Cloud-to-ground lightning flashes and debris-flow-generating rainfall in the post wildfire environment: An exploratory study of the Mitchell Creek debris flow in western Colorado, summer 2002

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[1] Cloud-to-ground (CG) lightning flash parameters collected by the National Lightning Detection Network were analyzed in conjunction with rainfall observations near Mitchell Creek (MC) at the Coal Seam Wildfire site in western Colorado, USA. Nine thunderstorms produced significant CG flashes in the area surrounding MC from 28 June (fire containment) to 5 August 2002. A debris flow was generated at MC by one of these storms at ~2058 LT on 5 August 2002. This study compares the CG flash parameters and rainfall characteristics of the 5 August thunderstorm with the eight thunderstorms (control group) that did not produce a hazardous hydrologic response at MC. The CG flash patterns and a synoptic analysis suggest that the 5 August thunderstorms occurred during a North American Monsoon "burst" period with a strong southwesterly surge of moisture advecting as far north as central Wyoming. The 5 August thunderstorm sequence was bimodal and more intense in terms of CG flash totals and rainfall rates than the control group. Moist southwesterly flow at lower levels and dry southeasterly flow in the upper troposphere may have enhanced orographically forced convection during the evening of 5 August. CG flashes and rainfall at spatial scales of 100 × 100 km, 50 × 50 km, and 25 × 25 km around MC confirm that the 5 August episode was more intense than any of the control group. The analysis concluded that the time of first flash and the number of consecutive 5-min intervals with CG flashes were temporally related with intense rainfall at the debris flow site. Additionally, there was a strong correlation between flash clusters within 40 km of MC and rainfall intensity at the site. The results of this study suggest that CG flash parameters may prove beneficial in modeling rainfall intensity thresholds in areas burned by wildfire. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3324 Meteorology and Atmospheric Dynamics: Lightning; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); *KEYWORDS:* lightning, wildfire, debris flow

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1. Introduction

[2] Debris flows are extremely destructive hydrologic events that occur very rapidly with little warning [*Iverson*, 1997]. These sudden slope failures pose hazards on even gentle slopes and can be dangerous to people and property. The U. S. Geological Survey (USGS) National Landslide Hazard Program estimates that debris flows and shallow landslides account for nearly two billion dollars in damage and upward of 25 deaths annually in the United States. The spatial and temporal distribution of debris flows in steep terrain in the western United States is controlled to a great extent by disturbance regimes in mountain drainage basins and by the distribution of intense rainfall in time and space [*Montgomery and Dietrich*, 1994]. One prevalent disturbance regime in the western U.S. is wildfire. After vegetation-removing wildfires, burned slopes may become more susceptible to erosion processes and debris flows during intense rainfall episodes [*Cannon et al.*, 2001].

[3] Post wildfire debris flows in the Rocky Mountains of Colorado become a threat each summer as wildfires burn vegetation from mountain slopes. According to the National Weather Service Office in Grand Junction, Colorado, the wildfire threat increases significantly in the later part of June, peaks in early July, and remains high throughout August. July and August also see an increase in the frequency of thunderstorms in central and western Colorado. The increased convective activity can be attributed in part to the seasonal onset of the North American Monsoon (NAM) across the Colorado Plateau.

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[4] One of the major problems in assessing debris flow potential in the post wildfire environment is the inability to accurately estimate convective rainfall in mountainous terrain. Rainfall estimates are very difficult to ascertain in mountain regions in part because of topographic-modulated convection common in such areas [*Banta*, 1990]. Mountain areas are also less likely to have dense networks of surface meteorological stations for data collection, complex terrain induces errors in Doppler radar coverage, and some satellite imagers have inadequate temporal resolution for analysis of convection. Satellite imagers also provide only cloud top information, and this alone may not allow for accurate estimates of surface precipitation in complex terrain [*Grecu et al.*, 2000; *Watson et al.*, 1994a]. This exploratory study uses cloud-to-ground (CG) flash information collected from the National Lightning Detection Network (NLDN) to investigate spatial and temporal relationships between lightning flash parameters, convective rainfall, and the generation of debris flows on burned slopes in the Rocky Mountains of western Colorado.

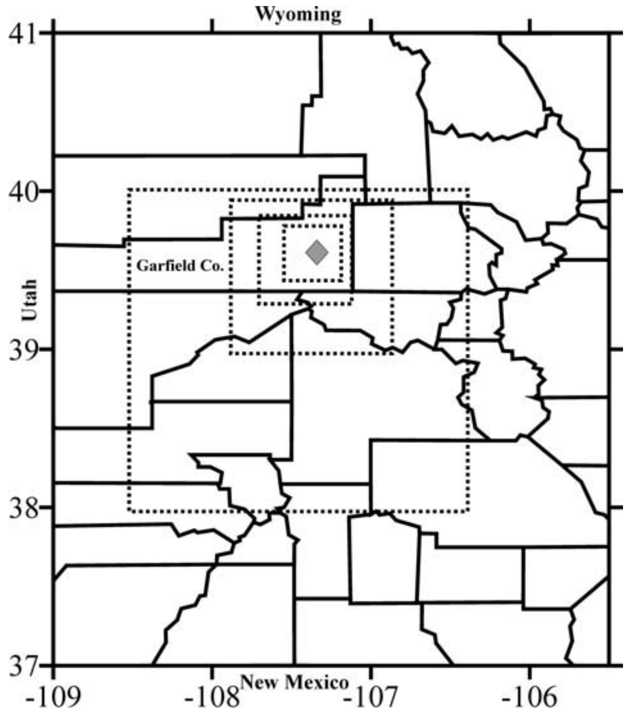

Figure 1. Study area for the analysis of cloud-to-ground (CG) flashes and rainfall in western Colorado. The debris flow sites are located in southeastern Garfield County (shaded diamond). The expanding rectangles outline the spatial analysis units. The full domain analysis unit is bounded at 38°–40°N and 106.5°–108.5°W. The smaller analysis units are 100 × 100 km, 50 × 50 km, and 25 × 25 km.

2. Background

2.1. Debris Flows in the Post Wildfire Environment

[5] The post wildfire hillslope environment is at great risk for a number of destructive hydrologic processes. The hydrologic response to heavy rainfall can range from slight erosion to flash flooding and debris flows along the length of a canyon [*Prosser and Williams*, 1998; *Meyer and Wells*, 1987; *Cannon et al.*, 1998]. Sediment yields have been shown to increase by as much as 25 times on a burned plot compared to an unburned plot, and severe flash flooding was reported in post wildfire Capulin Canyon, New Mexico, in conjunction with active debris flows [*Cannon and Reneau*, 2000].

[6] As the present study will concentrate on debris flow activity, two post wildfire debris-flow-generating processes should be noted: (1) infiltration-triggered soil slip and (2) runoff (overland flow)-triggered sediment mobilization. Infiltration-triggered debris flows are initiated on slopes with increased soil moisture after heavy rainfall episodes. Runoff-triggered debris flows are more likely to occur in conjunction with heavy rainfall and are initiated by eroded material carried in overland flow [*Meyer and Wells*, 1997; *Wells*, 1987]. Both of these processes are dependent on rainfall intensities that are usually associated with convective activity, and *Cannon et al.* [2001] concluded that it is more likely for debris flows to be generated from the first substantial thunderstorms to impact an area after a severe burn.

2.2. The North American Monsoon

[7] The NAM is a period of increased rainfall (primarily convective) over northwestern Mexico and the southwestern portion of the U.S. The core monsoon region is usually defined as those areas that receive at least 50% of their annual rainfall in the months of July, August, and September [*Douglas et al.*, 1993]. The core of the NAM effect is realized in the western foothills of the Sierra Madre Occidental in northwestern Mexico. Southern and eastern Arizona and much of New Mexico experience summer season precipitation that is slightly more variable. The study area for the current research project (western Colorado) is north of the core monsoon area but still receives greater than 30% of its annual precipitation during July, August, and September [*Douglas et al.*, 1993].

[8] The NAM circulation is characterized by periods of "bursts," when convective activity is abnormally high, and "breaks" when convective activity is dramatically reduced. Bursts in the NAM circulation may last for periods upward of 20 days, while breaks are usually much shorter [*Watson et al.*, 1994a]. Areas on the periphery of the NAM core realize the monsoon bursts with increased convection during the late summer months, especially convection that is modulated by topography [*Reap*, 1986]. Potential for convective activity in areas such as the Rocky Mountains of central and western Colorado is enhanced during NAM bursts by pulses of low-level and midlevel moisture from the Gulf of California and the Gulf of Mexico [*Hales*, 1972; *Brenner*, 1974; *Douglas et al.*, 1993]. During NAM bursts the moisture boundary as indicated by the 334°K θ_e surface at 850 hPa and the 332°K θ_e surface at 700 and 500 hPa can push as far north as southern Wyoming [*Watson et al.*, 1994a].

2.3. Cloud-to-Ground Lightning and Convective Precipitation

[9] A number of case studies and climatological analyses have found a strong relationship between convective parameters, CG flashes, and precipitation intensity [*Shackford*, 1960; *Piepgrass and Krider*, 1982]. Across the central plains of the U.S., positive and negative CG flashes were found to be correlated with a number of meteorological processes

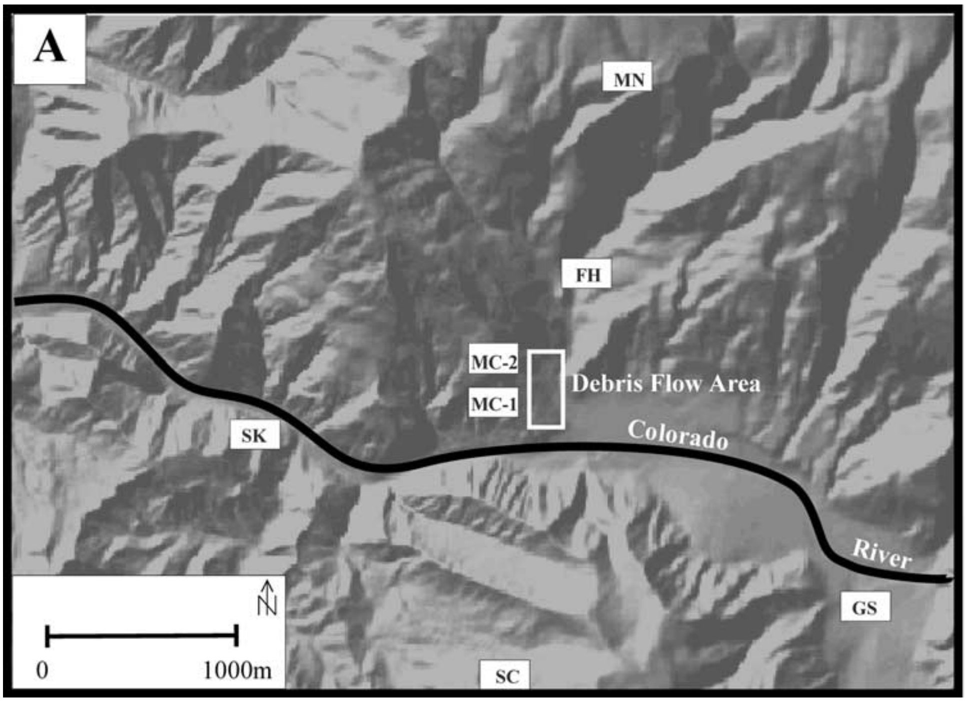

Figure 2a. Digital elevation model of area adjacent to the MC debris flow sites. The rainfall-gauging sites are indicated on the image (open rectangles) along with the area impacted by the debris flows (shaded vertical rectangle). The station names are indicated in Table 1.

including moisture convergence and strong upward vertical motion during severe storms [*Reap and MacGorman*, 1989]. *Soriano et al.* [2001] and *Orville and Silver* [1997] suggest that CG flashes can be used to describe the spatial distribution of convective rainfall, and *Grecu et al.* [2000] concluded that lightning flash data are useful for determining the convective component of mixed rainfall events (those with both convective and stratiform rainfall). For single convective events *Cheze and Sauvageot* [1997] determined that significant correlation exists between CG flash number and mean radar derived rainfall rate.

[10] The relationship between lightning flash parameters and rainfall is regionally variable and varies between climatic regimes. Season-long precipitation volume of 1.3×10^5 m^3 per CG flash was estimated during the large-scale flooding in the upper Mississippi Valley during the summer of 1993 [*Kempf and Krider*, 2003]. In a study of 22 convective rainfall events in Florida, CG flash frequency was shown to be highly correlated with rainfall flux (correlation coefficient = 0.60) [*Tapia et al.*, 1998]. *Petersen and Rutledge* [1998] reported a strong correlation between convective precipitation and CG flash counts across the continental U.S. However, the correlation coefficients varied regionally. The correlation coefficients for thunderstorms occurring in the southeast , the northeast, the midcontinent, and the arid southwest 0.90 were 0.71, 0.45, 0.87, and 0.90, respectively. Differing climatic regimes were also found to be an important consideration in determining the strength of the lightning-to-rainfall relationship across the Iberian Peninsula [*Soriano et al.*, 2001]. The semiarid region of the Iberian Peninsula exhibited stronger correlation (0.75) compared to the humid region of the peninsula, where the correlation coefficient was 0.67.

[11] In the semiarid southwestern region of the U.S. a number of obstacles, including the mountainous terrain, stand in the way of adequate forecasting and modeling of convective precipitation and the hydrologic processes generated by intense rainfall. As hydrologic processes such as flash flooding and debris flow generation are dependent on high-intensity convective rainfall, the ability to use CG flash data to model and predict these processes would represent a major advance in hydrometeorology. Since the development of the NLDN in 1989 the data gathered from the network have been used in a number of studies as an indicator of related atmospheric processes and hydrologic hazards. For example, *Hunter et al.* [2001] used CG flash patterns to indicate the potential for heavy frozen precipitation bands in the southeastern U.S. during thunder-snow episodes. *Holle and Bennett* [1997] analyzed the spatial and temporal correspondence of CG flashes and flash flooding in Tucson, Arizona, and concluded that rapid increases in streamflow were coincident with the occurrence of CG flashes in small urban watersheds. *Soula et al.* [1998] investigated the relationship between CG flash activity and heavy convective rainfall leading to flash flooding in a mountainous region of Spain. The researchers found that the lightning flash rate was quite high before precipitation was observed on the ground, and as the storm progressed, the core of CG flash intensity remained spatially aligned with the core area of heaviest rainfall.

3. Study Area

[12] The debris flow episode at the center of this analysis occurred on burned slopes along Mitchell Creek (MC) in southeastern Garfield County, Colorado, near to the town of

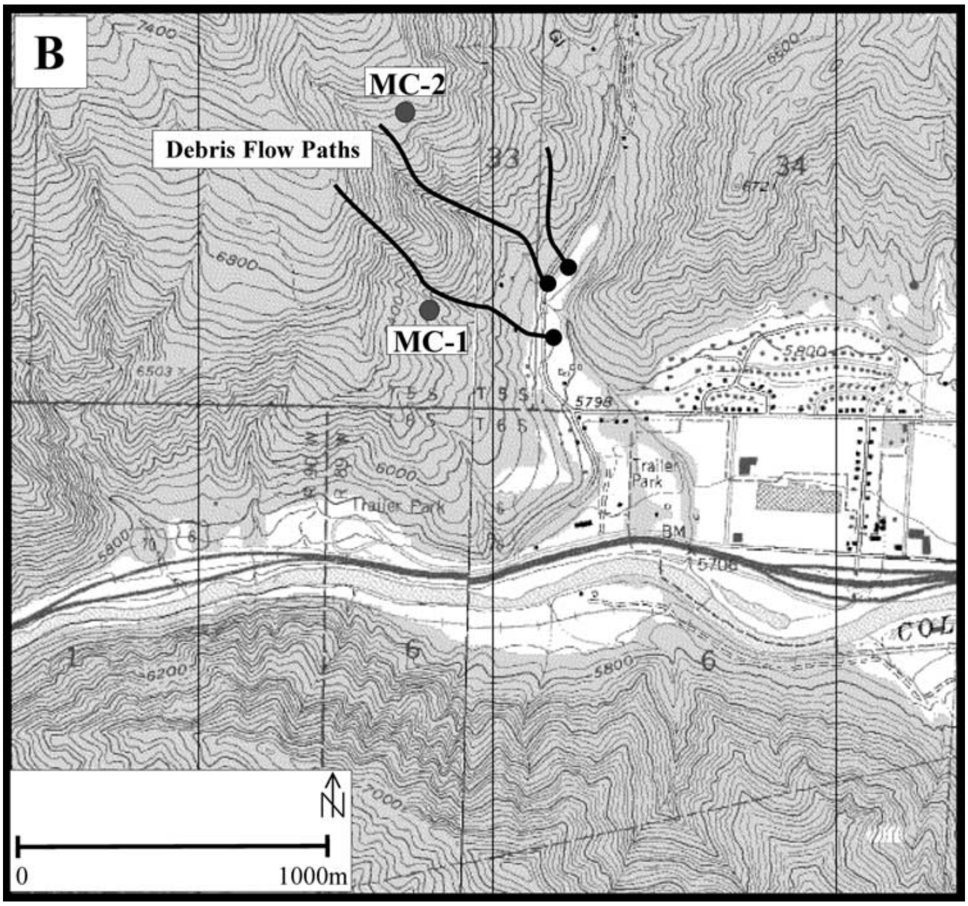

Figure 2b. Topographic representation of the immediate area where debris flows occurred on 5 August 2002. The two USGS rainfall-gauging sites are indicated on the map along with the approximated paths of the debris flows.

Glenwood Springs (GS) (Figure 1). The rainfall patterns associated with northward advecting monsoon moisture demand that a large portion of western Colorado (38°N–40°N and 106.5°W–108.5°W) serve as the CG flash analysis area. The study will also include detection and analysis of CG flashes and rainfall at smaller spatial scales which are defined at grids of 100 × 100 km, 50 × 50 km, and 25 × 25 km (Figure 1).

4. Data and Methods

[13] Lightning data for this project were acquired from Vaisala Inc. The data consist of time of flash, location, peak amperage, and multiplicity. These data represent CG flashes over the study area from 1 June through 30 September 2002. The NLDN data for this study were not corrected for detection error as the detection efficiency for the network is estimated to be 80–90% [*Orville and Huffines*, 2001; *Huffines and Orville*, 1999; *Cummins et al.*, 1998]. The location accuracy for NLDN-detected GG flashes in the western United States is 0.5–1.0 km [*Edman*, 1997]. Rainfall data were obtained from on-site tipping-bucket rain gauges set up by the USGS near MC after the Coal Seam wildfire and from five stations in the Cooperative Institute for Regional Prediction's Mesowest network (Figures 2a and 2b) [*Horel et al.*, 2002].

[14] To explore the relationship between CG flashes and debris-flow-generating rainfall at MC, flash data were first partitioned into 5-min increments [*Holle and Bennett*, 1997]. Next, CG flash parameters including flash frequency, flash density, and percent positive flashes were calculated for each of the spatial analysis units using 5-min interval flash information. Rainfall data for the MC area were used to calculate storm-relative intensity and storm total rainfall for each thunderstorm occurring from the date the Coal Seam wildfire was contained (28 June 2002) until the debris flow at MC (5 August 2002). Finally, CG flash characteristics and rainfall parameters for the thunderstorm that generated the MC debris flow episode were compared to a "control group" of thunderstorms in the same season that did not generate debris flows at the wildfire burn site.

5. Results

5.1. Cloud-to-Ground (CG) Lightning Activity in Western Colorado: Summer 2002

[15] During the summer of 2002 the entire western portion of Colorado (full-domain) saw a total of 27,140 CG flashes. Over this large portion of Colorado, 7.1% of the CG flashes were positive. Four distinct bursts-break cycles and two additional less distinct burst periods can be detected in the daily flash time series depicted in Figure 3a [*Watson*

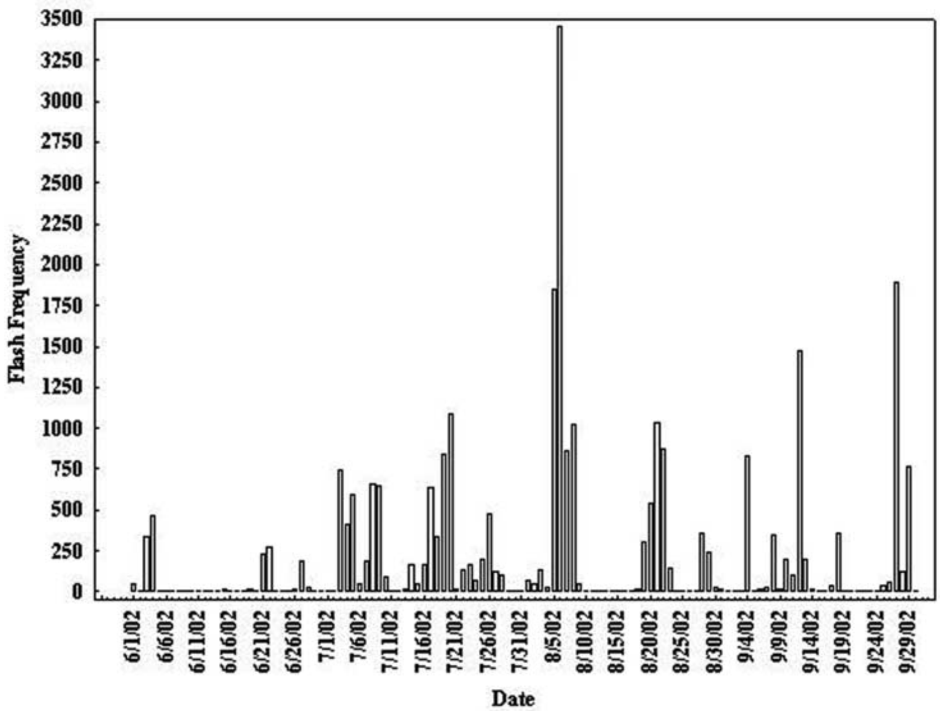

Figure 3a. Daily CG lightning flashes from 1 June through 30 September 2002 for the portion of western Colorado bounded by 38°–40°N and 106.5°–108.5°W. Seven burst/break periods can be identified in the time series.

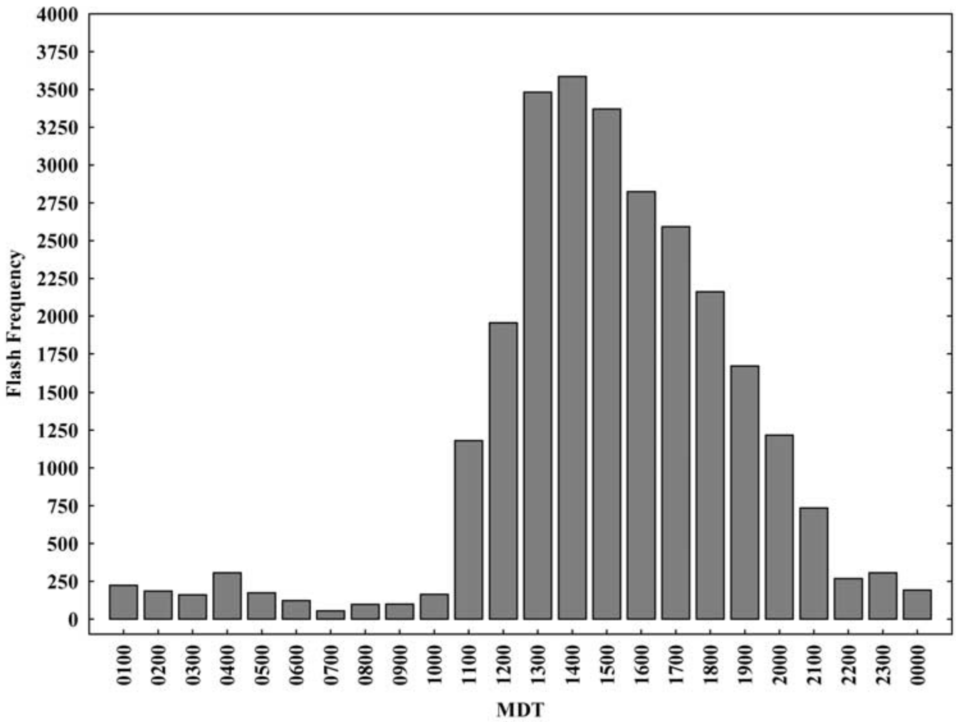

Figure 3b. Diurnal CG lightning flash frequency for the period 1 June through 30 September 2002 over the area of western Colorado bounded by 38°–40°N and 106.5°–108.5°W.

Table 1. Rainfall Observation Data for the Period Between 28 June 2002 and 5 August 2002[a]

Station	Elevation, m	17 July, mm	19 July, mm	20 July, mm	26 July, mm	5 August, mm
MC-1	2073	0.0	0.51	2.51	5.8	8.6
MC-2	1902	0.0	0.0	0.0	7.1	8.9
FH	1875	0.0	0.0	4.4	6.1	12.1
GS	1750	2.5	2.5	2.5	2.5	7.6
MN	2853	0.0	0.0	5.1	8.4	7.1
SC	2559	0.0	0.0	0.0	6.6	17.0
SK	2680	0.0	0.0	5.6	9.2	4.1

[a]Only the CG lightning episodes that produced rainfall at one of the seven sites are included. The MC stations are operated by the USGS, and the five auxiliary stations are operated as part of Mesowest. The locations of the stations are indicated in Figure 2a. MC-1, Mitchell Creek-1; MC-2, Mitchell Creek-2; FH, Fish Hatchery; GS, Glenwood Springs; MN, Mitchell Canyon; SC, South Canyon; SK, Storm King Mountain.

et al., 1994b]. The first burst begins on 3 July and ends on 10 July. The second burst begins on 14 July and continues for 14 days. Burst three, which incorporates the debris flow date, begins on 1 August and ends on 9 August. The fourth burst begins on 19 August 2002 and continues through 23 August. The periods around 5 and 27 September suggest that convection is evident on consecutive days but lightning flashes are not as prolific as the four prior periods. From this 4-month time series it is evident that the burst period in early August was the strongest in terms of daily flash frequency.

[16] The hourly distribution of CG flashes during summer 2002 is graphically represented in Figure 3b. As is common in the southwestern U.S., lightning activity is most pronounced in the afternoon hours [*Lopez and Holle*, 1986]. In this instance, CG flashes were detected with great frequency beginning at 1100 LT, and 1400 LT was the most prolific hour with a total of 3587 flashes during the 4-month period.

5.2. CG Flashes and Rainfall: Control Group

[17] Within the analysis domain at 100 × 100 km around the Coal Seam wildfire site there were 7217 CG flashes recorded for the entire summer of 2002. Of these flashes in the 100 × 100 km domain, 8.2% were positive. This is slightly higher than the percent positive for the entire western portion of the state. Eight thunderstorms that occurred between 28 June 2002 and 4 August 2002 had daily flash frequencies of 20 CG flashes or greater over the 100 × 100 km analysis area.

[18] Only three of the control group thunderstorms produced rainfall at the MC rain-gauging sites (Table 1). The 19 July 2002 lightning and rainfall episode produced a total of 0.5 mm of rainfall between 2220 and 2230 LT at MC-1. The MC-1 gauge measured 2.5 mm during the 20 July episode. This rainfall occurred between 1710 and 1815 LT. The 26 July thunderstorm produced 5.8 mm of rainfall at MC-1 and 7.1 mm at MC-2. The rainfall at MC-1 was collected between 0110 and 0315 LT with the greatest 5-min intensity (1.8 mm) occurring at 0100 LT. MC-2 collected rainfall from 0115 to 0325 LT. The most intense 5-min rainfall was recorded at 0120 LT (1.8 mm).

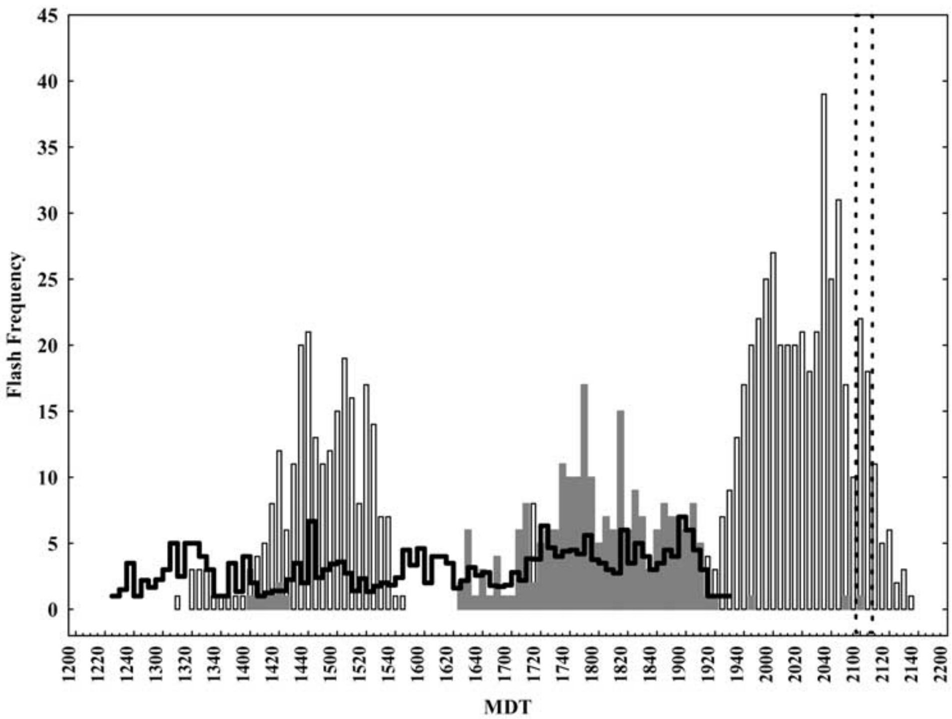

Figure 4. CG lightning flash sequence for 5 August 2002 over a 100 × 100 km area centered at the MC debris flow site (hatched bars). The flash frequency is presented at 5-min intervals. The flash frequency for the most prolific control episode (19 July) is superimposed with shaded bars, and the mean control group time series is represented by the dark stepped line. The time of debris flow initiation on 5 August is represented by dashed lines beginning at 2058 LT.

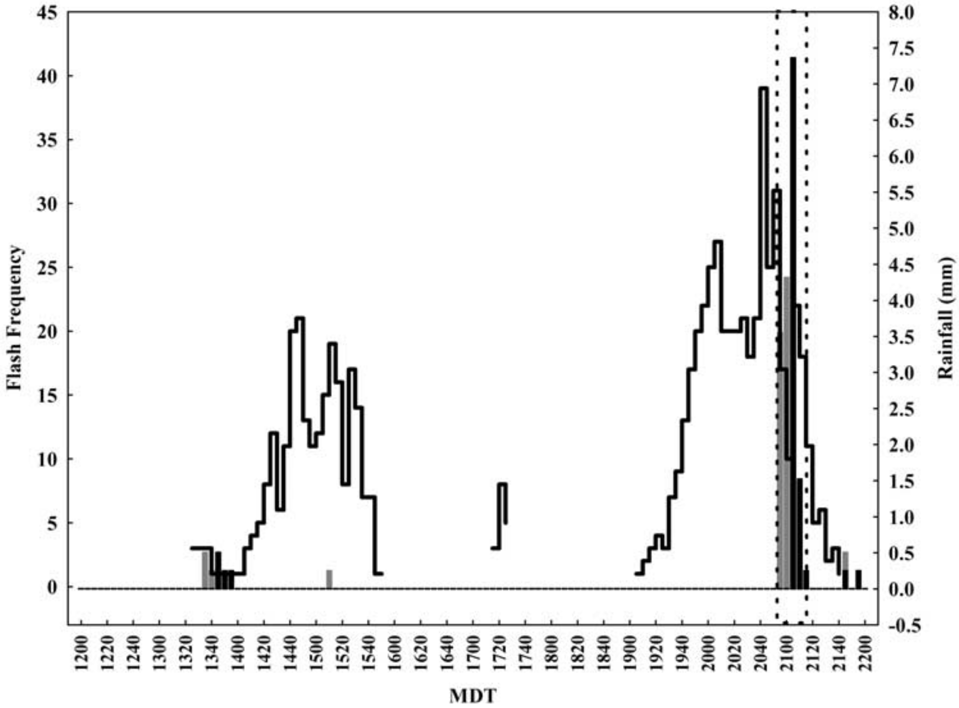

Figure 5a. CG lightning flashes and 5-min rainfall rates for the thunderstorms of 5 August 2002. The analysis area encompasses 100 × 100 km surrounding the MC debris flow site. CG flash frequency is indicated with the stepped line segments, and rainfall is represented by shaded columns (light shading denotes MC-1; dark shading denotes MC-2). The time of debris flow initiation is represented by dashed lines beginning at 2058 LT.

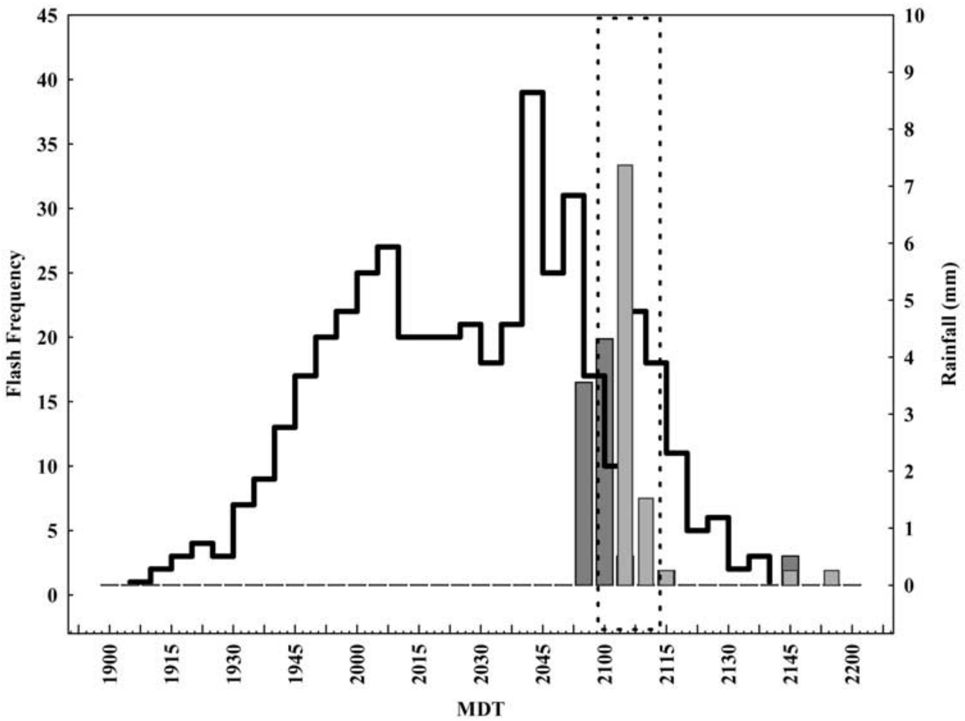

Figure 5b. Late evening CG lightning flash sequence and 5-min rainfall rates for 5 August 2002. The CG flashes are represented by the stepped line segment. Rainfall at MC-1 is represented by the lightly hatched columns and rainfall at MC-2 is represented by the heavily hatched columns. The time of debris flow initiation is represented by dashed lines beginning at 2058 LT.

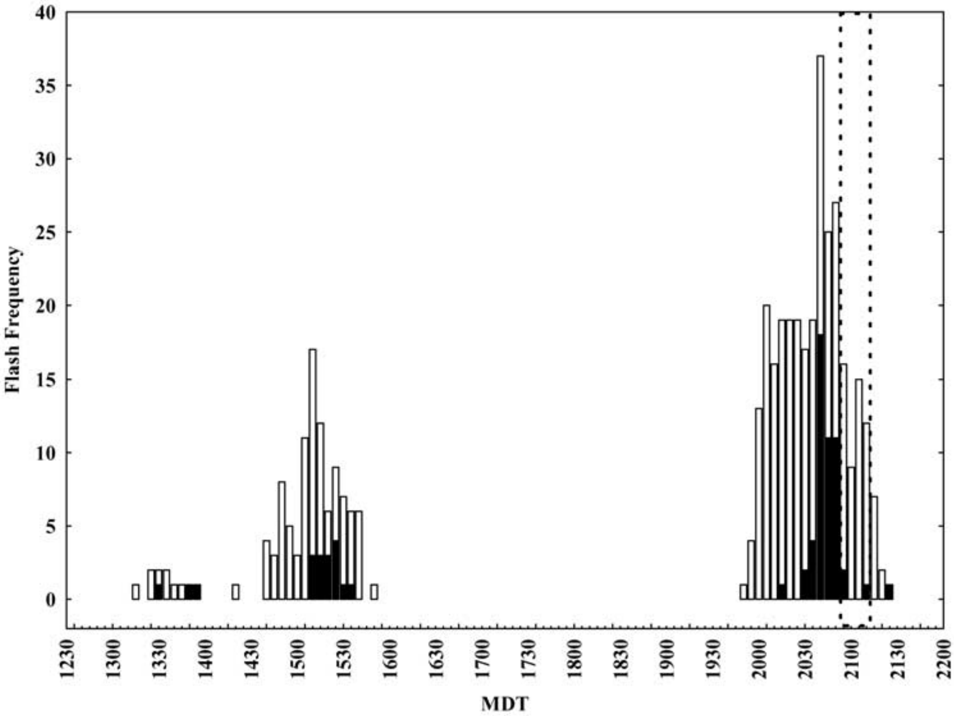

Figure 6. CG lightning flash sequences occurring on 5 August 2002. The spatial analysis units represented are 50 × 50 km (open bars) and 25 × 25 km (solid bars) centered at the MC debris flow site. The time of debris flow initiation is represented by dashed lines beginning at 2058 LT.

[19] The five Mesowest rainfall-gauging instruments that are sited near MC provide data at temporal intervals greater than 5 min so the Mesowest records will be discussed in terms of hourly rainfall. There was no rainfall recorded for the lightning episodes of 3, 4, 5, or 8 July 2002 at the Mesowest sites. Both GS and Storm King Mountain (SK) recorded light rainfall on 17 and 19 July. The heaviest rainfall was recorded during the 20 and 26 July episodes. The 26 July 2002 episode was the only control group event to produce rainfall at all seven observation sites (five Mesowest and two USGS). This event also produced rainfall totals as high as 9.2 mm over a 10-hour period at SK, 8.4 mm over 3 hours at Mitchell Canyon (MN), 6.6 mm over 3 hours at South Canyon (SC), and 6.1 mm over 3 hours at Fish Hatchery (FH). GS reported a single hour total of 2.5 mm during this episode.

5.3. CG Flashes and Rainfall: 5 August 2002

[20] The thunderstorm episode of 5 August 2002 produced rainfall with an intensity sufficient to generate debris flows along MC. The debris flows occurred at approximately 2058 LT after heavy rainfall was reported by emergency management personnel. The debris flow left 6–8 feet of mud and boulders in the canyon near the GS Fish Hatchery [*McGregor*, 2002].

[21] Figure 4 shows the 5 August CG flash time series from 1200 to 2200 LT for the 100 × 100 km grid around the MC site. The most prolific CG flash-producing control group storm (19 July 2002) is superimposed on the time series for comparison. The 5 August episode was much larger than any of the control thunderstorms in terms of CG flash activity. The episode produced a total of 725 CG flashes over a 9-hour period. Only 3.2% of the CG flashes lowered a positive charge to the ground. The 5 August lightning episode had a temporal pattern very different from both the mean control group thunderstorm and the 19 July episode, with an early afternoon CG flash sequence between 1330 and 1545 LT and a larger flash sequence in the evening hours. The early flash sequence consisted of 246 CG flashes. The later sequence was larger in total flashes

Table 2. Characteristics of the 5 August 2002 Thunderstorm Compared to the Mean Characteristics of the Control Group Storms[a]

	100 × 100 km		50 × 50 km		25 × 25 km	
	5 August	Control	5 August	Control	5 August	Control
Total flash count	463	119	408	34.41	69	6.4
Length of flash episode, min	155	280	95	97	70	17
Consecutive 5-min intervals with ≥1 flashes	31	26.31	20	11.4	9	3.4
Consecutive 5-min intervals with ≥5 flashes	24	6.25	16	3.0	3	0
Consecutive 5-min intervals with ≥10 flashes	20	0.88	14	1.0	3	0
Period between first flash and MC-1 rainfall, min	110	NA	65	NA	40	NA
Peak 5-min flash frequency	39	15	37	10	18	3
Period between flash peak and MC-1 rainfall, min	15	NA	15	NA	15	NA

[a]Three spatial scales are represented.

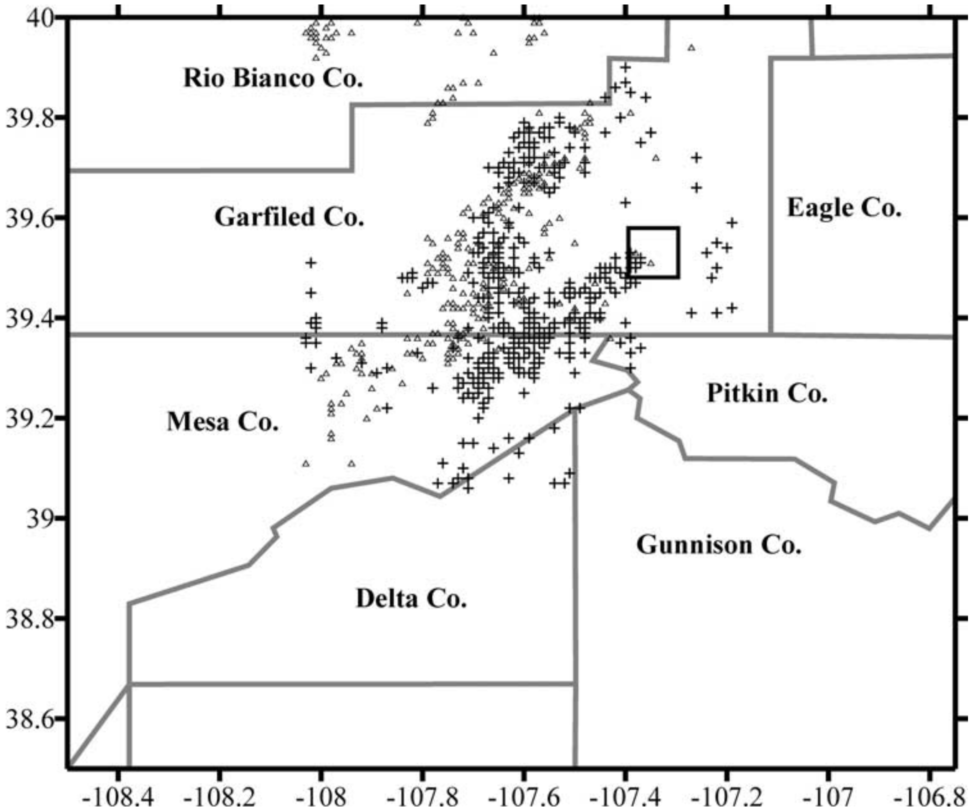

Figure 7a. CG lightning flash sequence for 5 August 2002. Flashes occurring from 1300 to 1600 LT are plotted as small triangles. Flashes recorded from 1900 through 2130 LT are plotted as crosses. The site of the MC debris flow is outlined with a dark box in eastern Garfield County.

(463) and had a single 5-min total of 39 flashes embedded in the sequence between 2040 and 2045 LT. Additionally, 13 intervals had 5-min CG flash totals of 20 or greater from 1950 through 2105 LT.

[22] Rainfall totals associated with the afternoon flash sequence included 0.8 mm at MC-1. This rainfall was recorded between 1330 and 1335 LT, with an additional 0.3 mm of rainfall recorded at 1510 LT. At MC-2, 1.0 mm of rainfall was recorded between 1340 and 1355 LT. The rainfall that accompanied the evening CG flash sequence was much more intense. MC-1 recorded a total of 8.9 mm from 2055 to 2140 LT. The greatest 5-min intensity was 4.3 mm between 2055 and 2100 LT. MC-2 recorded a total of 9.7 mm of rainfall from 2100 to 2150 LT. The greatest 5-min intensity recorded at MC-2 was 7.4 mm between 2100 and 2105 LT (Figure 5a).

[23] Rainfall recorded hourly at the five Mesowest stations in close proximity to the MC debris flow site recorded heavy rainfall during the period from 2000 to 2200 LT. During this period all the stations with the exception of SK recorded in excess of 7.0 mm of rainfall. The highest recording was at SC, with 17 mm of rainfall.

[24] The temporal relationships between 5-min CG flash frequency, 5-min rainfall rates, and the time of debris flow generation at MC are illustrated in Figure 5b. The first CG flashes in the 100 $\times$ 100 km area around the debris flow site were detected at 1905 LT. This preceded the highest rainfall intensity at MC-1 by 110 min and at MC-2 by 115 min, and it preceded the debris flow report by 115 min as well. The peak intensity of 39 flashes per 5-min interval between 2035 and 2040 LT preceded rainfall at MC-1 by 75 min and preceded the debris flow by 80 min.

[25] Figure 6 illustrates the temporal relationship between CG flashes, rainfall intensity, and the debris flow generation at the spatial resolutions of 50 $\times$ 50 km and 25 $\times$ 25 km. The total flash count at 50 $\times$ 50 km is 298 flashes over a period from 1950 to 2125 LT. The peak 5-min flash frequency is realized at 2040 LT with 37 flashes. The first flash detected at 50 $\times$ 50 km is 65 min in advance of the rainfall at MC-1 and 60 min in advance of the debris flow. The total flash count for the 25 $\times$ 25 km domain is 51 flashes, occurring from 2015 to 2125 LT. The highest 5-min flash frequency is recorded at 2040 LT (18 CG flashes). The first flash in this spatial domain preceded the debris flow by 45 min, and the peak flash interval occurred 20 min in advance of the debris flow at MC.

6. Discussion

[26] Table 2 summarizes a number of characteristics of the 5 August 2002 thunderstorm and presents the mean characteristics of the eight control episodes. The total count of CG flashes associated with the evening thunderstorm on 5 August is much larger (463) than the control mean (119) at the 100 $\times$ 100 km grid. The total flash count declines to 408 at 50 $\times$ 50 km and declines to 69 at the 25 $\times$ 25 km grid. Consecutive flash intervals at the 100 $\times$ 100 km grid number 31 for the 5 August episode and number 26.13 for

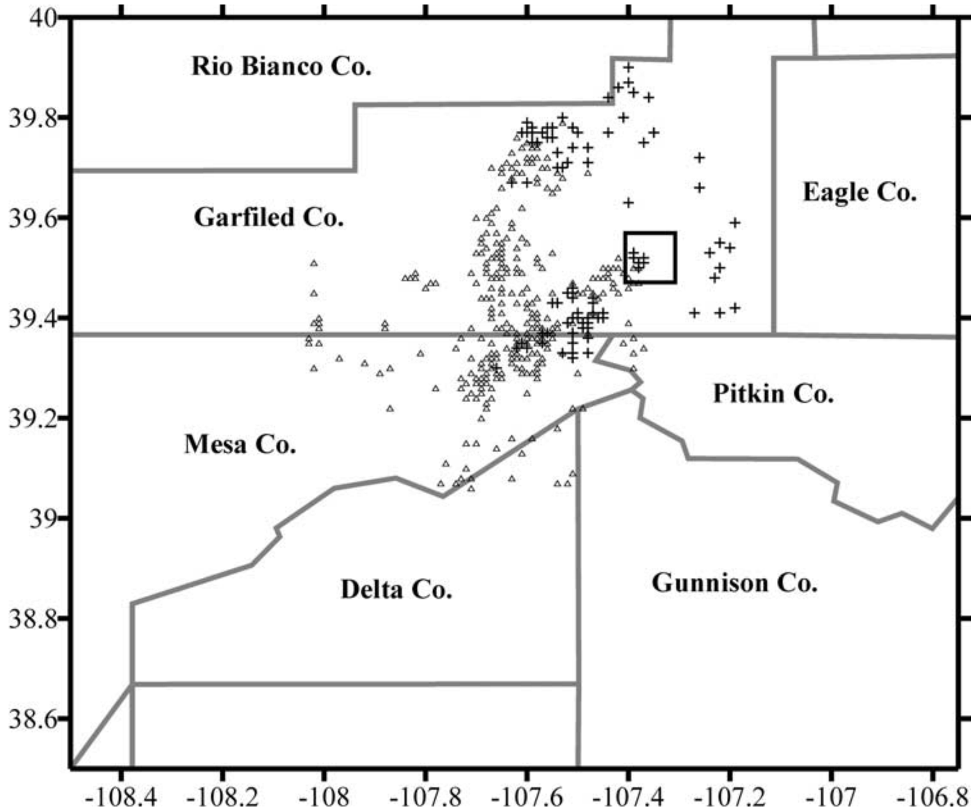

Figure 7b. Late evening CG lightning flash sequence for 5 August 2002. Flashes occurring from 1900 through 2045 LT are plotted as triangles. Flashes occurring from 2045 through 2115 are plotted as crosses. The latter plot coincides with the intense rainfall and debris at the MC site. The debris flow site is indicated with a dark box in eastern Garfield County.

the control group mean. The continuous CG lightning activity on 5 August decreases to 20 consecutive intervals in the 50 × 50 km grid and to nine intervals at 25 × 25 km. The control group declines to 11.4 at 50 × 50 km and 3.4 at 25 × 25 km.

[27] The 5 August thunderstorm distinctly separates itself from the control group in the count of consecutive 5-min intervals with multiple CG flashes. The 24 consecutive intervals with five flashes or greater is nearly four times greater than the control group mean at 100 × 100 km. The 16-interval sequence at 50 × 5 km is 81% greater than control group mean at that scale. The consecutive intervals with 10 or more flashes at 100 × 100 km number 20 for the 5 August episode compared to a mean of less than one for the control group. The longer periods of consecutive flashes associated with the debris-flow-generating thunderstorm suggests that flash duration and flash intensity are items for further investigation using a larger set of lightning and debris flow episodes. The question of CG flash duration was addressed by *Holle and Bennett* [1997], who found that flash flooding was more likely on days with prolonged uninterrupted periods of CG flashes (greater than 100 min). The work of *Holle and Bennett* [1997], however, does not give a strong indication of the rainfall intensity associated with consecutive flash periods.

[28] The period between the first recorded flash at 100 × 100 km and intense rainfall at MC-1 is 115 min. This period shortens to 65 min at 50 × 50 km and is 40 min at 25 × 25 km. The period between the 5-min flash frequency peak and heavy rainfall at MC-1 remains constant at 15 min for each spatial scale.

[29] Figure 7a is a plot of all the CG flashes that occurred during both thunderstorm sequences on 5 August 2002. The plot shows the early afternoon flashes as triangles and the later flash sequence (1900 to 2130 LT) as small crosses. A number of the early afternoon flashes are to the west and north of the MC area. The latter sequence in Figure 7a coincides with the heavier rainfall and the 2058 LT debris flows at MC. The plot shows a core of dense CG flashes to the southwest of the MC site.

[30] Figure 7b breaks the evening flash sequence into two temporal categories, those flashes occurring between 1900 and 2045 LT and those flashes occurring from 2045 to 2115 LT. The 1900–2045 LT plot represents the flash pattern prior to recorded rainfall at MC-1 or MC-2. The second plot represents the flashes occurring in close temporal association with heavy rainfall and the debris flow at MC. The two plots in Figure 7b indicate that the thunderstorm was moving from southwest to northeast. The flashes occurring from 1900 to 2045 LT cluster in the area centered at approximately 39.35°N and 107.7°W. The CG flashes that occur nearer the time of the intense rainfall reports at MC-1 and MC-2 are clustered at the debris flow site and just to the southwest of the site. Most of the clustered flashes occurring during this 30-min period are within approximately 10 km of the debris flow

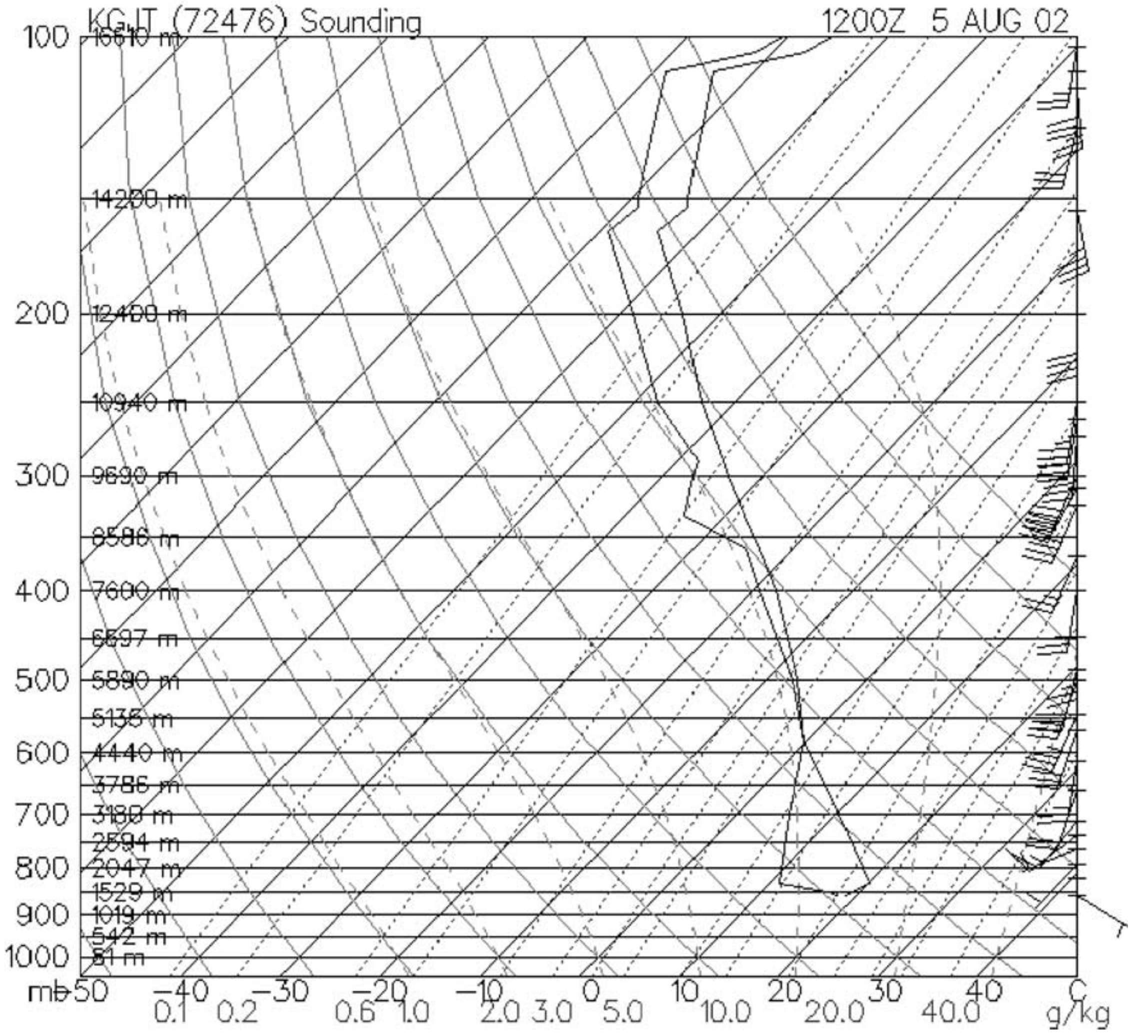

Figure 8a. Grand Junction Colorado sounding for 12Z 5 August 2002 (0600 LT).

site. There are also flashes to the northwest and to the east of the MC area during the 2045–2115 LT period. An Almon Polynomial Distributed Time-Lag (APDT) analysis suggests further the temporal relationship between CG flashes at a 5-min interval and rainfall rates. The APDT analysis is a time series design that designates the unit of analysis as a discrete time interval or period. The effects of at least one variable in the polynomial model, in this case CG flashes, is assumed to be distributed across time. In the case of CG flashes and rainfall rates at the MC-2 site, high-frequency CG flashes within 40 km of MC-2 are significantly related to intense rainfall at the site with a lag of six intervals (approximately 30 min). A statistically significant relationship is also suggested between CG flashes 20 km removed from MC-2 and rainfall at the site. The lag in this case is realized at two intervals (approximately 10 min).

[31] The thunderstorm intensity on 5 August as revealed in the CG flash data suggests that the convection followed the higher terrain of western Colorado to a great extent. CG flash clusters during the later sequence on 5 August are observed in areas noted by *Banta and Schaaf* [1987] as regions of increased orographic thunderstorm activity including Grand Mesa (southwest of the study area) and Flat Top (north of the study area). The thunderstorm that produced the debris flow at MC was fueled by a very strong southwesterly surge of moisture originating from the Gulf of California [*Hales*, 1972; *Douglas et al.*, 1993]. Surface charts show this warm moist surge as far north as central Wyoming, where a stationary front is analyzed for 1800 LT. This moisture plume is also analyzed on the 0600 and 1800 LT 05 synoptic charts at the 700 and 500 hPa levels. The 0600 LT Grand Junction Colorado sounding indicates strong southwesterly flow from 850 to 200 hPa with the atmosphere near saturation from 700 to 500 hPa (Figure 8a). The 1800 LT sounding shows a transition from moist southwesterly flow to dry southeasterly flow at levels above 500 hPa (Figure 8b). The atmosphere below 500 hPa, however, remains very moist with the southwesterly flow that actually increases in speed from 15 knots at 0600 LT to 20 knots at 1800 LT at 700 hPa. Forecast Systems Laboratory Local Analysis and Prediction System (LAPS) model runs on 5 August 2002 suggest that moisture levels at 850 and 700 hPa rise sharply early in the afternoon on 5 August and only subside slightly after the early thunderstorm sequence between 1300 and 1600 LT.

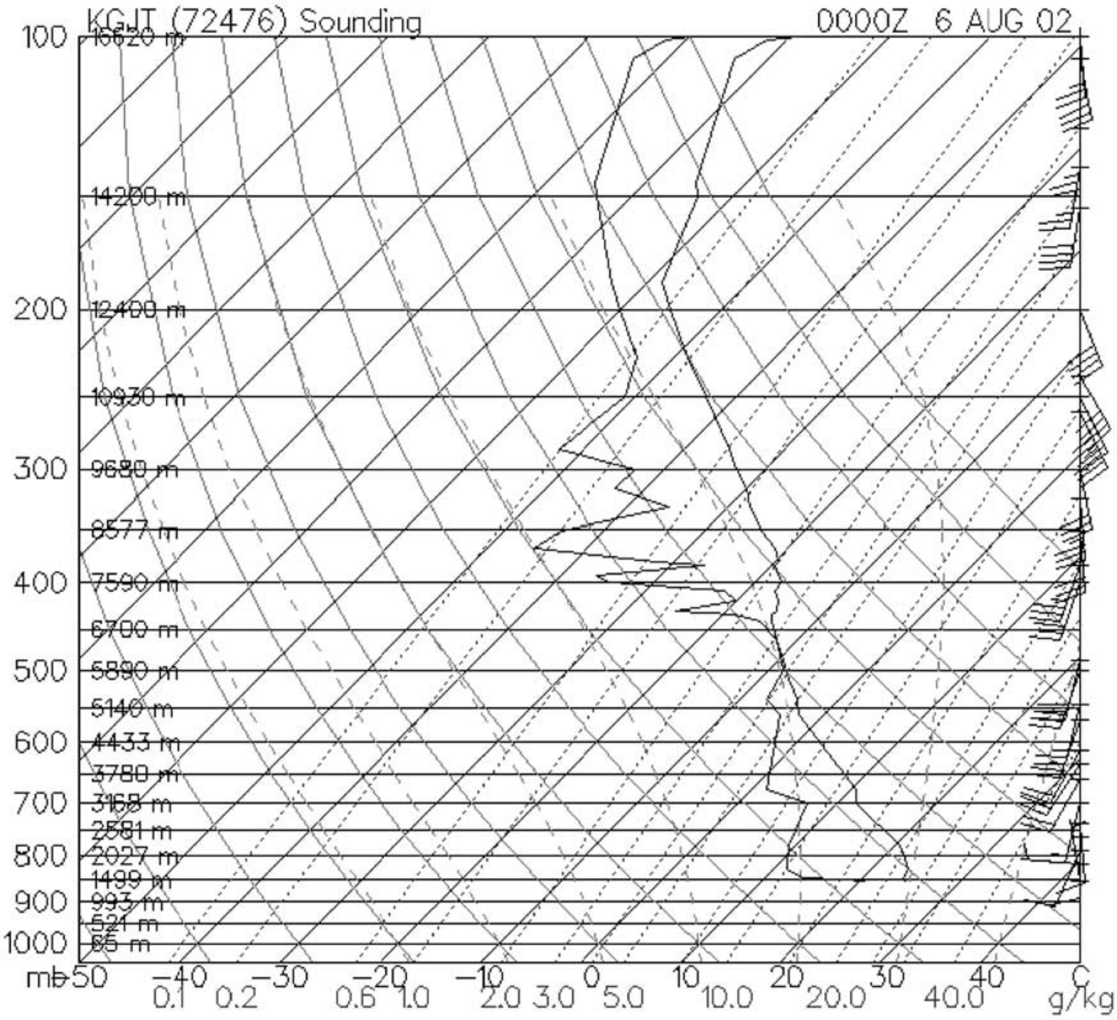

Figure 8b. Grand Junction Colorado sounding for 00Z 6 August 2002 (1800 LT 5 August 2002).

[32] This cursory analysis of the convective environment in western Colorado suggests a number of possible explanations for the increased intensity of the late thunderstorm sequence on 5 August 2002. One possible explanation is built around the strength of the low-level and midlevel southwesterly flow during this very strong surge episode in the monsoon flow. The moist low-level flow and the orientation of the topography, especially Grand Mesa to the immediate southwest of the Coal Seam wildfire site, sets up a scenario for orographic forcing described by *Banta and Schaaf* [1987]. The transition of the upper level flow to a dry southeasterly flow and the increase in flow velocity at lower levels may account for the intensity of thunderstorms experienced nocturnally on 5 August. Another explanation is suggested by the continued higher moisture conditions at the surface and in the lower troposphere after the first thunderstorm sequence on 5 August. As suggested by *Douglas et al.* [1993] a vertical moisture transport mechanism may be responsible for the low-level and midlevel moisture conditions during the NAM. The moisture in this case, advected from the Gulf of California, may have been entrained by both dry convection and the earlier rainfall-producing thunderstorms. The additional low-level and midlevel moisture might then increase convective instability, and with a nocturnal increase in wind speed, augment orographic convection.

7. Summary and Conclusions

[33] The 2002 Coal Seam wildfire site in western Colorado provided a good study area to investigate the spatial and temporal relationship between CG flashes and debris-flow-generating rainfall intensity. The USGS deployed a number of tipping-bucket rain gauges near MC, where the burn was rated as severe after the wildfire was contained on 28 June 2002. The rainfall recorded by the USGS gauges and rainfall recorded by stations in the Mesowest network provided data for the analysis.

[34] The debris flow of 5 August 2002 at MC was not produced by the first rainfall episode at the burn site. The on-site rainfall recordings show that the MC area received as much as 7.1 mm of rainfall on 26 July and 2.5 mm on 20 July. These rainfall totals, however, were recorded over 140 and 105 min, respectively. The 5 August rainfall total at MC-1 was 8.6 mm and the MC-2 total was 8.9 mm. The 5 August totals were recorded over a 15-min period, confirming that storm-relative rainfall intensity is the

parameter most closely linked with post wildfire debris flow generation [*Cannon et al.*, 1998].

[35] CG flashes patterns associated with the 05 August thunderstorm were very different from the patterns of a control group of eight lightning episodes that occurred from 28 June to 04 August 2002. The control group produced on average 119 CG flashes in a 100 × 100 km area around the wildfire burn area. There were a total of 725 CG flashes recorded by the NLDN on 05 August in the same spatial domain. The 05 August CG flashes were separated in time, with an afternoon peak of 289 CG flashes and a late evening peak of 463 CG flashes. The earlier flash sequence was coincident with only 1.0 mm of rainfall at the MC gauging sites. The evening episode coincided with intense rainfall and the 2058 LT report of the debris flows at the MC burn site.

[36] The findings of this exploratory study suggest that lightning flash patterns may prove useful in modeling and forecasting rainfall episodes that generate debris flows in a post wildfire environment. The study reveals that in the case of MC, greater rainfall intensity was associated with more prolific lightning-producing thunderstorms. The study also reveals that the spatial and temporal distributions of CG flashes are related to rainfall rates. Specifically, lighting flashes and clusters of flashes that were within 40 km of the southwest edge of the burn site produced a 30-min lagged indication of heavy rainfall at the site. The lag between the time of the first CG flash in the 100 × 100 km grid and the debris flow was 115 min. The lag relationships at the 50 × 50 km grid and the 25 × 25 km grid were 70 min and 45 min, respectively.

[37] More climatologically oriented studies of CG flashes, rainfall parameters, and post wildfire hydrologic response are necessary to produce a robust relationship between these processes in complex terrain [*Syed et al.*, 2003]. The present work does show, however, that CG flashes can be a valuable asset in assessing hydrologic response in complex terrain. Attention should also be accorded to the both the spatial distribution of CG flashes as well as the timing of flashes prior to rainfall response. Rainfall intensity on a temporal scale of 5 to 15 min should be looked at carefully as a possible threshold variable for debris flow generation in the post wildfire environment.

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