Cloud-to-Ground Lightning Downwind of the 2002 Hayman Forest Fire in Colorado

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Abstract

The Hayman forest fire occurred near Denver, burning ~138,000 acres during 8 June-2 July 2002. It produced aerosol that filled the troposphere over Colorado, allowing an investigation of the effects of increased aerosol concentration on cloud-to-ground (CG) lightning polarity. Specifically, we examine whether positive CG (+CG) flashes are favored in smoky environments. Aerosol optical depth (AOD) over eastern Colorado during the fire was tracked by satellite, and was compared to climatological observations. In addition, CG lightning during the fire was compared to climatology. The 2002 period showed enhancements in AOD and the percentage of +CG lightning. However, spatial patterns were different in the fire's vicinity, with increases in AOD but not in +CGs. Denver soundings during the fire were compared to climatology, and showed environmental differences that are associated with enhanced +CG lightning. Thus, our findings provide only mixed support for the idea that smoke aerosols impact CG polarity.

1. Introduction

Cloud-to-ground (CG) lightning from thunderstorms has predominantly negative polarity. However, researchers have observed enhanced positive CG (+CG) activity from pyrocumulus clouds, or from thunderstorms ingesting smoke from forest fires. For example, Latham (1991) observed entirely +CG lightning from a pyrocumulus cloud that formed over a prescribed burn. More recently, and on a larger scale, Lyons et al. (1998) reported an increase in +CG percentage and peak current over the southern plains of the United States during April-June 1998, relative to climatology. The region of enhanced +CG activity was filled with smoke aerosol advected northward from fires that burned in southern Mexico during this time. Furthermore, Murray et al. (2000) noted that in addition to the +CG changes, peak currents and multiplicity for negative CGs (-CGs) during May 1998 both decreased relative to climatology.

The reasons for this anomalous lightning behavior are still unclear, mainly because our understanding of the electrification processes that lead to enhanced +CG flashing is limited. Vonnegut et al. (1995) suggested that enhanced amounts of negative space charge over burning vegetation, which supplants the usual positive fair weather space charge, may play a role in anomalous pyrocumulus electrification. However, ion-based mechanisms are no longer viewed as playing a major role in thunderstorm electrification (e.g., Williams 2001).

In intense thunderstorms not affected by fire or smoke, recent work has pointed to strong, broad updrafts that allow near-adiabatic liquid water contents to form in the mixed-phase region (i.e., 0 °C to –40 °C) as playing a role in anomalous positive charging (e.g., Williams 2001; Williams et al. 2005). In high liquid water content regions, laboratory experiments suggest that graupel-ice collisions result in positive charging of the rimer, even at low temperatures (e.g., Saunders and Peck 1998). This could lead to the development of a mid-level (e.g., -10 to -20 °C) positive charge region in place of the usual negative charge at this level. Mid-level positive charge has been observed in several severe thunderstorms that occurred during the STEPS project (e.g., Lang et al. 2004; Wiens et al. 2005), and it played a major role in enhanced +CG discharging by these storms.

Enhanced +CG storms may be caused by environmental changes that favor the development of these strong, broad updrafts through increases in conditional instability and reductions in the warm cloud depth (e.g., Smith et al. 2000; Carey and Buffalo 2005). Reducing the warm cloud depth would minimize the impact of precipitation loading and mositure scavenging below the freezing altitude, maximizing updraft strength and supercooled liquid water contents in the mixed phase region.

A similar process could occur in storms affected by fire/smoke. Andreae et al. (2004) showed observations of "smoking" rain clouds near fires in the Amazon. They reported that the onset of precipitation occurs at higher altitudes in these storms, allowing the updrafts to stay vigorous. The reason for this is the larger aerosol concentration competes for condensed water, leading to smaller average cloud droplet size and limiting warm rain processes. Andreae et al. (2004) also suggest that fire heat may invigorate updrafts in pyrocumulus clouds. Their observations did not include lightning, but they could be applicable to enhanced +CG flashing, since the key mechanism may be the aforementioned strong, broad updrafts within the mixed-phase region. In this sense, the environment or the fire/aerosols can lead to the same basic result – high liquid water contents in the mixed-phase region, and subsequent positive charging of the rimer in graupel-ice collisions, leading to mid-level positive charge.

The Hayman fire occurred southwest of Denver in 2002. It started the afternoon of 8 June (local time), and when it was 100% contained on 2 July ~138,000 acres had burned. During the fire's lifetime it produced substantial quantities of aerosol, which were tracked by the MODIS instrument on board the Terra satellite. This provided an opportunity to further investigate the effects of forest fire smoke plumes and aerosol layers on CG lightning polarity. This study expands on the single-storm study of Latham (1991) by covering a broader region, while allowing for finer-scale analysis than that provided by Lyons et al. (1998) and Murray et al. (2000). Unlike prior studies, we use atmospheric soundings to determine if any differences from climatology existed in the environment, differences that may contribute to enhanced +CG flashing.

2. Lightning observations

We used CG strike information for the period 1995-2004 from the National Lightning Detection Network, which has close to 90% detection efficiency and better than 0.5 km location errors in eastern Colorado (Cummins et al. 1998). Per the recommendations of Cummins et al. (1998), we discounted +CG flashes with peak currents below 10 kA. For the Hayman fire period of 8 June-2 July 2002, we gridded the data to a latitude/longitude grid covering eastern Colorado (37-41 °N, 106-102 °W). The grid had a spacing of 0.2° in either direction. In each gridbox, we determined total number of days with CGs, mean numbers of -CGs and +CGs per each day with CGs, percentage of +CGs, and mean peak current and multiplicity for each polarity. We then did the same for surrounding years (1995-2004, excluding 2002), creating a 9-year climatological average for this 25-day period. We then examined departures from climatology during the 2002 Hayman fire, similar to the methodology employed by Lyons et al. (1998) and Murray et al. (2000).

Figure 1 shows these results. There are large reductions in -CG lightning during the Hayman fire, up to 10-20 fewer strikes per gridbox per CG day. In addition, there are modest increases in the total numbers of +CGs in some locations. This translates to a significant increase in +CG percentage during 2002, particularly in a ring surrounding the Hayman/Denver region, and a small area directly over the Hayman fire. In some areas the increase is of the order 50-75%. Overall, the total number of CG days decreased during 2002, usually on the order of 1-5 fewer days during the 25-day period. This is consistent with the drought conditions that fueled the fire (and why we normalized CG strikes by the total number of CG days). Though not shown, -CG peak currents and multiplicity also declined relative to climatology during 2002, with +CG peak currents slightly larger in the same region where their numbers increased, and +CG multiplicity largely unchanged.

3. MODIS aerosol observations

Overpasses by the MODIS instrument on board the Terra satellite were used to track aerosol optical depth (AOD) differences between 2002 and surrounding years. For more information on MODIS AOD data, including retrieval methodologies and measurement uncertainties, see Chu et al. (2002). Because Terra data are available from 2000, we only considered the Hayman period (8 June-2 July) for 2000-2004. AOD values from individual overpasses during a day (usually 0-4 per day) were gridded to the same grid as the lightning, then averaged together and considered representative of that day's aerosol coverage. Given the small overlap between data from individual overpasses, this tended to be more of a composite image than a true average. Our methodology assumes little variability in MODIS AOD values between overpasses. We averaged the composite images during the Hayman period for 2002, and for surrounding years (2000-2004, excluding 2002), and differenced them.

Figure 2 shows the departures from AOD climatology for 2002. Superimposed is the +CG percentage increase contours from Fig. 1. There is rough agreement between the increases in AOD and the increases in +CG percentage, particularly north and east of Denver. However, near the Hayman fire, there is considerable disagreement, with increases – indeed, local maxima – in AOD but little corresponding increase in +CG percentage (< 25%). At the level of individual days, the disagreement could be even worse. For example, on 22 June (not shown), there was a major outbreak of -CGs roughly collocated with the fire's plume.

4. Environmental observations

Environmental statistics for the Hayman period were computed from the Denver sounding. We used the 00 UTC launch, given its correspondence to the usual time of convection in this region (late afternoon). We did not control for soundings ascending into clouds, or for soundings that were distant (in time/space) from the day's convection. We focused environmental differences that existed between 2002 and climatology (1995-2004, minus 2002). Carey and Buffalo (2005) used a more comprehensive sounding set, available during the IHOP project in the U.S. southern plains, to investigate whether +CG storm environments were different than -CG storm environments. They found significant differences (at the 95% level) in parameters like lifting condensation level (LCL), freezing level (FL), and convective available potential energy (CAPE) between different levels. In our study, we only compare the 95%-confidence parameters found by Carey and Buffalo (2005), excluding storm-relative winds. We did not count null values (like a non-existent level of free convection, LFC, in a stable sounding) toward averages in the relevant parameter.

The results are shown Table 1. First off, the observed magnitudes are significantly different than those in Carey and Buffalo (2005), likely because of the different locations. Thus, we examine whether the observed departures from climatology for 2002 are consistent in sign, if not in magnitude, with those seen for +CG storms vs. -CG storms in IHOP. Here we see areas of agreement and disagreement. However, the areas of agreement such as LCL, warm cloud depth, and CAPE between different levels, have the most relevance to the high liquid water content hypothesis for +CGs. As Carey and Buffalo (2005) argued, reduced warm cloud depth would suppress warm rain processes, reducing precipitation loading of the updraft while also increasing supercooled liquid water in the mixed-phase region. Higher LCL (i.e., cloud base) tends to result in larger updraft widths, reducing entrainment and allowing more efficient coversion of CAPE and thus stronger updrafts and larger supercooled water contents (e.g., Williams et al. 2005).

One area of disagreement is the lack of increased shear in 2002, as higher shear values tend to be associated with stronger updrafts. However, shear values in 2002 are close to climatology, so this effect appears to be a wash. In addition, 2002 featured more convective inhibition, although topography and convergence zones would mitigate the increased difficulty in generating storms.

The relative instability differences are not that large. The instability magnitudes are not large either, especially compared to Carey and Buffalo (2005). Overall, these are not the sort of values typically associated with intense or severe storms of any type. Indeed, for 2002 the higher LCL, higher freezing altitude, higher convective inhibition, and lower moisture values are more evocative of drought conditions, which is unsurprising. Note, computing environmental statistics for only days with +CGs (i.e., 5 or more in at least one gridbox; 14 out of 25 total days) in 2002 yield similar departures from climatology, and slightly larger instability values than considering all days.

5. Discussion and conclusions

Our results provide only modest support for the hypothesis that +CG production is increased in pyrocumulus clouds or in storms ingesting smoke. The number and percentage of +CGs increased relative to climatology during the Hayman fire, and –CG production decreased. Results from the intercomparison of MODIS AOD values and +CG statistics were mixed for the entire Hayman period – some places there was rough agreement between maxima and minima, other places not. One of the most significant differences was near the Hayman fire itself, where AOD was large but +CG percentage was not. At the level of individual days the agreement could be even poorer. The environmental analysis further complicates the interpretation of these results. The soundings suggest that the 2002 environment was more conducive to strong, broad updrafts in the mixed-phase region than climatology. This means the 2002 environment was potentially more +CG friendly than other years.

Our results do not necessarily refute the aerosol hypothesis, nor do they provide full support to the environmental hypothesis, for explaining CG behavior during the Hayman fire. However, they do suggest that, if the aerosol mechanism is real, the effect of forest fires on CG lightning could be highly complex. Storms ingesting smoke aerosols do not necessarily lead to enhanced +CG flashing in all instances. They may require assistance from a more +CG conducive environment, or there may be a dependence on aerosol concentration, size, and type – which MODIS data can't provide with high accuracy, especially at the scale of individual storms (e.g., Chu et al. 2002). Moreover, the observed magnitudes for convective instability in 2002 are not those typically associated with intense convection, so perhaps the increased aerosol concentrations assisted the weak, but more +CG friendly, environment in producing the 2002 +CG storms. These are all issues and questions that could be investigated with a high-quality microphysical model that included aerosols and electrification.

One intriguing result is that, while the 2002 environment may have been more conducive to +CG production in thunderstorms, it also was an environment that was typical of drought weather; e.g., less moisture, and higher cloud bases and freezing levels. As research continues on the role of environment in creating +CG storms, it would be interesting to investigate whether a link exists between drought environments and +CG storms, as appears to be the case here.

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Tables

Table 1. Values of environmental parameters for the Hayman fire period (8 June-2 July) during 2002, and for the same period during 1995-2004 (excluding 2002). The final column states whether the departure from climatology agrees in direction with the differences seen by Carey and Buffalo (2005) for +CG vs. -CG storms.

	2002	**Climatology**	**Agree?**
Freezing Level (FL)	4811 m MSL	4439 m MSL	No
Lifting Condensation Level (LCL)	5064 m MSL	4172 m MSL	Yes
Mean Mixing Ratio in Lowest 100 mb	5.3 g kg^{-1}	6.2 g kg^{-1}	Yes
Wet-Bulb Zero Height	3980 m MSL	3776 m MSL	No
850-500 mb Lapse Rate	8.95 °C km^{-1}	8.24 °C km^{-1}	Yes
Warm Cloud Depth (FL-LCL)	0 m	267 m	Yes
700-500 mb Lapse Rate	8.72 °C km^{-1}	7.92 °C km^{-1}	Yes
Precipitable Water in the Surface to 400 mb Layer	15.5 mm	16.8 mm	Yes
0-3 km Shear	14.2 m s^{-1}	14.3 m s^{-1}	No
Equilibrium Level (EL)	10517 m MSL	9684 m MSL	No
Convective Inhibition (CIN)	57.9 J kg^{-1}	49.2 J kg^{-1}	No
Depth of Free Convective Layer (EL-LFC)	5009 m	4961 m	No
CAPE between LFC and –10 °C	19.2 J kg^{-1}	54.5 J kg^{-1}	Yes
CAPE between –10 °C and –40 °C	281.4 J kg^{-1}	266.5 J kg^{-1}	Yes
Normalized CAPE between LFC and –40 °C	0.064 m s^{-2}	0.058 m s^{-2}	Yes

Figures Captions

Figure 1. CG lightning differences in eastern Colorado between the 2002 Hayman fire period (8 June-2 July) and the climatological average for the same period during 1995-2004 (excluding 2002). Top left: # of -CGs per 0.2° x 0.2° gridbox per storm day (contours: -20, -10, 0); top right: # of +CGs per storm day (contours: -1, +1, +5); bottom left: % of +CGs (contours: +25%, +50%, +75%); bottom right: # of days with CG lightning (contours: -5, -1, +1). Regions with the largest changes are shaded. Also shown are locations of the Hayman fire and Denver.

Figure 2. MODIS AOD differences (shaded contours) between the 2002 Hayman fire period (8 June-2 July) and the climatological average for the same period during 2000-2004 (excluding 2002). Line contours show percentage of +CGs for 2002 vs. 1995-2004 (same as Fig. 1, bottom left).

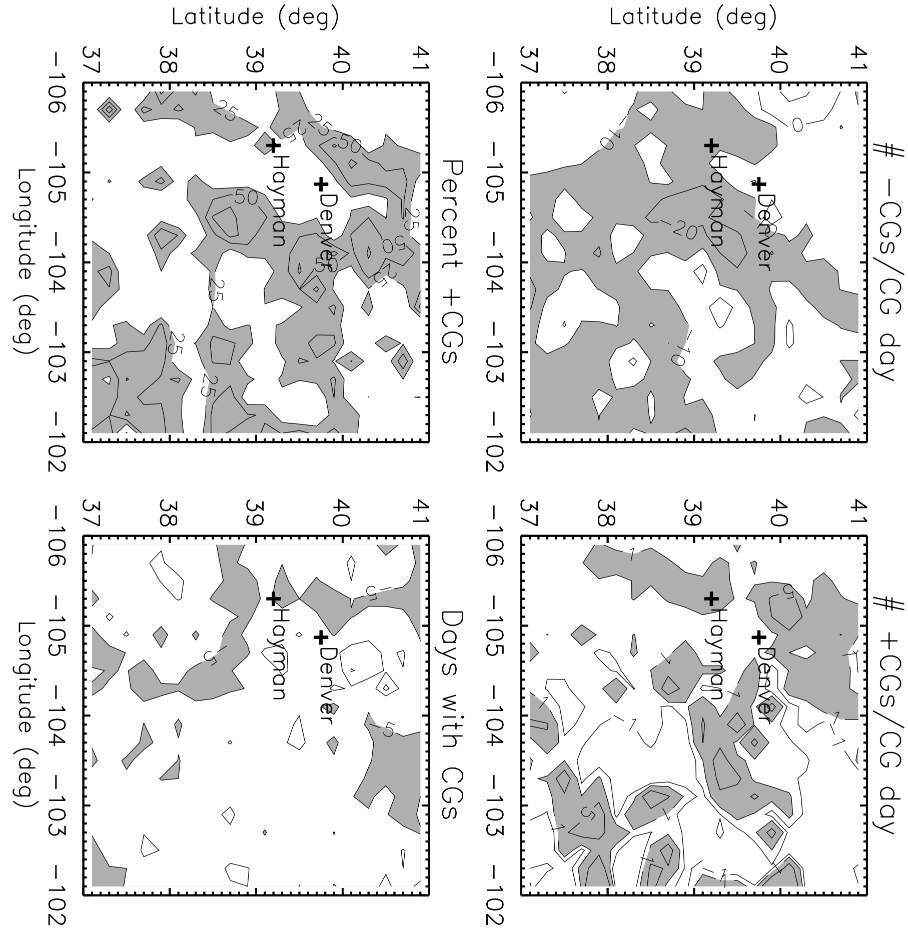
−CGs/CG day
+CGs/CG day
Percent +CGs
Days with CGs
Latitude (deg)
Longitude (deg)
Hayman
Denver

Figure 1

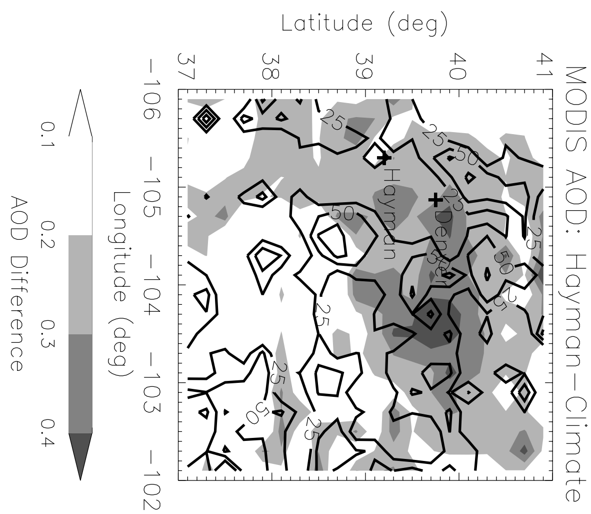
MODIS AOD: Hayman–Climate
Latitude (deg)
37
38
39
40
41
Longitude (deg)
−106
−105
−104
−103
−102
Hayman
Denver
25
50
AOD Difference
0.1
0.2
0.3
0.4

Figure 2