Lightning Climatology for the State of Colorado

Stephen Hodanish *
Paul Wolyn
NOAA/National Weather Service, Pueblo, Colorado

1. Introduction

Lightning detection in the State of Colorado has been ongoing since the 1970s. The Bureau of Land Management was first to use such a system in order to provide early warning of fire starts and to guide resources to potential fire start regions (Krider et. al. 1980). Throughout the 1980s the BLM system was upgraded (Reap 1986), and in 1989 it was combined with other regional lightning detection systems across the United States (Orville et al.1983; Mach et al. 1986) to form the National Lightning Detection Network (NLDN, Orville 1991, Orville 2008). The NLDN itself has gone through numerous upgrades and expansions through the 1990s and 2000s (Cummins et. al., 1998, Cummins 2006), and is now known as the North American Lightning Detection Network, operated by Vaisala (Orville et. al., 2002). For simplicity, throughout the remainder of this manuscript we will refer to the lightning detection system as the NLDN. Readers who wish to learn more about the history of the NLDN are encouraged to reference Orville (2008).

The primary motivating factor for this study is that there is no comprehensive Cloud to Ground (CG) lightning climatology for the state of Colorado in the formal literature. Several national and a couple of regional CG lightning studies have included all, or parts of, the Centennial State (see, for example, Zajac and Rutledge (2001), Orville and Huffines (2001), Lopez and Holle (1986) and Reap (1986)). The most comprehensive study in the formal literature which specifically discussed CG lightning over parts of the Centennial State was completed by Lopez and Holle (1986). They analyzed a single years' (1983) worth of CG data collected over the Northeast Colorado region. Lightning data was collected from 3 lightning detectors which were located over the greater Metropolitan Denver region. They found lightning activity over Northeast Colorado was mainly a warm season event, with a large majority of the flashes occurring from June through September (see their figure 2; note data for the month of May was missing). On a day to day basis during the warm season, lightning activity was found to be extremely large; some days had 5 minute flash rates in excess of 100, while other days had less than 10 flashes in a five minute time period. On a daily basis, they found that lightning first developed over the region around 11 am in the morning, with a peak in the activity occurring during the late afternoon. Spatially, overall maximum flash concentrations were found to run north-south along the eastern slopes of the Front Range, then southeast to east along the north facing slopes of the Palmer Divide.

Reap (1986) analyzed lightning, along with other remote sensed meteorological variables, over the Western United States (including Colorado) during the warm season, defined as mid June through September, for the years 1983 and 1984. Data was collected from the BLM lightning network (Krider et. al. 1980). A high correlation was found between terrain elevation and the hour of maximum frequency of lightning. A fairly stable seasonal and geographical distribution of lightning activity was found over the western United States (generally west of 103 degrees longitude), resulting from the strong control exerted by the underlying topographical features over with this part of the country. Similar to Lopez and Holle (1986), it was found that lightning over the West was also quite variable on a day to day basis, with the activity rapidly increasing after 11 am MST reaching a peak during late afternoon, then gradually tapering off during the evening hours.

2 Data

In complete operation since 1989, the NLDN detects CG lightning flashes over the North American Continent and immediate coastal waters. Although the NLDN has been in existence since the above aforementioned year, the authors began their analysis in 1994. The primary reason for this is due to apparent lack of lightning activity over Colorado in 1989 and the early 1990s. This apparent missing data over the Centennial State can be best seen in Orville (1991, see Fig. 4), and to a lesser extent in Orville (1994; see Plates 2a, 3a and 4a). More recent national studies (Orville and Huffines 1999, Fig. 3; Orville and Huffines 2001, Fig. 3; Zajac and Rutledge 2001, Fig. 3) show that a rather significant amount of CG activity occurs over the Centennial State. This discrepancy in the lack of lightning over Colorado in the Orville (1991) manuscript was noted by Smith (1993). Smith states: "Second, and perhaps most important, a cursory examination of Fig. 4 of O91 [Orville 1991] shows a pronounced local minimum in density covering most of the High Plains, including Eastern Colorado, a region well known for thunderstorm activity". In a formal reply to Smith, Orville (1993, page 1575) states "It appears that the NLDN detection efficiency problem in 1989 in eastern Colorado was real and continues to a lesser degree in 1990 and 1991".

An additional reason why we chose to begin our analysis in 1994 is that the NLDN went through a significant upgrade in 1994, which increased the

** Corresponding author address: Stephen Hodanish NOAA/NWS, 3 Eaton Way, Pueblo CO 81001 Steve.Hodanish@noaa.gov*

detection efficiency of the entire system (Wacker and Orville 1999, Cummins et. al. 1998). The data in this study comes from two separate NLDN data sets. The first, 1994 to 1999, was archived by NOAA, National Severe Storms Laboratory, while the second data set, (2001 to 2008) was archived locally via the AWIPS computer system at National Weather Service Pueblo (Glahn and Ruth, 2003: Ruth, 2002). The authors did not include NLDN data in 2000 as this dataset was not available for us to analyze.

As suggested by Holle (2009 – personnel communication), positive flashes less than 15 kA have been removed from this study. The reasoning for the removal of these flashes are based on camera and triggered lightning studies that showed almost all "detected" positive NLDN flashes <15kA were actually cloud flashes, while those >15kA were almost always cloud-to-ground positive flashes (Cummins and Murphy, 2009, Rudlosky and Fuelberg 2010).

Flash densities over the state of Colorado are calculated on a 0.01 degree latitude by 0.01 degree longitude grid spacing. For the state of Colorado (average latitude 39.00 degrees north), this corresponds to approximately 1.0 kilometer squared grid spacing. A total of 281,101 data points were analyzed.

3 Topography of Colorado

Before discussing the flash density plots, a discussion of the Centennials State topography is necessary (**Fig. 1**). A large majority of this discussion was taken directly from an internet article from the Colorado Climate Center by Doesken and Pielke (2003).

Emerging gradually from the plains of Kansas and Nebraska, the high plains of Colorado slope gently upward for a distance of some 321 km (200 mi) from the eastern border to the base of the foothills of the Rocky Mountains. The eastern portion of the State is generally level to rolling prairie broken by occasional hills and bluffs. Although subtle when compared to the high mountains of the Rockies, there are 3 important topographic features across the eastern Plains of Colorado. These topographical features, the Cheyenne Ridge, the Palmer Divide and the Raton Mesa are formed by 2 major rivers which dissect the eastern plains of Colorado - the South Platte River in northeastern Colorado and the Arkansas River in the southeast part of the State.

Elevations along the eastern border of Colorado range from roughly 1.0 km (3.3 kft) at the lowest point in the State where the Arikaree River crosses into northwest Kansas to near 1.2 km (4.0 kft). Elevations increase towards the west to between 1.5 km (5.0 kft) and 2.0 km (6.5 kft) where the plains meet the Front Range of the Rocky Mountain chain. Here elevations rise abruptly to 2.1 to 2.7 km (7.0 to 9.0 kft). Backing the foothills are the mountain ranges above 2.7 km (9.0 kft) with the higher peaks over 4.3 km (14.0 kft). The most dramatic feature is Pike's Peak near Colorado Springs where elevations rise abruptly from less than 1.5 km (5.0 kft) near Pueblo in the Arkansas Valley to over 4.3 km (14.0 kft) at the top of the mountain. West of these "front ranges" are additional ranges, generally extending north and south, but with many spurs and extensions in other directions. These ranges enclose numerous high mountain parks and valleys. Farther westward the mountains give way to rugged plateau country in the form of high mesas (some more than 3.1 km [10.0 kft] in elevation) which extends to the western border of the State. This land is often cut by rugged canyons, the work of the many streams fed by accumulations of winter snow.

4. Statewide Lightning Distributions

a. *Average flash amounts*

Figure 2 shows the average number of cloud to ground flashes for each day over the State of Colorado. Overall, it can be seen that lightning over the Centennial State is a warm season phenomena, as very little lightning occurs from mid October to mid March. Flash rates begin to become non-negligible from mid March through mid April as strong late Winter/early Spring synoptic systems move across the State. By mid April, flash rates begin to ramp up, averaging about ~500 flashes per day by the beginning of May. By the end of May, flash rates increase rapidly as diurnal influences play more of a role in initiating convection, with rates averaging over 3000 flashes per day. Although the data shows considerable "day to day" variability, the flash rates only gradually increase through the month of June. Flash rates begin to increase once again in July, reaching a maximum of over 8000 flashes per day at the end of the month. Flash rates begin to steadily decrease through August, averaging about 3500 flashes per day by the end of the month.

From September 1st through the 3rd week of September, the flash rates decrease rapidly over the State. However, they increase during the last week of September into early October. By mid October, flash rates values decrease to below 500 a day, with these values reaching less than 100 flashes a day by the end of October. By November, flash rates once again become negligible.

b. Annual Plot

Figure 3 is the result of contouring 7,396,085 cloud to ground lightning flashes for the State of Colorado and dividing by 14. The result is the average flashes per kilometer squared per year for the period 1994 through 2008, minus the year 2000. Overall, the annual flash density plot shows a diverse range of values across the Centennial State; ranging from over 6.5 flashes km^{-2} over the east central part of the state

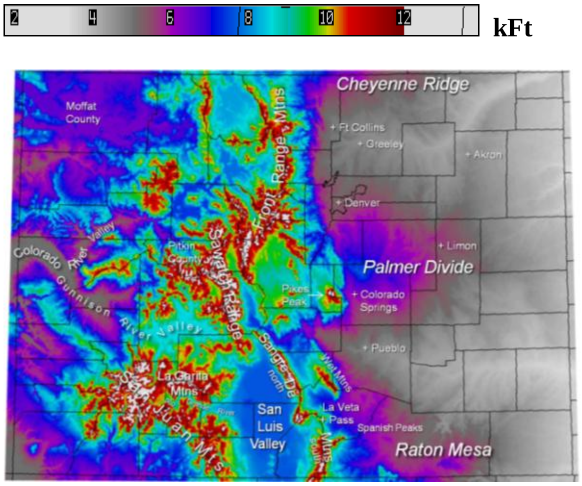


Fig 1. Topography of Colorado. County outlines and placenames used in the text are shown.

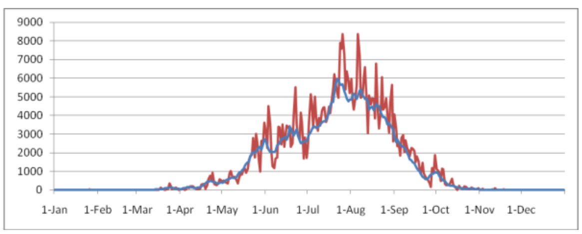


Fig 2. Day by Day (red) and 7 day running mean (blue) flash rates for the State of Colorado for the years 1994 through 2009 without 2000.

to less than 0.5 flashes km^{-2} over the south central part of the State.

Three regions of enhanced lightning activity are noted over Colorado. Two of these regions are located where the higher terrain of the Plains intersects the Rocky Mountains, while the third region is found over the southern slopes of the San Juan Mountains. The first of the two enhanced regions along the mountains/Plains interface is located where the Palmer Divide intersects the Pikes Peak Massif, while the second is located where the Raton Mesa intersects the Southern Sangre De Cristo Mountains. (Throughout the remainder of the manuscript, we will define these two areas as the “Palmer Divide region” and “Raton Mesa region” respectively). Generally speaking, flash maxima in these two regions are due to a *juxtaposition* of favorable topographical forcing associated with daytime, thermally driven upslope flow along with the availability of lower level moisture which initiates, and more importantly, sustains, convection as it moves off the mountain slopes and higher terrain. The third area of enhanced lightning

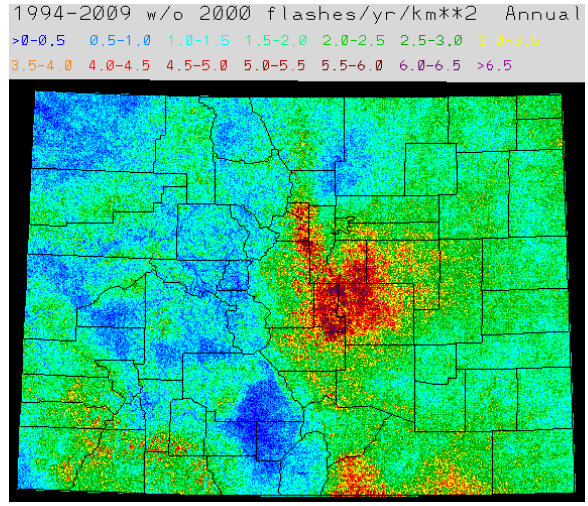


Fig 3. Flash density map for the state of Colorado for the years 1994 through 2009 without 2000. County outlines are shown.

activity is located over the southern slopes of the San Juan Mountains located over the southwest part of the State. The flash maximum in this region is due to a *juxtaposition* of favorable topographical forcing and mid to late Summer Monsoon moisture.

In addition to the flash density maxima, areas of flash density minima are also observed. Most of the minima in activity are located in the mountain valleys, with the most significant minima located over the San Luis Valley situated in south-central Colorado. Another minimum is located over the vast plateau region of northwest Colorado. The flash minima are located in areas mainly due to the fact of limited low level moisture, primarily due to blocking of surrounding higher terrain.

Another rather surprising minimum in lightning activity is located over the Plains, east of the Colorado Front Range and north of the Denver Metropolitan area. This minimum is likely due to a predominantly divergent lower level wind flow regime which develop relatively frequently over this region.

It should be noted that the maximum in flash density does not necessarily occur along the highest mountain ranges. As an example, the Sawatch Range, a north-south mountain range located over the central part of the State (see Fig. 1) is one of the tallest mountain ranges in Colorado, yet very little lightning occurs over this range (**see** Fig 3). On the other hand, the best low level moisture during the warm season is located over the far Eastern Plains, yet lightning activity over this region is rather modest.

5 Regional Lightning Distributions

We now hypothesize why the flash maxima and flash minima are located where they are across the State of Colorado. We will begin our discussion along the mountains/Plains interface.

a. Flash maxima and flash minima along the Mountain/Plains interface

Thunderstorm development is dependent upon the availability of lift, instability, and moisture. Moisture arrives over the eastern Plains of Colorado either directly or indirectly from the Gulf of Mexico. Moisture can be transported northward from the Gulf via the low level jet (Bonner, 1968), then drawn directly westward by weak synoptic mechanisms or by the diurnal upslope circulation (Johnson and Toth 1985, Abbs and Pielke 1986). It may also be transferred into the state by indirect methods. For example, Gulf moisture can be precipitated onto the plains of Kansas and Nebraska, and then evapotranspiration and northeasterly flow behind a stationary front could complete the transport into the Centennial state. In addition to moisture arriving from the Gulf of Mexico, moisture can advect over the entire state during the mid to late summer time period. This advection of moisture is associated with the North American monsoon flow (Hales 1974, Adams and Comrie 1997).

As was discussed in Section 3, three east-west ridges extend eastward onto the Plains from the Rocky Mountains of Colorado. Moisture advecting upslope across the Plains affects each of these ridges, however, the lightning flash distributions across these three ridges are not the same. By far, the most significant lightning activity occurs across the Palmer Divide region. Lightning flash values across a large part of this region are in excess of 4.0 flashes km^{-2}, with many areas in excess of 6.0 flashes km^{-2}. The Raton Mesa region along the Colorado/New Mexico border shows the 2^{nd} in maximum in activity, with flash values ranging between 4.0 to 5.0 flashes km^{-2}. Unlike the other two east-west ridges, the Cheyenne Ridge located along the Colorado/Wyoming border does not show a maxima in lightning activity. Flash distributions across this ridge are rather uniform, with values in the 2.0 to 3.0 flashes km^{-2} range.

Areas on the Plains between the 3 ridges (generally areas below 5000 feet), and areas along the Colorado/Kansas border show rather uniform flash values, ranging between 1.0 to 2.5 flashes km^{-2}. Exceptions are noted however. One area of anomalously low flash values is located just east of the Colorado Front Range, bounded roughly between the cities of Denver to Greeley to Ft Collins and back to Denver. Flash rates in this region range between >0.0 to 1.5 flashes km^{-2}. Another area of slightly higher activity is noted over extreme northeast Colorado where values range between 2.5 to 3.5 flashes km^{-2}.

We now present evidence that the flash distributions across the northeast Colorado region (i.e., the Palmer Divide and Cheyenne Ridge regions, the east slopes of the Colorado Front Range and the adjacent Plains), are driven by the low level wind flow regime which occurs across the northeast Colorado region during the warm season.

During the 1980s, the Program for Regional Observing and Forecasting Services (PROFS: Beran and Little 1979; Reynolds 1983) operated a mesonetwork of weather stations across the northeast Colorado region. Toth and Johnson (1985; denoted as TJ85 throughout the remainder of this document) analyzed surface wind data collected from this mesonetwork, along with wind data from National Weather Service manned stations, to investigate the diurnal wind flow pattern over the northeast Colorado region. Data for three years (1981 to 1983) during the warm season were analyzed*[1].

Overall, the TJ85 analysis of the mean wind data over the northeast Colorado region showed a wind flow pattern typical of a mountain-valley circulation (Defant 1951). Surface wind flow during the early morning hours was downslope off the higher terrain of the mountains (Front Range) and the ridges (Cheyenne Ridge and Palmer Divide; see TJ85, fig 2a and 2b;). By mid morning the mean wind flow over the mountainous terrain became upslope while the flow off the east-west ridges of the Palmer Divide and Cheyenne Ridge continued to drain into the Platte River valley. (TJ85, fig 2c). By late morning the flow had transitioned to upslope across the entire region (TJ85, fig 2d). It is of interest to note three characteristics shown in fig 2d of TJ85; first, convergence along the Palmer Divide is rather sharp, as implied by the wind observations at Elbert (ELB) and Colorado Springs (COS). Second, flow in the region bounded by Denver (DEN) -Greeley (GLY) - Ft Collins (FCL) - Denver (DEN) area is diffluent. Third, confluence of the wind field on the Cheyenne ridge is evident, but is not as strong as it is on the Palmer Divide.

By mid afternoon (TJ85, fig e), confluence continues to be noted over the Palmer Divide, while diffluence continues to be noted in the area bounded by DEN-GLY-FCL-DEN. It is of interest to note the lack of confluence over the Cheyenne Ridge during this time as flow is shown to be east-southeasterly across the entire ridge.

By late afternoon (TJ85, fig f), a well defined north-south convergence line is noted propagating east of the foothills, generally at the longitude of Denver.

*[1] It should be noted, however, only results for July 1981 was presented in their study as data for the other two years was found to be quite similar to the July 1981 results.

Interestingly, areas to the east of this confluence line have not shown much change, as a well defined area of confluence is still noted over the Palmer Divide (although this area of confluence has drifted northward); diffluence in the flow is still noted from Denver - Greeley - Nunn, and the flow over the Cheyenne Ridge is still generally unidirectional.

Although the TJ85 manuscript was an analysis of the averaged warm season wind flow over the northeast Colorado region, it did identify some important characteristics in the low level wind field. First, the TJ85 study showed that the confluence of the wind field over the two east-west ridges that extend from the mountains are not the same, as the confluence over the Palmer Divide was much more pronounced then over the Cheyenne Ridge. The area of confluence over the Palmer Divide was also observed to exist for an extended period of time, 5-6 hours, on a daily basis. Second, an area of persistent diffluence was observed over the lower elevations of the Plains, bounded roughly by DEN-GLY-FCL-DEN. This area of diffluence lasted for ~4 – 5 hours.

The averaged wind patterns shown in the TJ85 study were likely influenced in part by a mesoscale circulation which develops under favorable synoptic conditions over the High Plains of Northeast Colorado. This mesoscale circulation, known as the Denver Convergence and Vorticity Zone (DCVZ), is a stationary, terrain induced mesoscale cyclonic gyre which is often observed over the Plains between the Cheyenne Ridge and the Palmer Divide when the surface (~850 hPa) geostrophic wind is southerly. This 850 hPa geostrophic flow typically occurs approximately 24 hours after a Canadian frontal passage as an area of high pressure settles over the north Central Plains of the United States. First documented in 1981 (Szoke et. al. (1984)), the DCVZ wind gyre has a typical diameter of 50-100 KM and has been observed to be a nearly stationary feature for the periods on the order of 10 hours (Wilczak and Glendening 1988). The DCVZ circulation is a relatively common feature over Northeast Colorado as studies by Szoke et. al. (1984), Szoke et. al. (2006) and Szoke and Augustine (1990) found that this gyre occurs more than 1 out of 3 days (35%) during the months of May through August.

Severe weather activity associated with post-frontal flow over the High Plains has been well documented in the literature (Doswell 1980, Maddox et. al. 1981). The DCVZ itself has been studied extensively due to its preponderance for non supercell tornado activity which occurs along the convergence zone (Brady and Szoke 1989, Szoke et. al. 1984, Szoke et. al. 2006, Szoke and Augustine 1990 and Wakimoto and Wilson 1989). In this study, we hypothesize that the wind flow pattern associated with the DCVZ affects the lightning distributions over the greater northeast Colorado region; enhancing the activity over the Palmer Divide region while decreasing the activity over both the Cheyenne Ridge region and over the area of the Plains just east of the Colorado Front Range north of Denver.

Figure 4 shows a typical surface wind regime associated with the DCVZ (Szoke et. al. 2006). During a DCVZ event, a surface trough develops and extends from areas south of the Denver metropolitan region north-northeastward to near Greeley. To the south and east of the trough axis, south-southeasterly winds predominate across the Plains of Colorado. To the west of the trough axis, the wind flow shows a more divergent pattern; southeasterly wind flow in the Fort Collins area generally backs as one travels south, and becomes northerly across the Boulder/Denver area. An area of well defined convergence is noted along the trough axis, especially east and south of the immediate Denver area.

A flash density map and topographic map which is identical in area to Figure 4 (DCVZ cartoon) is shown in Figure 5a-b. Note the lightning activity increases significantly from areas west and south of Denver. This area of increasing lightning activity matches up well with the north and northeasterly surface flow associated with the DCVZ circulation. Likewise, a noticeable minimum in lightning activity is noted in an area bounded roughly by Denver-Fort Collins-Greeley-Denver. This area of lower lightning flash density matches up quite well with the area of divergent wind flow which was shown in Figure 4.

In addition to the favorable low level wind flow pattern which enhances the lightning activity over the Palmer divide region, The topography and geophysical location of the Palmer Divide region is likely more conducive for initiating, and *sustaining*, thunderstorm activity. First, Pikes Peak, which abuts up to Palmer Divide, is a very tall (4.3 km msl), isolated peak. In addition to being one of the tallest mountains in Colorado, the Pikes Peak Massif extends the farthest east onto the Plains. The mountains' south, east and to a certain extent, northern flanks are immediately adjacent to the moisture rich Plains. Secondly, the slope of Pikes Peak adjacent to the Plains is quite steep. To put this elevation change in perspective, the horizontal distance between the top of Pikes Peak (4.3 km msl) and the Colorado Springs metropolitan area (elevation ~1.8 msl) on the elevated Plains below is 19.3 km. This calculates to a slope angle of 0.13. In a study of convective initiation using satellite imagery, Klitch et. al. (1985), found initiation occurred "along the rugged slopes of the Rockies" implying slope angle was important in initiating convection in the mountains of Colorado.

As discussed above, the lightning activity over the Cheyenne Ridge region was considerably less than the Palmer Divide region. The primary reason is likely due to less confluence on this ridge as compared to the Palmer Divide region (see Figure 4 and TJ85 figure 2d-2g). Less confluence would likely lead to less deep convection. Evidence in the literature suggests this may be a factor. A satellite study by Klitch et. al. (1985) analyzed visible satellite imagery over the State of Colorado for a 2 month period (July and August) in 1982. Although their study was limited in duration, they found that deep moist convection over Cheyenne Ridge region as compared to the Palmer Divide region was relatively infrequent.

A 30 year average of summer precipitation (June/July/August) over the State of Colorado is shown in Figure 6. Similar to the lightning distribution over the 3 ridges, the Cheyenne Ridge shows the least amount of summer precipitation as compared to the Palmer Divide and Raton Mesa.

The topography of the Cheyenne Ridge may also play a part. Although the Cheyenne Ridge is similar to the other two ridges; e.g. an area of higher terrain extending west to east from the Rocky Mountains, the ridge itself is not as high as the Raton Mesa or the Palmer Divide **(see** Figure 1) and thus the slope of the terrain from the river basins to the top of the ridge is less. Also, the north-south mountain range (The Laramie Range and northern section of the Front Range) are not as high in elevation as the Mountains that abut up to the Palmer Divide and Raton Mesa.

Based on what has been discussed to this point, it has been shown that the Cheyenne Ridge receives less summer time precipitation then the Palmer Divide and the Raton Mesa. A brief satellite study has shown that there is less deep moist convection on the Cheyenne Ridge compared to the other two ridges during the July and August time period. It was also shown that the vertical extent of the Cheyenne Ridge is less than the Palmer Divide and Raton Mesa. Additionally, the DCVZ circulation (which typically occurs 1/3[rd] of the time during the summer months) likely plays a role in decreasing the upslope component on the south side of the Cheyenne Ridge. It is likely a combination of all these factors which allows for less lightning over the Cheyenne Ridge when compared to the other two ridges.

Up to this point we have discussed the lighting activity over the northeastern part of the Mountains/Plains interface. We now wish to switch gears and discuss the lightning activity in more detail over the southeastern part of the mountains/Plains interface. This area encompasses a region generally south of the Arkansas River and east of the Sangre de Cristo Mountains. Within this region we find another maximum in lightning activity, located adjacent to the east facing slopes of the Southern Sangre De Cristo mountains and extending eastward across the Raton Mesa ("Raton Mesa region"). This area of higher lightning flash rates then extends south into the State of New Mexico.

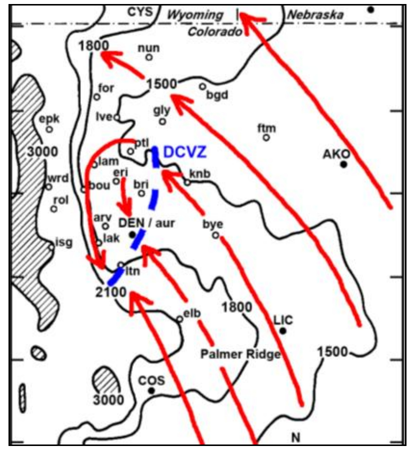


Fig 4. Schematic of the Denver Cyclone Vorticity Zone overlaid on a topographic map (m). PROFS mesonet stations are shown in open circles while NWS stations are shown as darkened circles. For reference, "for" is Fort Collins; "gly" is Greeley, and DEN is Denver. Image from Szoke et. al. 2005.

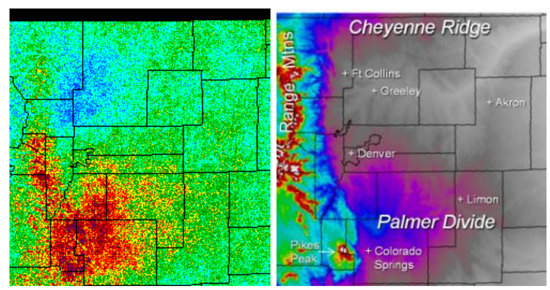


Fig 5. Flash density map (a) and topographic map (b) of the northeast Colorado region. Geographic areas shown in above figures are identical to geographical area in Figure 4.

In order to explain the lightning flash rates of this region, a description of the Sangre De Cristo Mountain range and nearby higher terrain is necessary. The Sangre De Cristo Mountain range is roughly a north-south mountain range located over Southern Colorado which separates the San Luis Valley to the west and the Plains to its' east. Many of the peaks along this range are in excess of 3.7 km (12.0 kft). This mountain range can be further broken down geographically into the Northern Sangre De Cristo Mountains (which extend from just south of Salida south to La Veta Pass), and the Southern Sangre De Cristo Mountains (which extends from La Veta Pass southward into the State of New Mexico). A small mountain range, the Wet Mountains, parallels the Northern Sangre De Cristo Mountains on its eastern flank. A small mountain spur, the Spanish Peaks, extends northeastward from the Southern Sangre De Cristo Mountains near Cuchara.

A majority of the lightning activity over the Sangre De Criston (SDC) mountain region occurs primarily over the southern SDC Mountains. More specifically, this maximum occurs over the east and southeast facing slopes of the SDC Mountains from the Spanish Peaks south to the Colorado New Mexico border. This maximum in activity then extends eastward out onto the Raton Mesa.

So why is there relatively little lightning over and near the east facing slopes of the Sangre de Cristo Mountains north of the Spanish Peaks as compared to areas south of the Spanish Peaks? The reason is likely due to a lack of lower level moisture to sustain convection. Although many mountain tops of the entire SDC Mountain range have been found to be a favorable for initiating convection (Klitch et al 1985, Schaaf et al 1988, Banta and Schaaf 1987), the lack of low level moisture to the east of the SDC mountain range north of the Spanish Peaks limits the amount of lightning activity. Flash densities to the immediate east of the Northern SDC Mountains are rather low, ranging between 2.0 – 3.0 f/km2. This lack of moisture is primarily due to the blocking by the Wet Mountains. The Wet Mountains themselves show higher flash rates with values ranging between 3.5 – 4.5 f/km2 along and to the east this smaller mountain range.

Unlike the SDC Mountains north of the Spanish Peaks which are blocked by the Wet Mountain range to the east, the SDC Mountains south of the Spanish Peaks are located in a much more favorable area to initiate and sustain convection. First, there is no blocking terrain east of the Southern SDC Mountains. Secondly, an area of higher terrain over the Plains, the Raton Mesa, extends immediately east of the Southern SDC Mountains. It is hypothesized that diurnal heating across the Mesa allows low level flow to travel up the mesa, converging at the center along the Colorado/New Mexico border. Convection which then initiates off the Southern SDC Mountains travels to the east in the prevailing westerly flow into this favorable unstable low level atmosphere, sustaining the convection (Unfortunately, unlike the PROFS network in northeast Colorado, no mesonetwork was ever in place over southeast Colorado, and thus studies were never able to be completed to thoroughly analyze the wind flow regime over the Raton Mesa region).

b. Interior Mountains and High Mountain Valleys

Up to this point we have discussed the CG flash density along and to the east of the Mountain/Plains interface. We now shift our focus to the west and discuss the lighting activity in the interior mountains/high mountain valleys of Colorado.

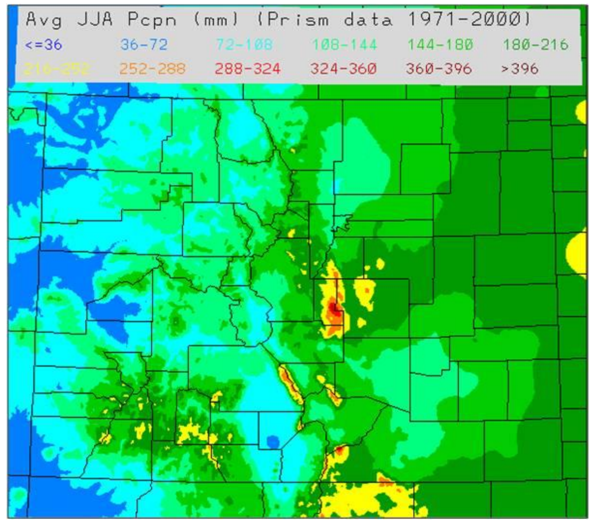


Fig. 6. Thirty year (1971 – 2000) precipitation data for the months of June, July and August over the state of Colorado. Data from PRISM Climate Group (2010)

1. The San Luis Valley

The San Luis Valley, located over south-central Colorado and extending into northern New Mexico, is an extensive high alpine valley covering over 21,000 km2, and sits at an average elevation of 2.3 km (7.5 kft). The valley is surrounded by mountains with elevations in excess of 3 km on nearly all sides (except due south), with the San Juan Range to the southwest-west and northwest, and the Sangre de Cristo Mountains to the northeast-east and southeast. A terrain map of the valley and surrounding mountainous terrain seen in Figure 1.

The San Luis Valley (SLV) is one of the drier (**see** figure 6) and sunniest locations in the State of Colorado. Not surprisingly, the least amount of lightning in the state of Colorado occurs in the SLV, where flash rates in most of the valley are 1.0 fl/km2 or less. Why are the flash rates so low in the SLV?

The primary reason for the minimum in lightning activity over the SLV is likely due to the high terrain that surrounds the valley and blocks low level moisture from entering the valley. Quality low level moisture, located over the eastern Plains of Colorado, is blocked by the Sangre de Cristo Mountains to the east. The extensive San Juan Mountains block any low level moisture arriving from the west and southwest.

An additional reason for the anomalously low flash density values within the valley may be due to the size of the valley floor itself. As discussed above, the SLV is a rather large high terrain valley. On a typical summer day, heating will allow for upslope winds to develop along the mountains. As air rises along the mountain slopes, compensating downward vertical motion will occur over the valley floor. Continued heating of the valley floor will gradually erode the inversion, and the convective boundary layer will gradually mix out. Once mixing is complete, surface winds across the valley will blow from the direction of the ridge-top level winds (Banta 1984). In the case of the San Luis valley during the warm season, a southwesterly wind will prevail by afternoon across the surface of the valley.

Given the lack of low level moisture over the SLV and the overall downward vertical motion which occurs over the large valley floor, any thunderstorms which move off the higher terrain of the San Juan Mountains and into the valley will move into an unfavorable environment and weaken. Additionally, thunderstorm initiation over the valley floor is typically not favorable due to the overall downward vertical motion of the valley.

Although overall conditions are not favorable for lightning over the SLV, some lightning is observed. This lightning activity is likely due to either stronger dynamic systems which occasionally move across the SLV during the warmer months, or when there is sufficient low level moisture in the valley (mainly during the monsoon season) and the flow in the lower atmosphere is light. Regarding the latter case, when sufficient lower level moisture is available and the flow is relatively light, storms forming over the mountains will develop cool pools which will propagate over the valley floor. If sufficient instability exist, these cool pools will initiate new convection. Additionally, collision of these boundaries will initiate new convection.

2. The San Juan Mountain Region

The third area of relative maximum lightning activity over the Centennial State occurs across the San Juan Mountain region located across the southwest part of the Colorado. The San Juan mountain region actually consists of two mountain ranges; the La Garita Mountain Range located to the north, and the San Juan Range located to the south through southeast. These two large mountain ranges are divided by Rio Grande River drainages. The lightning distribution across the entire San Juan Mountain region shows that most of the activity occurs across the San Juan Range, where values range between 3.0 and 5.0 fl/km2. Significantly lesser amounts, ranging between 2.0 and 3.0 fl/km2 occur across the La Garita range.

Compared to the Eastern Plains/Mountains interface, a majority of the lightning activity which occurs across the San Juan Mountain region occurs during the latter part of the warm season. Figure 7a-d shows the lightning activity on a monthly basis across the state of Colorado for the months of June through September. During June (Fig. 7a), areas of enhanced lightning activity can be clearly seen over the Pikes Peak/Palmer Divide region and the Raton Mesa region while lightning activity over the interior mountain areas, including the San Juan mountain region, is minimal. By July (Fig. 7b), enhanced areas of activity are noted across the Palmer Divide region and the Raton Mesa region along with the San Juan Mountain region. This pattern continues into August (Fig. 7c) where all 3 areas show enhanced activity. By September (Fig. 7d), activity statewide decreases significantly, however, the southwestern part of the State shows the most active area as compared to the remainder of the State.

Moisture for the deep convection which occurs over the San Juan Mountain region of Colorado is likely related to the North American (NA) monsoon. Briefly, the NA monsoon is a seasonal shift in the subtropical ridge which affects the precipitation over the Southwest United States and Northwest Mexico. From a sensible weather standpoint, it is experienced as a pronounced increase in precipitation between the months of June and July across the region; with the increased precipitation continuing through September. It has been found that over 50% percent of the annual precipitation which occurs over small parts of Arizona, New Mexico and a large area of Northwest Mexico occur during the months of July, August and September (Douglas et. al. 1993, Adams and Comrie 1997).

Although the San Juan mountain region does not receive 50% of its annual precipitation between July and September (most precipitation falls during the winter months), it does show a marked increase in precipitation between the months of June and July. An examination of precipitation data for 23 weather stations across the San Juan mountain region during a 30 year period (1971-2000) indicate precipitation nearly doubles between the two months. The average precipitation for all stations in June is 1.3 inches, increasing to 2.4 inches in July (an increase of 185%; NRCS 2009, NOAA NOWdata 2009). All of the 23 stations showed a positive increase in precipitation between these two months.

We now explain why most of the lightning occurs across the San Juan range, with lesser amounts over the La Garita range. As was discussed above, it was shown most lightning activity across the San Juan Region occurs during NA monsoon season which is most pronounced during the months of July, August and into September. With regards to the San Juan Mountain region, nearly all of the moisture from the NA monsoon advects northward from the states of New Mexico and Arizona. As this moist and unstable air moves up the higher terrain, thunderstorms form over the southern flanks of the San Juans. Interestingly, once storms initiate over the mountains, the storms typically move back down the higher terrain (see http://www.crh.noaa.gov/Image/pub/ltg2/ltg_ALL_02_ densityPlot_dot5s_loop.gif for hourly loop of lightning across the state of Colorado). The reason for this we believe is due to the overall weak flow aloft. Once storms initiate, they send out cold pools which then propagate back down the higher terrain forcing new convection at lower elevations. This pattern is similar to the convection which develops over the higher terrain of Arizona and moves onto the desert floor (Watson et. al. 1994).

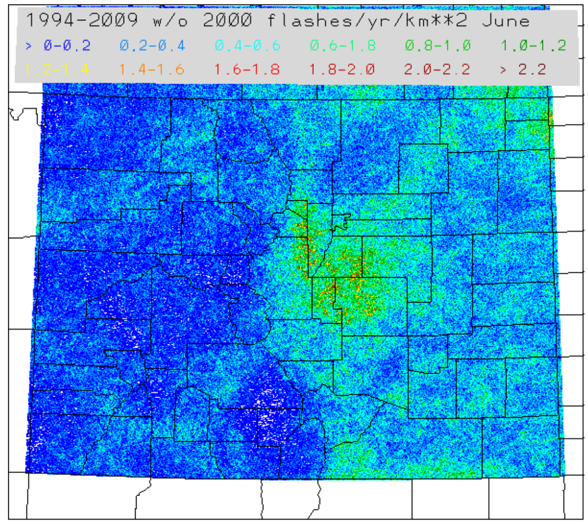
3. West Central and Northwest Colorado

Overall lightning flash values over the northwest Colorado region are low. Values across the lower elevations (<7500 feet) are typically less than 1.5 fl/km2 while higher elevations the flash rates are typically in the 2.0 to 3.0 fl/km2 range. The overall low flash amounts across this region are likely due to the blocking of quality moisture during the warm season. Abundant low level moisture on the eastern Plains is blocked by the mountains along the mountains/plains interface (Primarily the Colorado Front Range/Ten Mile Range and the Sangre De Cristo Mountains. The San Juans to the south block the North American Monsoon moisture which develops during the mid to late summer season.

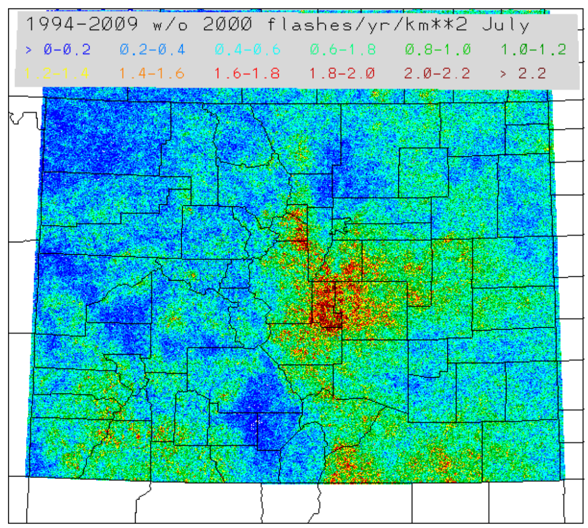
Specifically, another relative minimum in lightning activity is noted over the northwest part of the state. Flash values over this region (primarily Moffat County) are typically range between >0.0 to 1.5 fl/km2. This region is dominated by high plateaus and is well removed from any moisture source.

Interesting characteristics in the lightning flash values are seen over the west central part of the state. This area is predominantly drained by the Colorado River and its associated tributaries, including the Gunnison River. The valleys of these river valleys can be clearly seen in figure 3. Some of these valleys can be seen in rather intricate detail, especially across Pitkin County. Overall, lightning flash values across these regions range from 0.5 to 1.5 fl/km2 over the valleys to 2.0 to 3.0 fl/km2 across the mountains and higher mesa regions.

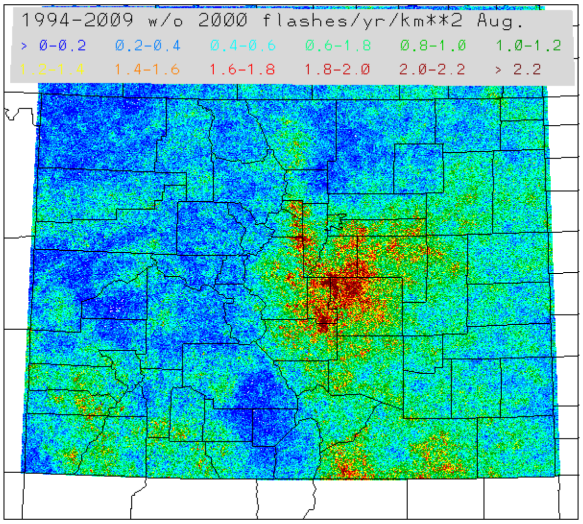
As was stated at the earlier in this paper, there is little relationship between the height of the mountains and the amount of cloud to ground lightning activity. Some of the taller mountain ranges located in the west central/central part of the state, including the Sawatch range and Elk range do not show much in the way of lightning activity. Many of the peaks within these ranges are well over 3.7 km (12.0 kft) in elevation.



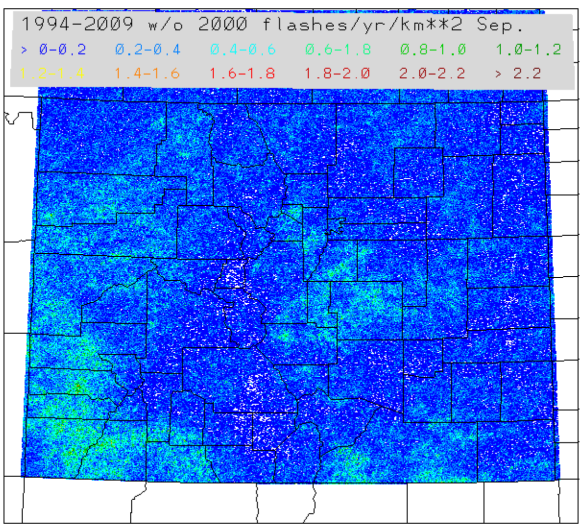
(a)



(b)



(c)



(d)

Fig. 7 a-d. Monthly lightning plots for June (a), July (b), August (c) and September (d).

6 Acknowledgments

The Authors would like thank Jennifer Stark (MIC NWS Pueblo CO) for her support, Precipitation data was supplied by the Prism Group, Copyright 2010, Oregon State University, http://prism.oregonstate.edu/

7 REFERENCES

Abbs, D. J. and R. A. Pielke, 1986: Thermally forced surface flow and convergence patterns over Northeast Colorado. *Mon. Wea. Rev*., **114**, 2281-2296.

Adams, D. K. and A. C. Comrie, 1997: The North American Monsoon. *Bull. Amer. Meteo. Soc.,* **10**, 2197-2213.

Banta, R. M., 1984: Daytime boundary-layer evolution over the mountainous terrain. Part 1: Observations of the dry circulation. *Mon. Wea. Rev*., **112**, 340-356.

Banta, R. M. and C. B. Schaaf, 1987: Thunderstorm genesis zones in the Colorado Rocky Mountains as determined by traceback of Geosynchronous satellite images., *Mon. Wea. Rev*., **115**, 463-476.

Beran, D. W. and C. G. Little, 1979: Prototype regional observing and forecasting service: From concept to implementation. *Natl. Wea Dig*., **4**, 2-5.

Bonner, W. E., 1968: Climatology of the low level Jet. *Mon. Wea. Rev.,* **96**, 833–850.

Brady, R. H. and E. J. Szoke, 1989: A Case Study of Nonmesocyclone Tornado Development in Northeast Colorado: Similarities to Waterspout Formation. *Mon. Wea. Rev.,* **117**, 843-856.

Cummins, K. L. and M. Murphy, 2009: An Overview of Lightning Locating Systems: History, Techniques, and Data Uses, With an In-Depth Look at the U.S. NLDN. *IEEE Transactions on Electromagnetic Compatability*, **51**, 499-518.

Cummins K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, 1998: A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys. Res.*, **103**, 9035–9044.

Cummins, K. L., J. A. Cramer, C. J. Biagi, E. P. Krider, J. Jerauld, M. A. Uman, and V. A. Rakov, 2006: The U.S. National Lightning Detection Network: Postupgrade status. Preprints, *Second Conf. on Meteorological Applications of Lightning Data,* Atlanta, GA, Amer. Meteor. Soc., 6.1.

Defant, F., 1951: Local winds. *Compendium of Meteorology*. Amer. Meteor. Soc., 655-672.

Doesken, N. J., and R. A. Pielke, 2003: Climate of Colorado. Internet document: http://ccc.atmos.colostate.edu/climateofcolorado.php

Doswell, C. A., 1980: Synoptic-scale environments associated with High Plains severe thunderstorms. *Bull. Amer. Meteo. Soc.,* **61**, 1388–1400.

Douglas, M.W., R. Maddox, K. Howard and S. Reyes, 1993: The Mexican Monsoon. *J. Climate*, **6**, 1665-1677.

Edman, D.A., 1997, National Lightning Data on the Western Region Wide Area Network. *Western Region Technical Attachment 97-20.*

Glahn, H. R., and D. P. Ruth, 2003: The new digital forecast database of the National Weather Service. *Bull. Amer. Meteor. Soc*., **84,** 195–201.

Hales, J. E., 1974:. Southwestern United States summer monsoon source-Gulf of Mexico or Pacific Ocean? *J. of App. Meteo.,* **13**, 331–342.

Klitch, M. A., J. F. Weaver, F. P. Kelley, and T. H. Vonder Haar, 1985: Convective cloud climatologies constructed from satellite imagery. *Mon. Wea. Rev*., **113**, 326-337.

Krider, E. P., R. C. Noggle, A. E. Pifer, and D. L. Vance, 1980: Lightning direction finding systems for forest fire detection. *Bull. Amer. Meteor. Soc.,* **61,** 980–986.

LaJoie, M. and A. Laing, 2008: The Influence of the El Niño–Southern Oscillation on Cloud-to-Ground Lightning Activity along the Gulf Coast. Part I: Lightning Climatology. *Mon. Wea. Rev.,* **136**, 2523–2542.

López, R. E., and R. L. Holle, 1986: Diurnal and spatial variability of lightning activity in northeastern Colorado and central Florida during the summer. *Mon. Wea. Rev.,* **114,** 1288–1312.

Maddox, R. A., D. M. Rodgers, W. Deitrich and D. l. Bartels, 1981: Meteorological settings associated with significant convective storms in Colorado. NOAA Tech. Memo. ERL OWRM-4, U.S. Dept. Commerce, Washington DC. 75 pp.

Mach, D. M., D. R. MacGorman, W. D. Rust, and R. T. Arnold, 1986: Site errors and detection efficiency in a magnetic direction-finder network for locating lightning strikes to ground. *J. Atmos. Oceanic Technol.,* **3,** 67–74.

NOAA, 2004: The North American Monsoon. Reports to the Nation. Climate Prediction Center.

NOAA – Western Regional Climate Center 2009: http://www.wrcc.dri.edu/htmlfiles/westcomp.clr.html#COLORADO

NOAA NOWdata – NOAA Online Weather Data 2009 http://www.weather.gov/climate/xmacis.php?wfo=pub

NRCS – Natural Conservation Resource Service – Colorado Precipitation Data http://www.co.nrcs.usda.gov/

Orville, R. E.,R. W. Henderson, and L. F. Bosart, 1983: An East Coast lightning detection network. *Bull. Amer. Meteor. Soc.,* **64,** 1029–1037.

Orville, R. E., 1991: Lightning ground flash density in the contiguous United States—1989. *Mon. Wea. Rev.,* **119,** 573–577.

——, 1994: Cloud-to-ground lightning flash characteristics in the contiguous United States: 1989–1991. *J. Geophys. Res.,* **99,** 10 833–10 841.

------, 2008, Development of the National Lightning Detection Network. *Bull. Amer. Meteo. Soc.*, **89**, 180-190.

——, and G. R. Huffines, 2001: Cloud-to-Ground lightning in the United States: NLDN results in the first decade, 1989–98. *Mon. Wea. Rev.,* **129,** 1179-1193.

——, and G. R. Huffines, 1999: Lightning ground flash measurements over the contiguous United States: 1995–97. *Mon. Wea. Rev.,* **127,** 2693–2703.

—, G. R. Huffines, W. R. Burrows, R. L. Holle, and K. L. Cummins, 2002: The North American Lightning Detection Network (NALDN)—First results: 1998–2000. *Mon. Wea. Rev.,* **130,** 2098–2109.

Prism Climate Group, Copyright 2010, Oregon State University, http://prism.oregonstate.edu/

Reap, R. M., 1986: Evaluation of cloud to ground lightning data from the Western United States for the 1983-84 Summer seasons. *J. Appl. Meteo.*, **25**, 785-799.

Reynolds, D. W., 1983: Prototype workstation for mesoscale forecasting. *Bull. Amer. Meteo Soc*., **64,** 264-273.

Rudlosky, S. D. and H. E. Fuelberg, 2010: Pre- and postupgrade distributions of NLDN reported cloud-to-ground lightning characteristics in the contiguous United States. *Mon. Wea. Rev.,* **138,** 3623-3633.

Ruth, D. P., 2002: Interactive forecast preparation—the future has come. Preprints, *Interactive Symp. on the Advanced Weather Interactive Processing System (AWIPS),* Orlando, FL, Amer. Meteor. Soc., 20–22.

Schaaf C. B., J. Wurman and R. M. Banta, 1988: Thunderstorm producing terrain features. *Bull Amer Meteo Soc*., **69**, 272-277.

Smith, S. B., 1993: Comments on “Lightning ground flash density in the contiguous United States”. *Mon. Wea. Rev.,* **121**, 1572-1573.

Smith, J. R., H.E. Fuelberg, and A. I. Watson 2005: Warm Season Lightning Distributions over the Northern Gulf of Mexico Coast and Their Relation to Synoptic-Scale and Mesoscale Environments. *Wea. Forecasting,* **20**, 415–438.

Smith, W. P. and R. L. Gall, 1989: Tropical squall lines of the Arizona monsoon. *Mon. Wea. Rev.,* **117**, 1553–1569.

Szoke, E. J. and M. L. Weisman, J.M. Brown, F. Caracena and T. W. Schlatter, 1984: A subsynoptic analysis of the Denver tornadoes of 1981. *Mon. Wea. Rev.* **112**, 790-808.

Szoke, E. J. and J. A. Augustine, 1990. A decade of tornado occurrences associated with a surface mesoscale flow feature – the Denver cyclone. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Amer. Meteor. Soc., 40-45.

Szoke, E. J., J., D. Barjenbruch, R. Glancy and R. Kleyla, 2006: The Denver cyclone and tornadoes 25 years later: The continued challenge of predicting non-supercell tornadoes. Preprints, *23rd Conf. Severe Local Storms*., St Louis, MO. , Amer. Meteor. Soc.

Toth, J. J. and R. H. Johnson, 1985: Summer surface flow characteristics over Northeast Colorado. *Mon. Wea. Rev.* **113**, 1458-1469.

Wacker, R. S. and R. E. Orville, 1999: Changes in the measured lightning flash count and return stroke peak current after the 1994 U.S. National Lightning Detection Network upgrade. *J. Geophys. Res*., **104**, D2 2151-2157.

Wakimoto, R. M. and J. W. Wilson, 1989: Non supercell tornadoes. *Mon. Wea. Rev*., **117**, 1113-1140.

Watson, A. I, and R. L. Holle, 1996: An Eight-Year Lightning Climatology of the Southeast United States Prepared for the 1996 Summer Olympics. *Bull. Amer. Meteo. Soc.* **77**, 883–890.

Watson, A. I., R. E. López and R. L. Holle, 1994: Diurnal cloud to ground lightning patterns in Arizona during the Southwest Monsoon. *Mon. Wea. Rev*., **122,** 1716-1725.

Wilczak, J. M. and J. W. Glendening, 1988: Observations and mixed modeling of a terrain-induced mesoscale gyre: the Denver cyclone. *Mon. Wea. Rev*., **116**, 2668-2711.

Zajac, B. A. and S. A. Rutledge, 2001: Cloud-to-Ground Lightning Activity in the Contiguous United States from 1995 to 1999. *Mon. Wea. Rev*., **129**, 999-1019.