (PROFS) mesoscale network of surface sensors (Beran and Little, 1979) to analyze diurnal patterns in the surface flow for the high plains of northeastern Colorado. They found cycles in the location of surface convergence zones to be related closely to the daily cycle of thunderstorm formation, which usually begins either along the Continental Divide or the more gradual ridges which jut east into the plains. They, too, found that convection subsequently moved east over the plains.

Using primarily satellite data, Banta and Schaaf (1987) explored convection initiation over the mountainous terrain of Colorado and evaluated its dependence on wind direction at the ridge tops. The resulting thunderstorms, which typically begin before 1100 Local Solar Time,
were referred to as primary convection. The authors suggested that the outflows from these storms could later contribute to the initiation of so-called secondary convection on the plains to the east. This mechanism could not be observed by satellite, however, because of the obscuring layer of cirrus which tends to emanate from the primary convection.

The importance of surface convergence in the initiation of thunderstorms is noted in many studies. Purdom (1976) showed that thunderstorms frequently initiated at the intersection of convergence lines, which can be formed from convection initiated over elevated terrain. These convergence lines were detected as cloud arcs in satellite imagery, but have since been detected as convergent flow in surface mesonetworks (Toth and Johnson, 1985; Wilson and Schreiber, 1986) and as thin lines of enhanced radar reflectivity (Wilson and Schreiber, 1986; Wilson and Mueller, 1993). Convergence has also been studied in association with phenomena more unique to northeastern Colorado such as leeside convergence zones (Schreiber-Abshire and Rodi, 1991) and the Denver Convergence-Vorticity Zone (Szoke, et al., 1984).

In the present study, we aim to use the Denver TDWR to further examine the connection between the thunderstorms observed over the mountains of Colorado’s Front Range during the morning and those that affect the plains later in the day during the warm season. We also determine the environments in which the transition of convection from the mountains to plains is most likely. Ultimately, we suggest methods for observing and forecasting these transitions operationally.
Chapter 2

Data

For this study, we wish to observe and record the mechanisms by which primary convection over the mountains transitions to secondary convection over the plains. Radar is a convenient observation platform for this as it provides, from a single source, data with fairly high spatial and temporal resolution over a large domain. We use the data from the Federal Aviation Administration Terminal Doppler Weather Radar (TDWR), located near Denver International Airport.

TDWR was chosen over the National Weather Service WSR-88D for some advantages in resolution and for other features that benefit this study. The TDWR performs a full scan every 6 minutes, regardless of the operating mode. The WSR-88D matches this for its precipitation mode, but scans only every 10 minutes otherwise. Spatially, the TDWR has a 0.55 degree beam width and range resolution of 150 meters for reflectivity and velocity, all comparable or superior to the specifications for WSR-88D. The beam width in particular can be crucial to avoid beam-filling issues when tracking boundary layer echoes. The reflectivity range for the TDWR is 297 kilometers; this is less than that of WSR-88D but is more than sufficient for the area examined in this study (Stern et al., 2003).

The TDWR has a transmitter wavelength of 5.3 centimeters, which lies in the C-band. Other weather radars, such as the WSR-88D, transmit S-band wavelengths (around 10 centimeters). In the TDWR returns, thin lines of reflectivity less than 15 dbZ are frequently observed at low radar elevations, especially during the day in the summer season. The presence of these thin lines has been attributed to the convergence of particulate matter, insects, birds, and plant material, as well as moisture inhomogeneities, although scattering from insects is likely the
main source of reflectivity in clear air for this C-band radar (Wilson and Schreiber, 1986; Christian and Wakimoto, 1989; Achtemeier, 1991; Wilson et al., 1994). The insects, and therefore the convergence lines into which they are concentrated, are better detected with the C-band TDWR than the S-band WSR-88D (Wilson, et al., 1980).

TDWR data are available for download from the National Climatic Data Center website <http://www.ncdc.noaa.gov/nexradinv/>. Visualization of these data is facilitated by the National Oceanic and Atmospheric Association Weather and Climate Toolkit which is also available online.

Radiosonde data are used to determine environmental characteristics which may be correlated to the radar observations. We use the data from the National Weather Service balloon launch from Denver, Colorado. These data are archived online by the University of Wyoming Department of Atmospheric Science <http://weather.uwyo.edu/upperair/sounding.html>. 
Chapter 3

Methods

TDWR data were acquired for the months of May through September 2009, the only warm season for which data was available at the start of this study. We visually inspect the radar data for days on which a thunderstorm is reported in the daily climatological report for the Denver International Airport. The long-range reflectivity scan must be used to detect thunderstorm initiation over the mountains and foothills to the west of the radar site. This scan is performed with a 0.6 degree tilt and provides a range of 297 kilometers, although the weather of interest for this study occurs within 125 kilometers of the TDWR. Conveniently, this long-range scan is performed at regular 6 minute intervals regardless of the operating mode of the radar.

For each of the thunderstorm days, the TDWR data are examined from 1500 UTC to 0700 UTC the following day (8AM to 12AM Local Standard Time). This time interval should cover the entire cycle of convection as outlined by previous studies (Karr and Wooten, 1976; Banta and Schaaf, 1987). If the thunderstorm is reported outside of this interval, the data for that day are not examined as storms out of phase with the diurnal cycle are apt to be synoptically forced. Likewise, because we are concerned with the transition of convection from the mountains to the plains independent of large scale forcing, we only consider days when storms are first observed over the mountains and later detected over the plains. We discard the days on which precipitation is present in the first radar image or on which precipitation moves into the focus area from elsewhere. Few days were lost to these restrictions because these warm season months are generally characterized by weak synoptic forcing and thunderstorm initiation occurs mainly due to daytime instability. Also discarded are days when radar data are missing immediately before the first detection of precipitation associated with either primary or secondary convection.
Of the 63 days on which a thunderstorm was reported at the Denver International Airport, 43 days have complete TDWR data that satisfies our criteria. For each of these 43 days, we record the time and location of primary initiation over the mountains, the type(s) of mountain-to-plains transition (discussed later), and the time and location of the first observed secondary initiations if there are any. We use the Weather and Climate Toolkit to visually inspect and record these phenomena, following a set of rules.

When inspecting the long-range TDWR reflectivity, we record the time at which the first echo of at least 20 dBZ is detected over the mountains. It is common to find returns of up to 15 dBZ over a large area near the radar, but it is most likely that these returns are mainly from insects as described in Data. Convective precipitation is very simple to differentiate visually from clear air returns as it always exceeds our threshold substantially and propagates as a thunderstorm cell. We do not require the cell to be maintained for a long period of time to be recorded, but its presence does have to be evident in at least one subsequent radar image to ensure that it is not a false return.

A minor issue for identifying precipitation in the reflectivity imagery comes from returns due to terrain, i.e. ground clutter. At the elevation angle of 0.6 degrees, the radar beam intersects some of the higher ridges of the Continental Divide (Figure 1). The returns from this source are stationary, so they are easy to filter out, but they obscure some true precipitation returns. We assume the errors due to this are small as new thunderstorms generally move quickly enough to be identified around their time of initiation.
Figure 1. Reflectivity from Denver TDWR (location indicated by magenta dot, left middle) at a time with no precipitation. dBZ color scale is provided. Labeled white dots indicate the locations of, from top to bottom, Fort Collins-Loveland Municipal Airport, Denver International Airport, Centennial Airport, and City of Colorado Springs Municipal Airport. The radar receives returns from higher mountains (reds, 50 to 60 dBZ) and foothills (blues and greens, 10 to 30 dBZ) which the 0.6 degree elevation beam intersects at least partially.

In addition to recording the time of the first detection of precipitation, we note the latitude and longitude of the first cell. The location that we use is that of the highest reflectivity within the cell. If multiple cells appeared in the same scan, we record the location of the strongest.
The primary objective of this study is to observe the relationship between the early mountain convection and the secondary thunderstorms later in the day over the plains. From our inspection of the reflectivity, it appears that this primary convection transitions to secondary convection by three distinct modes. While there some days on which no relationship between mountain and plains convection could be detected with the TDWR data, a majority of days show a clear connection between the two.

On most days, the cells we observe will initiate over the mountains and propagate eastward toward the plains, but fail to be maintained as they cross the fairly sharp interface between these two types of terrain. Those cells that are maintained usually either propagate eastward in association with a cold pool or along a preexisting east-west oriented convergence line on the plains. We treat these two mechanisms separately when recording the type of transition. The third primary-to-secondary transition is more indirect and occurs when surface outflows from mountain convection interact with convergence lines preexisting on the plains. We examine the radar data for each of these transition modes independently. These modes are not mutually exclusive, so there are some days when all are observed and there are some days when none are observed.

When recording instances in which the transition of convection takes place by interaction of outflows and convergence lines, we first look for outflows from the primary convection. The outflow is seen as an arc in the radar imagery that propagates radially away from a cell. Following the same rules as we did for the primary initiations, we record the time and location of the storm producing the outflow. We also record the time and location of the first initiation of a thunderstorm along that outflow. We are only concerned with outflows when at least one of them originates from cells over the mountains. There are frequently interactions between two or more outflows originating on the plains, but these do not represent the transition in which we are interested. Secondary initiations usually occur where the radar-indicated convergence line
associated with the outflow intersects another convergence line which is preexisting over the plains. Because we cannot assume to detect all convergence lines, we consider any secondary initiation occurring along an outflow convergence line to be an “intersection” transition, even if an obvious intersection does not take place.

We notice while inspecting the radar data that the cells which are more likely to survive as they move over the plains are those that follow preexisting convergence lines on the plains. This transition mechanism was noted by Wilson and Schreiber (1986) and is easily detected by the TDWR. We call these “track” transitions because the cells appear to follow a convergence line as a train would follow a track. Storms that use this type of transition are also observed to have a tendency to develop rotation; this is discussed in Discussion.

To determine if a thunderstorm transitions in association with a cold pool, we begin by looking for outflow from primary convection like we did for intersection transitions. If the cell from which the outflow originates is able to propagate from the mountains to the plains, we tag it as a “cold pool” transition. These transitions often mark the birth of a mesoscale convective system (MCS), a connection which is discussed later.

With a complete set of data analyzed from the radar, we may now attach the environmental parameters that we collect from the radiosonde data. For each day of interest we use the 12UTC sounding from the Denver International Airport. This morning sounding captures the environment before it is altered by convection later in the day, so it may provide insight into what conditions tend to precede each of our convection transition modes.

The radiosonde parameters which we use in our analysis are the temperature, dew point depression and winds from the surface, 700 millibars, and 500 millibars. From these parameters we can derive wind components, layer shear, and layer lapse rates. We recognize that the 12UTC surface conditions are not representative of the conditions throughout the day nor do they apply to our entire domain, much of which has a much higher surface altitude. We will mainly use surface
temperature to evaluate the morning static stability in the layer between the surface and 700 millibars. 700 millibars roughly represents the ridge top height for most of the mountains in our domain.

With our combined data set of radar observations and radiosonde parameters, we wish to calculate statistics for comparing and contrasting the conditions that favor each transition mode. In the interest of being able to visually examine the data, we create box plots for each parameter. These plots are made for each transition mode separately and they display the median, upper quartile, lower quartile, the tenth percentile and the 90th percentile.

Due to the relatively small sample size for this study, the bootstrapping method is applied to provide non-parametric confidence intervals for all calculations (Efron, 1979; Burnham and Anderson, 2010). We provide the 95 percent confidence interval in parenthesis following every bootstrapped statistic. This bootstrapped confidence interval is created by randomly selecting \( n \) elements with replacement from a set of size \( n \), then calculating and recording the desired statistic (median, upper quartile, lower quartile, etc.) for this randomly selected set. The process is repeated until there are 10,000 records of the desired statistic. After ordering these statistics, the 250\(^{th}\) and 9750\(^{th}\) values represent the bounds of the 95 percent confidence interval.
Chapter 4

Results

Cold Pool Transition Mode

In our examination of the bootstrap box plots for environmental parameters (hereafter parameter statistics) associated with the cold pool transitions, we notice that there is a significant association between this transition mode and the 700 millibar temperature (Figure 2). On days when the cold pool transition was observed, the 700 millibar temperature tended to be much higher than on those when cold pool transition did not occur. We hypothesize that this temperature signal reflects a difference in the stability profile, so we present the layer temperature differences as a more direct lapse rate proxy.

For the eight days when cold pool transition was observed the median temperature difference between the surface and 700 millibars was also significantly different between days with cold pool transitions and those without (Figure 3). The less substantial temperature difference between the surface and 700 millibars on cold pool days represents greater static stability in this layer at the sounding time\(^1\), suggesting two hypotheses:

- Stronger lid near 700 millibars restricts initial convection to the mountains, setting the stage for cold pool transition by curtailing competing mechanisms. Moreover, the lid is strong enough to prevent triggering along the gust front, but not over the deeper interior of the cold pool. See the radar case study below.

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\(^1\) Boundary layer evolution is to be expected between the morning sounding time that we use for calculating the stability parameters and the convective transition time. This issue is further discussed in *Conclusions*. 
• Alternatively, warmer air at 700 millibars may be related to dry (continental tropical) air at that level, resulting in thermodynamically favorable conditions for downdraft-fed cold pool formation.

The temperature difference between 700 millibars and 500 millibars also reflects the warmth at 700 millibars. The median temperature difference from the bottom of this layer to the top is more negative (less stable) for days with cold pool transitions than for those without, again suggesting the presence of continental tropical air aloft (Figure 4). This box plot indicates that although the difference in the median values is small, it is significant due to the limited range into which these temperature differences usually fall.

Other parameters that are (marginally) supportive of the second hypothesis are the 700 millibar dew point depression and the 700 millibar to 500 millibar shear magnitude. The 700 millibar level tends to have a greater dew point depression for the days with cold pool transition, as expected for a continental tropical air mass (Figure 5). The 700 millibar to 500 millibar shear is low on days with cold pool transitions (Figure 6). This is likely due to weak 500 millibar winds which yield slow storm motion and stronger cold pools as described later in the section on intersection initiations.
Figure 2. Box plots for 700 millibar temperature (given in degrees C). “True” columns show bootstrapped statistics for the 8 days on which cold pool transition was observed, “False” for the 35 days with no cold pool transitions. Whiskers represent the 90th and 10th percentiles, the box is bounded by the upper quartile and lower quartile, and the middle bar in the box plot is the median. Markers to the right side of the box plots indicate the bounds of the 95% confidence interval for the median. Numerical values for these statistics and 95% confidence intervals are given to the left of the plots.
Figure 3. Box plots for surface to 700 millibar temperature difference. As in Figure 2.

<table>
<thead>
<tr>
<th></th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>90th</td>
<td>0.1 (-1.1, 0.6)</td>
<td>-1.5 (-2.6, -0.8)</td>
</tr>
<tr>
<td>UQ</td>
<td>-0.6 (-2.4, 0.6)</td>
<td>-2.6 (-3.0, -1.6)</td>
</tr>
<tr>
<td>Median</td>
<td>-1.9 (-3.2, 0.0)</td>
<td>-3.6 (-5.0, -2.8)</td>
</tr>
<tr>
<td>LQ</td>
<td>-3.0 (-4.6, -1.5)</td>
<td>-5.8 (-7.2, -4.0)</td>
</tr>
<tr>
<td>10th</td>
<td>-3.9 (-4.6, -2.4)</td>
<td>-7.3 (-8.0, -6.0)</td>
</tr>
</tbody>
</table>
Figure 4. Box plots for 700 millibar to 500 millibar temperature difference. As in Figure 2.
Figure 5. Box plots for 700 millibar dew point depression. As in Figure 2.
Example Case: July 13, 2009

The clearest example of a cold pool transition in our data occurs on July 13, 2009. On this day, mountain convection is first detected at 1701 UTC over the foothills west of Denver, about 70 kilometers west of the TDWR site (Figure 7a). Several cells develop in this area but quickly dissipate as they move east away from the elevated heat source. At 1845 UTC, a particularly intense cell with reflectivity greater than 60 dBZ exists in this area west of Denver. In the following time steps, the outflow from this thunderstorm becomes evident as an arc of light radar returns propagates eastward ahead of the cell (Figure 7b). Unlike previous cells, this one is maintained for longer than an hour as it propagates eastward over the plains behind the leading edge of the outflow cold pool (Figure 7c). The cell finally dissipates as the cold pool outruns it to
the east and new cells develop closer to the leading edge of the cold pool. Several more cells follow a similar life cycle as they develop over the mountains and propagate onto the plains behind arcs of radar reflectivity. The consistency with which the convection trails the leading edge of the cold pool is consistent with the first hypothesis above.

After 2000 UTC, the cold pools from multiple cells appear to merge, and the associated convection coalesces into a MCS which is maintained as it moves eastward out of radar range (Figure 7d). The evolution of MCSs is common among our cold pool transition cases. Several reports of damaging wind and small hail were reported with this system. A couple of these reports come from our study area, and many more come from later in the evening when the system moved over the state of Kansas (Figure 8).

The 1200 UTC environmental parameters for July 13 are shown in Table 1. For all five parameters that our box plots suggest to be associated with the cold pool transition mode, July 13 fits better with the days on which we do have cold pool transitions than with those without. Alone, this is not particularly notable as the data from July 13 is one of only eight sets contributing to our statistics. What is more notable is that we qualitatively refer to this case as the clearest example of the cold pool transition and we also quantitatively see the most extreme values for 700 millibar temperature and surface to 700 millibar temperature difference. It may be possible to infer a relationship between these numerical parameters and the prominence of the cold pool transition mode, but more cases would have to be examined to be certain.
Figure 7. Reflectivity maps from Denver TDWR on July 13, 2009. a) 1757UTC: Small cells begin to develop over the mountains and foothills (circled). b) 1857UTC: Intensifying convection (circled) and gust front convergence line (irregular blue, highlighted with arrows). c) 1945UTC: Continued convection (circled) and gust front convergence line (thin blue, highlighted with arrows). d) 2056UTC: Convection moves to the east as an MCS with leading gust front.
Figure 8. Storm reports from July 13-14, 2009. Green triangles represent reports of hail at least .75 inches in diameter. Blue squares represent reports of wind damage. The UTC time of the report is given next to each marker. Shading on the left side represents the higher terrain of the Palmer Divide and Continental Divide.

Table 1. Comparison of median environmental parameters for days with and without cold pool transitions, and observed environmental parameters for the cold pool transition example case of July 13, 2009. Bootstrapped 95% confidence interval for medians are given in parenthesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Median for Days with Cold Pool Transitions</th>
<th>Median for Days without Cold Pool Transitions</th>
<th>July 13, 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 mb Temperature</td>
<td>13.2 (10.6,14.6)°C</td>
<td>8.7 (7.6,10.4)°C</td>
<td>15.6°C *</td>
</tr>
<tr>
<td>Surface to 700 mb Temperature Difference</td>
<td>-1.9 (-3.2,0.0)°C</td>
<td>-3.6 (-5.0,-2.8)°C</td>
<td>0.6°C *</td>
</tr>
<tr>
<td>700 mb to 500 mb Temperature Difference</td>
<td>-22.0 (-23.9,-20.7)°C</td>
<td>-20.1 (-21.9,-18.7)°C</td>
<td>-23.3°C</td>
</tr>
<tr>
<td>700 mb Dewpoint Depression</td>
<td>13.9 (10.0,17.0)°C</td>
<td>8.8 (5.0,13.0)°C</td>
<td>15°C</td>
</tr>
<tr>
<td>700 mb to 500 mb Shear Magnitude</td>
<td>13.3 (6.2,22.0)kts</td>
<td>20.2 (16.6,23.7)kts</td>
<td>13.2 kts</td>
</tr>
</tbody>
</table>

*Indicates an extreme value for all days with cold pool transitions.
**Intersection Transition Mode**

The parameter statistics for the intersection transition mode indicate a significant dependence on 500 millibar wind. We find that the median value of 500 millibar wind magnitude is weak relative to that of days without intersection initiations (Figure 9). The 700 millibar to 500 millibar shear magnitude reflects this tendency with weaker shear in this layer on days when intersection transition was observed (Figure 10).

Temperature and dew point parameters for intersection transition days follow a similar pattern to those of cold pool transition days. The parameter statistics show slightly higher 700 millibar temperature and dew point depression for the days with intersection transitions (Figure 11 and Figure 12). Temperature differences between the surface and 700 millibars and between 700 millibars and 500 millibars reflect the relative warmth at 700 millibars (Figure 13 and Figure 14), just as they did for the cold pool transition days. When we compare these thermal parameters on days when intersection transition was observed to the parameters on days when it was not, we find the differences are not as pronounced as they were in the cold pool transition statistics. Physically, we attribute the disparity to the following:

- Early thunderstorms over the mountains are promoted for both cold pool and intersection transition days, but on intersection transition days, there will be slightly less stability at low levels over the plains to be overcome by daytime surface heating and/or lift. As a result, the boundary layer is more suitable for initiations along cold pool boundaries.
- Weak 500 millibar winds likely yield slower moving thunderstorms over the mountains, so these thunderstorms are more likely to be outrun by their cold surface outflows.
Weak shear in the 700 millibar to 500 millibar layer would also promote primary and secondary thunderstorm initiation because the initial cumulus would experience less entrainment.

A final notable parameter for the intersection transition is the time of primary initiation. On all of our intersection transition days, primary initiation over the mountains was first detected before 18:30 UTC. The bootstrapped median primary initiation time for intersection transition days was approximately 17:18 (16:48,18:06) UTC. This is in contrast to the days without intersection transition when the median was approximately 18:06 (17:24,18:36) UTC. Our observation of early initiations for the intersection transition days substantiates the bulleted comments above.
Figure 9. Box plots for 500 millibar wind magnitude (given in knots). “True” columns show bootstrapped statistics for the 12 days on which intersection transition was observed, “False” for the 31 days with no intersection transitions. Whiskers represent the 90th and 10th percentiles, the box is bounded by the upper quartile and lower quartile, and the middle bar in the box plot is the median. Markers to the right side of the box plots indicate the bounds of the 95% confidence interval for the median. Numerical values for these statistics and 95% confidence intervals are given to the left of the plots.
**Intersection Transition Mode**

700mb to 500mb Shear Magnitude (knots)

<table>
<thead>
<tr>
<th></th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>90th</td>
<td>20.5 (16.7, 22.0)</td>
<td>32.7 (27.0, 39.5)</td>
</tr>
<tr>
<td>UQ</td>
<td>17.7 (11.1, 21.5)</td>
<td>26.9 (23.6, 29.9)</td>
</tr>
<tr>
<td>Median</td>
<td>11.8 (6.1, 18.2)</td>
<td>21.7 (17.9, 24.9)</td>
</tr>
<tr>
<td>LQ</td>
<td>7.1 (5.4, 11.2)</td>
<td>15.7 (13.2, 19.8)</td>
</tr>
<tr>
<td>10th</td>
<td>5.8 (4.4, 7.9)</td>
<td>13.1 (12.2, 14.9)</td>
</tr>
</tbody>
</table>

Figure 10. Box plots for 700 millibar to 500 millibar shear magnitude. As in Figure 9.
Figure 11. Box plots for 700 millibar temperature. As in Figure 9.
Intersection Transition Mode

700mb Dew Point Depression
(degrees C)

<table>
<thead>
<tr>
<th></th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>90th</td>
<td>19.0 (14.9,22.0)</td>
<td>17.7 (14.4,21.2)</td>
</tr>
<tr>
<td>UQ</td>
<td>15.9 (11.0,20.0)</td>
<td>14.2 (12.0,17.2)</td>
</tr>
<tr>
<td>Median</td>
<td>11.5 (7.0,16.5)</td>
<td>9.6 (5.0,13.0)</td>
</tr>
<tr>
<td>LQ</td>
<td>7.4 (3.6,12.0)</td>
<td>3.6 (1.3,8.0)</td>
</tr>
<tr>
<td>10th</td>
<td>4.7 (2.3,9.1)</td>
<td>1.4 (0.5,2.6)</td>
</tr>
</tbody>
</table>

Figure 12. Box plots for 700 millibar dew point depression. As in Figure 9.
Figure 13. Box plots for surface to 700 millibar temperature difference. As in Figure 9.
Figure 14. Box plots for 700 millibar to 500 millibar temperature difference. As in Figure 9.

Example Case: May 31, 2009

We choose May 31, 2009 as our example intersection transition day because all of the thunderstorms to affect the Denver area that day were the direct result of intersection initiation. Apart from the typical dry convection over the plains, the radar first detects primary convection between 1630 and 1700 UTC. During this period, several cells appear over the mountains and foothills to the west of Denver, the Palmer Divide to the south, and the Cheyenne Ridge to the north (Figure 15a). By 2000 UTC, outflows radiate from the western and northern convection, but the thunderstorms remain confined to the elevated terrain (Figure 15b). After 2100, these outflows begin to interact close to the Denver International Airport, and new cells readily develop at their intersection (Figure 15c). New cells develop from intersection initiation through 0100 as
outflow from new storms interact with existing outflows. Thereafter, most of the precipitation occurs in a cluster to the southwest of Denver (Figure 15d) and gradually diminishes over the course of several hours.

Table 2 provides the May 31, 2009 12UTC environmental parameters that we found to be associated with the intersection initiation mode. The parameters for May 31 fall in line with the tendencies for intersection initiation days in general. The 500 millibar winds and 700 to 500 millibar shear are both very light for May 31, which is consistent with what we would expect, based on the statistics, for such a clear intersection initiation case. Likewise, our expectation of an early primary initiation time verifies as this day had one of the earliest times for this parameter in the entire study. The temperature and dew point parameters are too ambiguous to make any conclusions, but this is to be expected as these parameters were not found to be greatly significant for this transition mode anyway.
Figure 15. Reflectivity maps from Denver TDWR on May 31, 2009. a) 1803 UTC: Cells begin to develop over higher terrain (circled). b) 2002 UTC: Convergence lines (indicated by arrows) radiate from convection to the north and west of Denver. c) 2220 UTC: Convergence lines (arrows) intersect; three thunderstorms develop near their intersection. d) 0143 UTC (June 1, 2009): A large, dissipating area of rain is seen south of Denver.
Table 2. Comparison of median environmental parameters for days with and without intersection transitions, and observed environmental parameters for the intersection transition example case of May 31, 2009. Bootstrapped 95% confidence interval for medians are given in parenthesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Median for Days with Intersection Transitions</th>
<th>Median for Days without Intersection Transitions</th>
<th>May 31, 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 mb Wind Magnitude</td>
<td>13.4 (7.5,24.0) kts</td>
<td>29.4 (26.0,32.0) kts</td>
<td>7 kts</td>
</tr>
<tr>
<td>700 mb to 500 mb Shear Magnitude</td>
<td>11.8 (6.1,18.2) kts</td>
<td>21.8 (17.9,24.9) kts</td>
<td>6.1 kts</td>
</tr>
<tr>
<td>700 mb Temperature</td>
<td>11.6 (8.7,14.4) °C</td>
<td>9.1 (7.8,10.6) °C</td>
<td>8.4 °C</td>
</tr>
<tr>
<td>700 mb Dew Point Depression</td>
<td>11.5 (7.0,16.5) °C</td>
<td>9.6 (5.0,13.0) °C</td>
<td>10 °C</td>
</tr>
<tr>
<td>Surface to 700 mb Temperature Difference</td>
<td>-2.6 (-3.6,-1.8) °C</td>
<td>-3.6 (-4.6,-2.8) °C</td>
<td>-3.4 °C</td>
</tr>
<tr>
<td>700 mb to 500 mb Temperature Difference</td>
<td>-20.9 (-23.2,-18.7) °C</td>
<td>-20.5 (-21.9,-18.7) °C</td>
<td>-18.9 °C</td>
</tr>
<tr>
<td>Primary Initiation Time</td>
<td>17.3 (16.8,18.1) UTC</td>
<td>18.1 (17.4,18.6) UTC</td>
<td>16.6 UTC</td>
</tr>
</tbody>
</table>

**Track Transition Mode**

Standing out in the statistics for the track transition mode is the 500 millibar wind direction. The box plot for this parameter (Figure 16) shows a particularly compact interquartile range, indicating that the observed wind direction at 500 millibars tends to fall in a very narrow range for the track transition days. This range indicates track transitions occur when winds are west-southwesterly, while days without track transitions average closer to due west. The importance of wind direction in northeastern Colorado is further addressed in the discussion. We note that in producing these statistics, a single case of 500 millibar wind from 010° was aliased as 370° for the sake of continuity in the data. This case was part of the set of days without track transitions.
The track transition days tend to have a slightly stronger 500 millibar wind magnitude than days without track transitions (Figure 17). This wind magnitude, combined with the tendency for a southwesterly direction on track transition days, results in a 500 millibar meridional wind component that is very positive relative to that component on days when track transition is not observed (Figure 18). 700 millibar to 500 millibar shear, particularly the meridional component of the shear, is also greater on track transition days as a result of these 500 millibar winds (Figure 19, Figure 20).

For the other two transition modes, median 700 millibar temperature was higher for the days on which those modes were observed. The track transition mode has the opposite tendency, with colder 700 millibar temperatures on days when track transitions are observed (Figure 21). The temperature differences across layers also follow this pattern, with track transition days tending to have a less stable (more unstable) surface to 700 millibar layer and a more stable 700 millibar to 500 millibar layer than days without track transitions (Figure 22 and Figure 23). Again, these statistics are in contrast to what was the case for the other two transition modes.
Figure 16. Box plots for 500 millibar wind direction (given in compass degrees). “True” columns show bootstrapped statistics for the 14 days on which track transition was observed, “False” for the 29 days with no track transitions. Whiskers represent the 90th and 10th percentiles, the box is bounded by the upper quartile and lower quartile, and the middle bar in the box plot is the median. Markers to the right side of the box plots indicate the bounds of the 95% confidence interval for the median. Numerical values for these statistics and 95% confidence intervals are given to the left of the plots.
Figure 17. Box plots for 500 millibar wind magnitude. As in Figure 16.
Figure 18. Box plots for the meridional component of the 500 millibar wind. As in Figure 16.
Figure 19. Box plots for 700 millibar to 500 millibar shear magnitude. As in Figure 16.
Figure 20. Box plots for the meridional component of the 700 millibar to 500 millibar shear. As in Figure 16.
Figure 21. Box plots for 700 millibar temperature. As in Figure 16.
Figure 22. Box plots for surface to 700 millibar temperature difference. As in Figure 16.
Figure 23. Box plots for 700 millibar to 500 millibar temperature difference. As in Figure 16.

**Example Case: June 9, 2009**

Unlike the example cases for the cold pool and intersection transition modes shown above, there is no case that is particularly clear among the track transitions. Nevertheless, the track transitions of June 9, 2009 provide a useful example of this mode.

The day begins the same as most summer days in northeastern Colorado, with the development of TDWR-detectable dry convection over the plains. Starting around 1700 UTC, we notice organization of the dry convection along the Palmer Divide to the south of the radar site. This further organizes into weak showers over the divide after 1900 UTC (Figure 24a). The radar returns at this time show that these developing showers generally have a substantial east-west dimension (parallel to the ridge on which they developed) and that they produce large outflows of
the same orientation, which propagate northward (Figure 24b). Meanwhile, the cells that have begun to develop in the foothills west of the Denver area are dissipating as they move eastward away from the terrain. Beginning around 2200 UTC, we observe the cells over the foothills transitioning to the plains, but only where they happen to move over the convergence lines from the aforementioned outflows (Figure 24c). These storms usually continue to propagate along the convergence line that aided their transition onto the plains, like a train on a track, hence the “track” designation.

One particularly strong cell on this day moves from the foothills to the plains along one of the convergence lines northwest of Denver between 2200 UTC and 2230 UTC. As the storm moves northeast in association with the convergence line, it strengthens further (Figure 24d). A tornado is reported with this thunderstorm at 2311. We note in the discussion section that weak landspout tornadoes are common with this transition mode as the updrafts of storms stretch any preexisting vertical vorticity which forms from shear instabilities along the convergence line.

Important environmental parameters for July 9 are compared with the typical track parameters in Table 3. The 500 millibar wind direction for this case falls, if only barely, within the narrow range observed for the majority of track transition days. The direction for this case is one of the most southerly of the track transition cases. This direction does put July 9 well into the expected range for track transition when it is translated into the v component of the 500 millibar wind and the resulting 700 to 500 millibar meridional shear. For the thermal variables, this case falls around the median of track transition days for 700 millibar temperature and the surface to 700 millibar temperature difference, but falls more in the range for days without track transition for 700 millibar dew point depression and 700 to 500 millibar temperature difference. It seems that, at least for this case, the track transition mode is favored due to the rather southerly 500 millibar wind direction and the resultant meridional shear situation.
Figure 24. Reflectivity maps from Denver TDWR on June 9, 2009. a) 2013 UTC: Showers over the Palmer Divide and their outflows (indicated by arrows). b) 2107 UTC: Arrows indicate the same northward-propagating convergence line as in a. Convection over the foothills remains in the foothills. c) 2201 UTC: Convergence line again indicated by arrows. Cells begin to undergo track transition (circled). d) 2231 UTC: The track-transitioned cell (circled) strengthens over the plains.
Table 3. Comparison of median environmental parameters for days with and without track transitions, and observed environmental parameters for the track transition example case of June 9, 2009. Bootstrapped 95% confidence interval for medians are given in parenthesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Median for Days with Track Transitions</th>
<th>Median for Days without Track Transitions</th>
<th>June 9, 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 mb Wind Direction</td>
<td>250.5(240.0,255.0)°</td>
<td>278.3(260.0,300.0)°</td>
<td>230°</td>
</tr>
<tr>
<td>500 mb Wind Magnitude</td>
<td>29.1 (23.0,32.0)kts</td>
<td>24.7 (19.0,29.0)kts</td>
<td>21 kts</td>
</tr>
<tr>
<td>500 mb Meridional Wind</td>
<td>9.0 (6.5,13.5)kts</td>
<td>-2.6 (-8.9,3.1)kts</td>
<td>13.5 kts</td>
</tr>
<tr>
<td>700 mb to 500 mb Shear Magnitude</td>
<td>22.4(17.7,26.9)kts</td>
<td>17.2(13.3,21.3)kts</td>
<td>15.8 kts</td>
</tr>
<tr>
<td>700 mb to 500 mb Meridional Shear</td>
<td>7.1 (-1.5,13.9)kts</td>
<td>-8.2 (-11.6,-10.7)kts</td>
<td>12.9 kts</td>
</tr>
<tr>
<td>700 mb Temperature</td>
<td>7.6 (5.7,9.2)°C</td>
<td>11.3 (9.4,14.4)°C</td>
<td>7.2°C</td>
</tr>
<tr>
<td>Surface to 700 mb Temperature Difference</td>
<td>-4.6 (-7.1,-3.0)°C</td>
<td>-2.8 (-3.8,-2.2)°C</td>
<td>-4°C</td>
</tr>
<tr>
<td>700 mb to 500 mb Temperature Difference</td>
<td>-18.8 (-20.5,-17.9)°C</td>
<td>-21.6 (-22.7,-20.5)°C</td>
<td>-21.9°C</td>
</tr>
</tbody>
</table>
Chapter 5

Discussion

Our goal with this research is to exploit TDWR and radiosonde observations to develop forecast methods for the likelihood of each transition type. All upper air parameters in the analysis were derived from the 1200 UTC Denver sounding. The sounding data would be available several hours before the transition of convection from the mountains to the plains takes place along the Front Range of northeastern Colorado. Alternatively, one could use model generated soundings to obtain greater lead time. Once the sounding is available, a forecaster could at least be aware of the possibilities for transition. Monitoring the TDWR data would enhance the forecast by allowing tracking of convergence line evolution and motion.

Also important to the forecaster is knowledge of what hazards and threat areas may be more likely with each transition mode. We mentioned a couple of recurring, transition mode-specific phenomena in the results section. In particular, we saw that MCSs frequently developed from storms transitioning via the cold pool transition method and landspout tornadoes were commonly associated with track transitions. As discussed below, the transition mode also affects which areas east of the mountains are likely to be affected.

Existing literature provides some insight into the mode-specific phenomena that we have noted. Cotton et al (1983) observed a line of thunderstorms which first initiated over the mountains of the Continental Divide in Colorado and propagated eastward, eventually developing into a Mesoscale Convective Complex (MCC). We observed several similar events among our cold pool transition cases, including the July 13, 2009 case that we detailed above. The Cotton et al. paper concluded that the MCS was able to form over the mountain because abnormally persistent stability in the boundary layer over the plains caused the development of thunderstorms
over the mountains to be favored. Therefore all of the convection over the north-south oriented ridges was able to coalesce and propagate eastward as a coherent system.

It is interesting that Cotton et al. stresses the importance of stability in the boundary layer in the development of the MCS. Our results show that cold pool transitions are more likely when 700 millibar temperature is high and the surface to 700 millibar layer is more stable than average. Furthermore, our July 13, 2009 MCS case occurred with the surface to 700 millibar stability at an extreme for all 43 days of data in our study. The collective evidence here suggests that this phenomenon has the potential to be highly forecastable.

A numerical modeling study by Tucker and Crook (1999) also looked at the development of an MCS from mountain convection in northeastern Colorado. It was determined that, for the case studied, the surface outflow from the earlier mountain convection was necessary for the formation of the MCS. They essentially observed, in their model, what we refer to as the cold pool transition and deemed it critical in MCS development.

There are several studies which involve tornado outbreaks in northeastern Colorado that touch on what we observe on our track transition days. Wakimoto and Wilson (1989) studied non-supercell tornadoes in the Denver area. They found that, often, these tornadoes formed as shearing instabilities along a convergence line created vortices which were stretched by the updrafts of developing thunderstorms. In our study, we often saw this happen as thunderstorms moved out of the foothills along the convergence lines and soon thereafter developed a radar reflectivity hook echo and/or an inbound-outbound radar velocity couplet. These tornadoes form in environments that would not otherwise be considered favorable for tornadoes, so understanding when such tornadoes could be more likely is particularly important.

We sometimes observe the track transitions taking place in conjunction with an obvious Denver Convergence-Vorticity Zone (DCVZ). Szoke, et al (1984) associates the DCVZ with severe weather and tornado outbreaks in northeastern Colorado. The study indicates that synoptic
scale south to southeasterly flow at the surface is prerequisite for the formation of this phenomenon. A modeling study by Crook et al (1990) suggests that the DCVZ is a wake vortex that occurs in the lee of the Palmer Divide and that it is more likely to form in southerly surface flow with a low Froude number. These results are invaluable for stable atmospheres, but warm season convective transition in the Denver area occurs with deep unstable mixed layers, so mountain valley circulations are potentially more relevant.

The radiosonde data we collected do not definitively indicate a connection between our track transition environments and a low Froude number environment, but there are some notable similarities in the flow direction between the findings of Crook et al. (1990) and our observations on track transition days. While the flow at 500 millibars is definitely more southerly for our track transition days than for days without track transition, our data for winds at 700 millibars and the surface show no specific tendency to favor any abnormal direction. We must consider the site of observation, however, as the data may be collected before the DCVZ forms and the radiosonde launch site may be on either side of the vortex. There is a strong tendency for the surface and 700 millibar levels to be cold on track transition days and for the 700 millibar to 500 millibar layer to be very stable which would favor a low Froude number, but this stable layer is well above the elevation of the Palmer Divide. The surface to 700 millibar layer actually tends to be relatively unstable for track transition days, at least in the Denver area, which would indicate a higher Froude number and greater likelihood of solenoidal forcing. Clearly, more study is required to make any conclusions about the strength of the relationship between conditions favorable for track transition days and those favorable for the formation of the DCVZ.

It is possible that some of the convergence lines that are involved in track transitions are the result of leeside convergence. These convergence lines form where daytime instability in the higher terrain allows the ridge top winds to mix to the surface. Schreiber-Abshire and Rodi (1991) document these roughly east-west oriented convergence lines propagating northward
through northeastern Colorado on days when there is southwesterly flow at 700 millibars. These observations are consistent with our observations and with the environmental conditions that we associate with the track transition mode.

While thunderstorm initiation at the intersection of convergence lines has been studied thoroughly in general (Purdom, 1976), it has largely been overlooked with specific regard to the relationship between mountain and plains convection. The intersection transition mode did not typically produce the most severe storms, but the convection which did arise from convergence line intersection had the tendency to develop very quickly and relatively early in the day. Additionally, we saw these initiations tend to cluster near the city of Denver (Figure 25). This is most likely because we focused on intersection initiations associated with surface outflow from terrain-supported convection. The outflows from the western foothills and the Palmer divide tended to collide in the Denver area and could presumably pose a sudden hazard to aviation and other interests around the city.

Of the 43 days we visually inspected, there were 15 days on which convergence lines from the surface outflows of thunderstorms were observed. We saw showers and thunderstorms initiate along these outflows on twelve of those days. Without more data, we cannot make conclusions about the environmental characteristics prohibitive to intersection initiations, but we can say that on most days when outflows are observed, intersection initiations occur.
Figure 25. Intersection transitions in northeastern Colorado. Red markers indicate the location of the first primary initiation over the mountains; the green markers show the location of the storms from which outflows originate; the blue markers indicate the first secondary initiation over the plains as a result of intersection. Magenta markers and four letter identifiers indicate the locations of airports or, in the case of TDEN, the radar. Surface elevation is given by the shading and contours at 300 meter intervals.
Chapter 6
Conclusions

The Federal Aviation Administration Terminal Doppler Weather Radar (TDWR) was used to examine warm-season convection along the Front Range of northeastern Colorado with the following goals:

- To determine if TDWR is useful in observing the ways in which thunderstorms transition from the mountains to the plains along the Front Range of northeastern Colorado.
- To examine these transitions, find distinct modes of transition, and determine the meteorological conditions which are favorable for each mode.
- To suggest ways in which these relationships can aid in the short-term forecasts of thunderstorm initiation and propagation.

We discovered that thunderstorms tended to transition from the elevated heat sources to the high plains along the Front Range by three distinct, TDWR-observed modes. Several parameters from morning radiosonde data were analyzed in conjunction with the radar data to determine favorable environments for each mode. We found that the transition modes are not mutually exclusive and there is no transition mode that is the most prominent, but each of the three modes is favored by a different environment and accompanied by different phenomena:

- The cold pool transitions are characterized by thunderstorms propagating away from their supporting terrain behind the leading edge of a convective cold pool which appears on the radar as an arc of slightly enhanced reflectivity. Cold pool transitions tend to take place on days with relatively warm air at 700 millibars, which creates a
relatively stable layer between the surface and 700 millibars and a relatively unstable layer between 700 millibars and 500 millibars. Mesoscale convective systems often evolve from thunderstorms or clusters of thunderstorms that transition to the plains in this way.

- Intersection transitions occur when mountain thunderstorms produce surface outflows that move over the plains and initiate new thunderstorms there. These transitions tend to take place in environments thermally similar to cold pool environments (warm air at 700 millibars), but with relatively weak 500 millibar winds. The weak winds at 500 millibars are also reflected in the relatively weak 700 millibar to 500 millibar shear parameter. The storms resulting from this transition form early, quickly, and usually near the Denver metropolitan area.

- We observe track transitions as thunderstorms which form over the mountains and move over the plains by following preexisting convergence lines, the way a train would follow a track. These transitions tend to occur in a narrow directional range of southwesterly 500 millibar winds. The thermal environments for this mode are opposite those of the other modes as the surface to 700 millibar layer tends to relatively unstable, and the 700 millibar to 500 millibar layer tends to be relatively stable. Transitions by this mode may be connected to the existence of a leeside convergence zone or the Denver Convergence-Vorticity Zone, both of which result from southerly flow over the Palmer Divide. The occurrence of landspout tornadoes may be associated with this mode.

Our findings on the favorable environmental conditions for these transitions of convection may be paired with the utility of the TDWR to offer an opportunity to improve short term forecasting of convection. Convection-resolving model forecasts can be used to determine whether precipitation should be expected over the Front Range of northeastern Colorado on a
particular day, and would also likely be accurate in predicting whether or not precipitation would be limited to the mountains. While this information is useful, current models yield but one realization of an uncertain outcome. We suggest the use of our results with either radiosonde observations or modeled profiles to provide the forecaster with a more general awareness concerning the range of possible convective transitions. This information can be used to assess how individual thunderstorms may be expected to evolve in the area and what hazards may arise based on the expected transition modes. The sounding analysis covers lead times for which radiosonde or model temperature and wind profiles are felt to be accurate and representative, i.e. a few hours to at most a day or two. At lead times of an hour or two, the TDWR itself offers the means to track the movement of thunderstorms and convergence lines, allowing these transition modes to be monitored and plains thunderstorm initiation to be anticipated.

The data used in our work are available in real time and we encourage their use in applying the findings of this study. Many of the features we observed would be invisible in WSR-88D data, especially when that radar is in its precipitation mode. The scan we used from the TDWR is available regardless of the operating mode, so the convergence lines on which much of the study is based are detected consistently (Stern, et al., 2003). TDWR has a place in both research and forecasting and should be utilized in nowcasting beyond its role in automated shear detection.

To better resolve and confirm our findings about how environmental parameters relate to each transition mode, the first course of action could be to process several more years of data in the way that we have here (at the time of this study, 2009 was the only available year). Analyzing more years could also mitigate the potential errors arising from the human factor of manually inspecting the radar data. The exploration of other environmental parameters using radiosondes, surface stations, other data sources, or observation times other than 1200 UTC could also be enlightening. In particular, mid- or later morning soundings from mesoscale models
would provide surface winds and surface to 700 millibars stability values more directly relevant to the transition convection than the 12UTC radiosonde soundings. Using TDWR for studies like this in other mountainous or coastal areas would be productive as well. Finally, as many past studies have shown, numerical modeling is invaluable for better understanding of the physics behind thunderstorm evolution and could be applied to these transition modes.
References


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