Do Forest Fires Affect Lightning?

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This is to certify that I have examined this copy of a master's thesis by

Jeremy Smith

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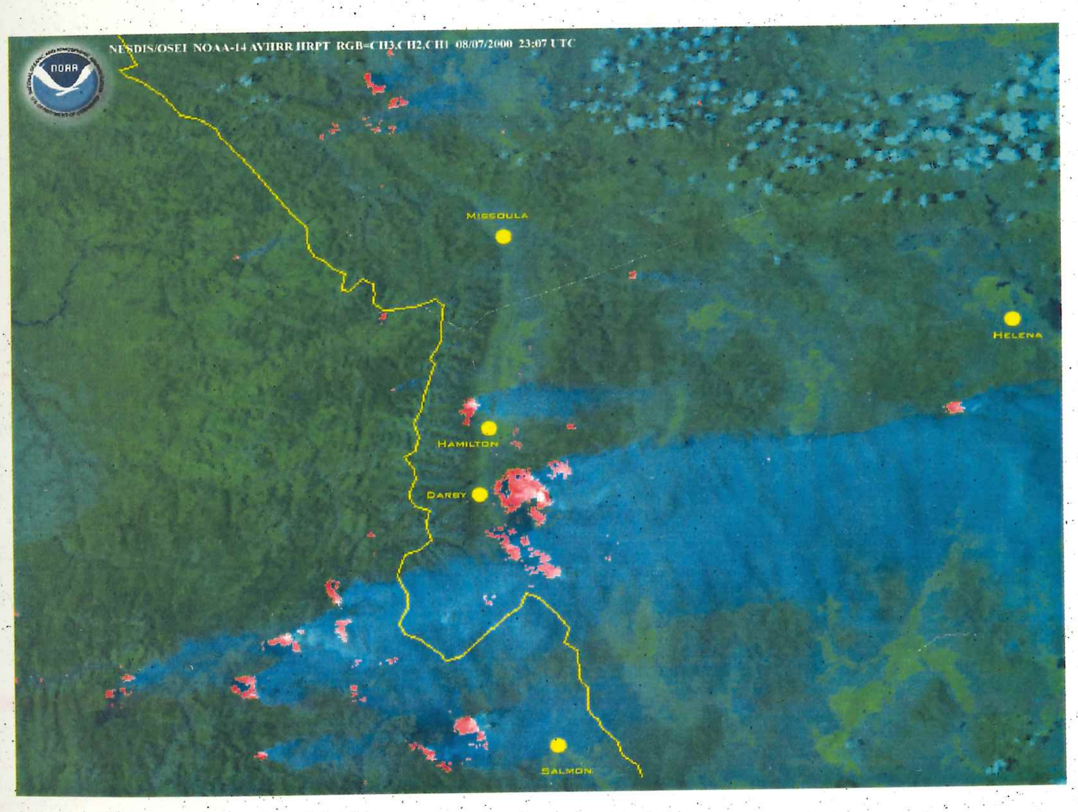

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Chapter 1

INTRODUCTION

1.1 Thunderstorm Electrification

In order to understand why forest fires may affect lightning, it is necessary to first review the basics of thunderstorm electrification. In a convective storm, rimed ice or graupel particles grow in updrafts until they become too large to be supported by the updraft and begin to fall. The graupel particles collide with smaller ice crystals rising in the updraft. A number of laboratory studies (*e.g. Saunders et al.* [1991] and *Takahashi* [1978]) demonstrate that charge is transferred during these collisions, typically with negative charge transferred to the larger graupel particle and positive charge to the ice crystal. As graupel particles continue to fall and ice crystals continue to rise, charge is separated, creating an electric field. If the electric field exceeds a critical value, lightning is initiated.

1.2 Why would we expect forest fires to affect lightning?

When water vapor condenses in a cloud, it condenses onto particles. The aerosols upon which water vapor can condense at typical atmospheric conditions in order to form cloud droplets are called cloud condensation nuclei or CCN.

Forest fires are a huge source of particulate matter. *Reid et al.* [1999] measured total particulate or condensation nuclei (CN) concentrations from Brazilian fires which exceeded 150,000 cm^{-3} directly downwind of the fire. Figure 1.1 shows how the ratio of CCN to CN varies after combustion has ceased. This ratio is very close to one for white pine, indicating that burning wood is a very efficient source of CCN. *Levine* [1991] compiled data from several field studies in which this ratio was measured for forest fires and found it to be between 80 and 100%. This can result in a modified drop size distribution in a cloud that

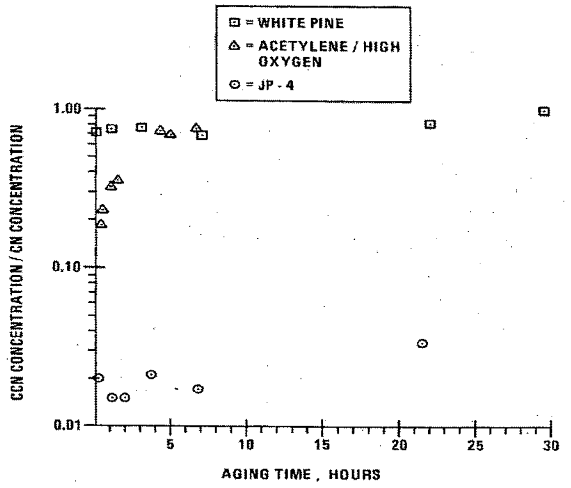


Figure 1.1: Ratio of CCN to CN as a function of time after combustion. From *Hallett et al.* [1989].

forms in the polluted air [*Warner and Twomey*, 1967]. With increasing CCN concentration, drop concentration increases, but mean drop size decreases. This effect has been observed in cloud chambers [*Jayaratne et al.*, 1983]. These drops may be less likely to rain out, thereby increasing the liquid water content of the cloud. *Rosenfeld and Lensky* [1998] and *Rosenfeld* [1999] give examples of forest fire smoke possibly inhibiting rainfall.

The liquid water content of the charging zone of a thunderstorm can affect the collisional charging mechanism. As previously mentioned, in typical collisions between ice crystals and graupel, the graupel charges slightly positively, while the ice crystals charge slightly negatively. However, in cases of high liquid water content and relatively higher temperatures, the sign of the charging may switch, leaving the graupel particles with a positive charge, as seen in figure 1.2. This could significantly alter the charge structure of the storm.

The charging mechanism may also be influenced by the chemistry of the CCN. *Jayaratne et al.* [1983] discovered that charging patterns were significantly altered when traces of impurities were added to a cloud chamber. In their experiment, two metal rods were moved through a cloud of supercooled water, allowing riming to occur on the leading edges of the rods. Ice crystals, formed in the cloud by seeding it with a liquid nitrogen cooled wire, collided with the rod, producing a current. This current was then used to derive the charge transferred to the rod per collision. The water droplets were doped with traces of $(NH_4)_2SO_4$ and NaCl. As seen in figure 1.3, the $(NH_4)_2SO_4$ caused a charge reversal, making the rime charge positively in conditions in which unpolluted rime would normally charge negatively. *Cofer et al.* [1988] studied aerosol emissions from fires and found significant quantities of NH_4^+, $\mathrm{SO}_4^=$, Na^+, and Cl^- aerosol ions.

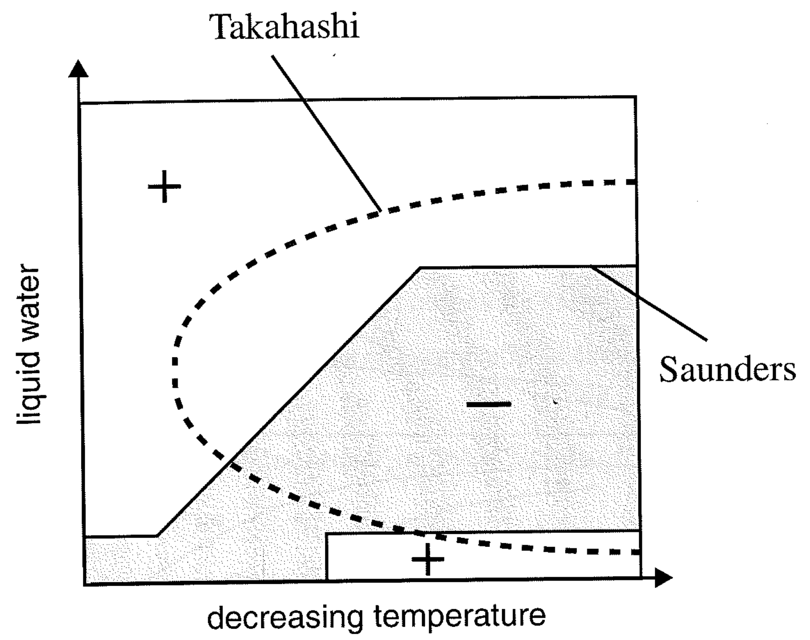


Figure 1.2: Schematic of variation in sign of charge transfer to a riming target with liquid water content and temperature during a collision with an ice crystal. Figure describes charging regimes described by *Brooks and Saunders* [1995] and *Takahashi* [1978]. From *Schroeder* [2000].

Finally, *Vonnegut et al.* [1995] show that forest fires release charge when exposed to an electric field. The approximate relation is found to be:

$$J\left[\frac{nA}{m^2}\right] = 0.3\left[\frac{nA}{m\times V}\right] E_{incident}\left[\frac{V}{m}\right] \tag{1.1}$$

where J is the current density in nanoamperes/m^2. Assuming $E_{incident}$=-100V/m, singly-charged ions, and a velocity of 5m/s, the concentration of ions is approximately 10^4 cm^{-3}

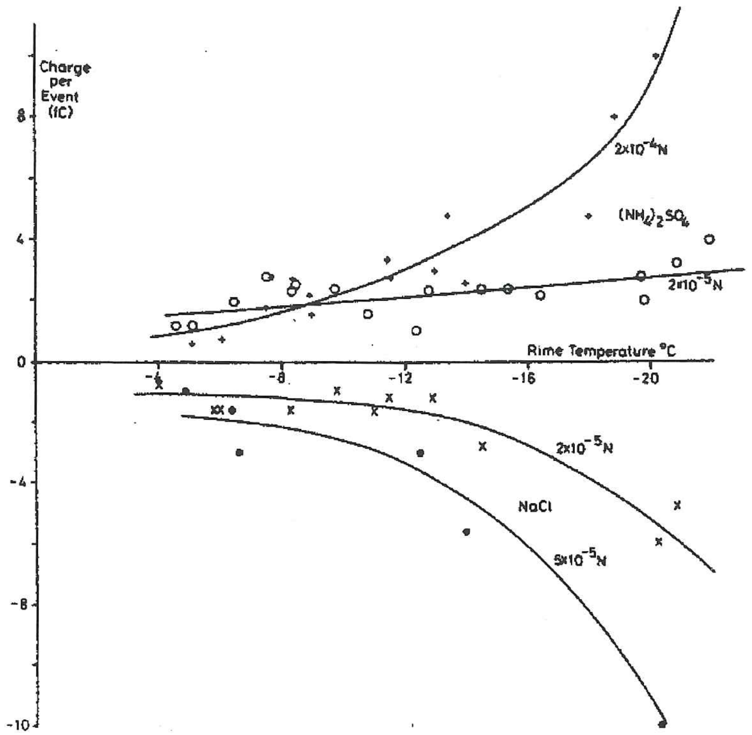


Figure 1.3: Variation in charge transferred to a riming target during a collision with an ice crystal as a function of temperature when the cloud contains $(NH_4)_2SO_4$ or NaCl. From *Jayaratne et al.* [1983].

just downwind of the fire. The evolution of small ions in time can be derived from an equation of recombination:

$$\frac{dn}{dt} = q - \alpha n^2 - \beta n Z \tag{1.2}$$

where q is the in situ rate of production of ions, n is the concentration of positive and negative small ions, α is the recombination coefficient, β is the effective attachment coefficient, and Z=aerosol concentration. Assuming q to be negligible, the characteristic timescale of this process is then:

$$\tau = \frac{1}{\alpha n + \beta Z} \tag{1.3}$$

Using α=1.7x10^{-6}, β=10^{-5} [*Volland*, 1982], and Z=10^5, it is clear that the time scale is very short (~1s) and that the second term in the denominator dominates by two orders of magnitude. Therefore, most of the ions are immediately attached to particles. If these particles are then advected into a storm, there could be effects on the charge structure of the storm. 10^4 singly-charged ions per cm^3 corresponds to a charge density of about 2 nC m^{-3}. According to *MacGorman and Rust* [1998], maximum charge densities in thunderstorms are typically ~< 10 nC m^{-3}, the same order of magnitude as the charge advected from the fire.

1.3 The Two Fire Seasons Included in This Study.

1.3.1 May 1998

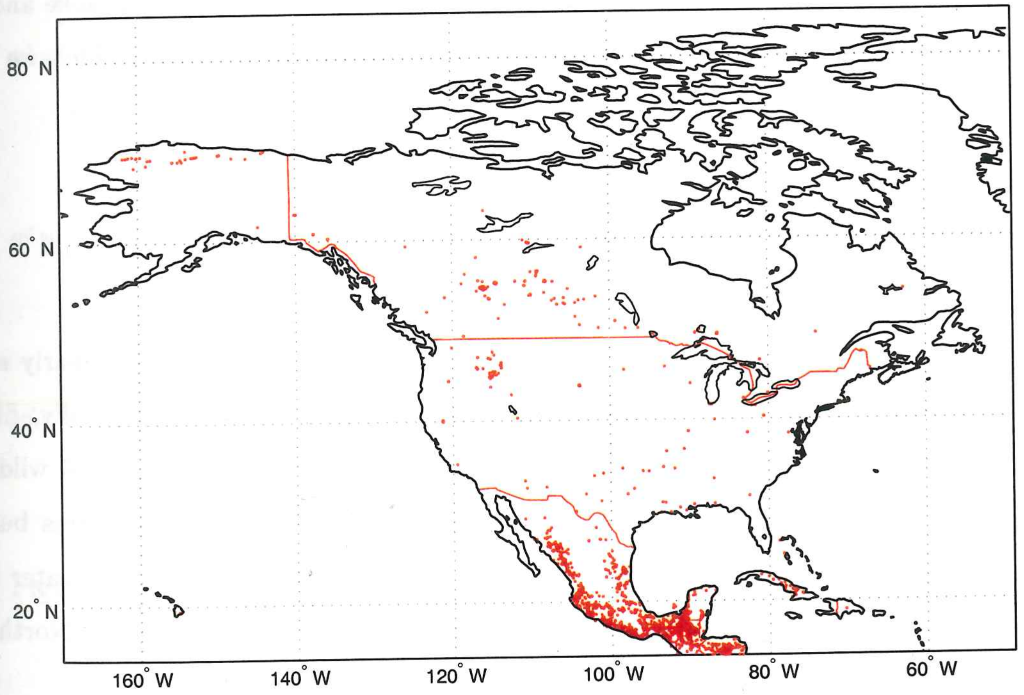


Figure 1.4: May 1998 fire locations from the ESA's ATSR World Fire Atlas.

In the Spring of 1998, drought related to El Niño led to massive fires in Mexico and Central America. In three months, over 4000 km^2 were burned by more than 10,000 fires in Southern

Mexico alone [*Lyons et al.*, 1998]. Fires located by the Along Track Scanning Radiometer (ATSR) on the European Space Agency's (ESA) European Research Satellite-2 (ERS-2) for the month of May are shown in figure 1.4.

Strong southerly and southwesterly winds transported much of the smoke associated with these fires into the United States. The smoke reached as far east as Florida, as far west as New Mexico and as far north as Canada. Air quality and visibility were seriously compromised in several Plains states. An excellent source for images associated with this smoke plume is the Center for Air Pollution Impact and Trend Analysis, Washington University in St. Louis, Missouri (http://capita.wustl.edu/Central-America/). Additionally, *Peppler et al.* [2000] present a thorough overview of the smoke event as recorded by the U.S. Department of Energy's Atmospheric Radiation Measurement program Southern Great Plains Cloud and Radiation Testbed in Oklahoma and Kansas. The smoke and the lightning anomalies both peaked during the month of May, the month on which we have concentrated in this study.

1.3.2 August 2000

The 2000 wildland fire season in the United States was a devastating one. Nearly seven million acres were burned, losses could exceed 10 billion dollars, and, tragically, fifteen firefighters were lost in the blazes *USFA* [2000]. Table 1.1 compares the 2000 wildland fire season with the 10-year average and shows clearly that the number of acres burned in 2000 was twice the national average. Table 1.2 shows the the states with greater than 200,000 acres burned. Although large fires burned throughout the country, the Northwest was hardest hit, especially Idaho and Western Montana.

The fire season started in mid-February and continued well into November; however, we limited this study to the month of August. Analyses of smoke plumes detected by satellite showed that the month of August 2000 had the largest smoke anomaly of the fire season by a substantial fraction. Fire locations for the month of August from ESA's ATSR World Fire Atlas are presented in figure 1.5

Table 1.1: Year 2000 Wildland Fire Season Vs. 10-Year Average. From *USFA* [2000].

	2000 Season	**10-Year Average**
Number of Fires	92,250	66,120
Acres Burned	7,393,493	3,128,669
Acres Burned per Fire	80.0	47.3

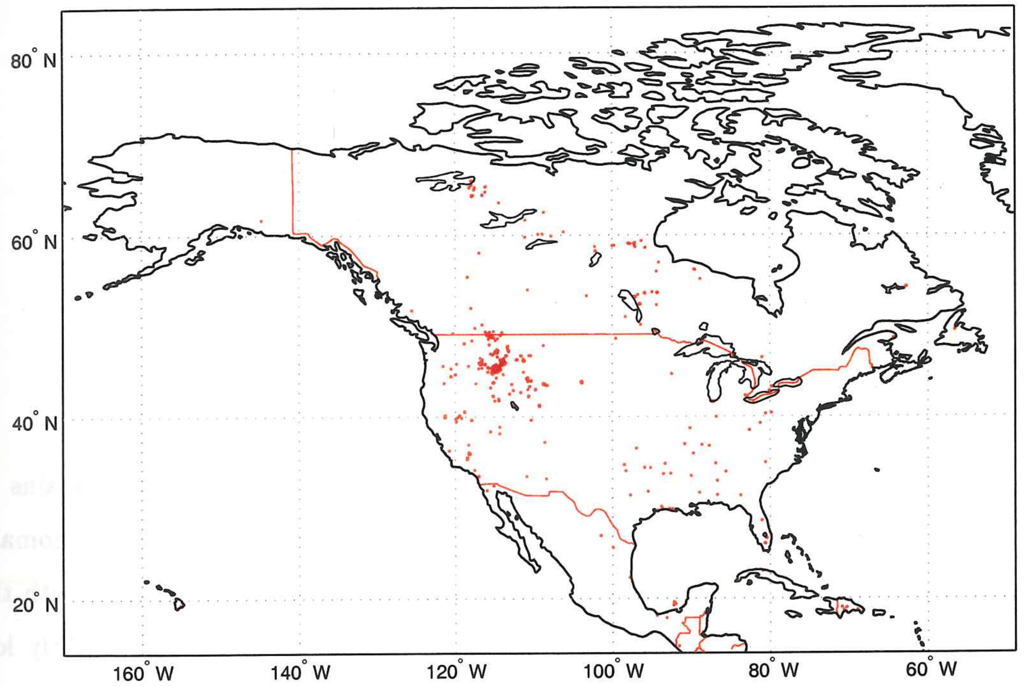


Figure 1.5: August 2000 fire locations from the ESA's ATSR World Fire Atlas.

1.4 *Previous Studies*

1.4.1 Lightning and Forest Fires

The two main papers which influence this work both examine the Spring 1998 Central American fires. The first, by *Lyons et al.* [1998], noted that the percentage of cloud-

Table 1.2: States With Greater Than 200,000 Acres Burned. From *USFA* [2000].

State	**Number of Fires**	**Acres**
Arkansas	351	751,233
California	7,283	235,248
Florida	6,572	200,980
Idaho	1,599	1,361,459
Montana	2,437	949,817
New Mexico	2,466	519,177
Nevada	1,078	635,715
Oregon	2,006	477,741
Utah	1,929	227,827
Washington	1,116	256,781
Wyoming	651	279,583

to-ground lightning which lowered positive charge (+CG%) in the southern plains was triple the climatological norm during the Spring 1998 smoke event. The +CG% anomaly is illustrated in figure 1.6. Additionally, they noted that peak currents associated with these +CG's were double the expected values, while peak currents of -CG's were slightly lower than expected. *Lyons et al.* [1998] hypothesized that elevated CCN concentrations from the smoke affected the drop size distribution, altering the charging mechanisms of the storm. Additionally, since some of the anomalous storms were found in regions where the smoke was not dense enough for satellite detection, it was postulated that the changes are possible even at relatively low concentrations.

Expanding upon this study, *Murray et al.* [2000] included two additional years of lightning data in their climatology and removed +CG's with peak currents less than 10kA, to minimize the contamination of intracloud flashes on the data set. They produced "difference value" maps for polarity, peak currents, and multiplicity with 1 degree resolution by

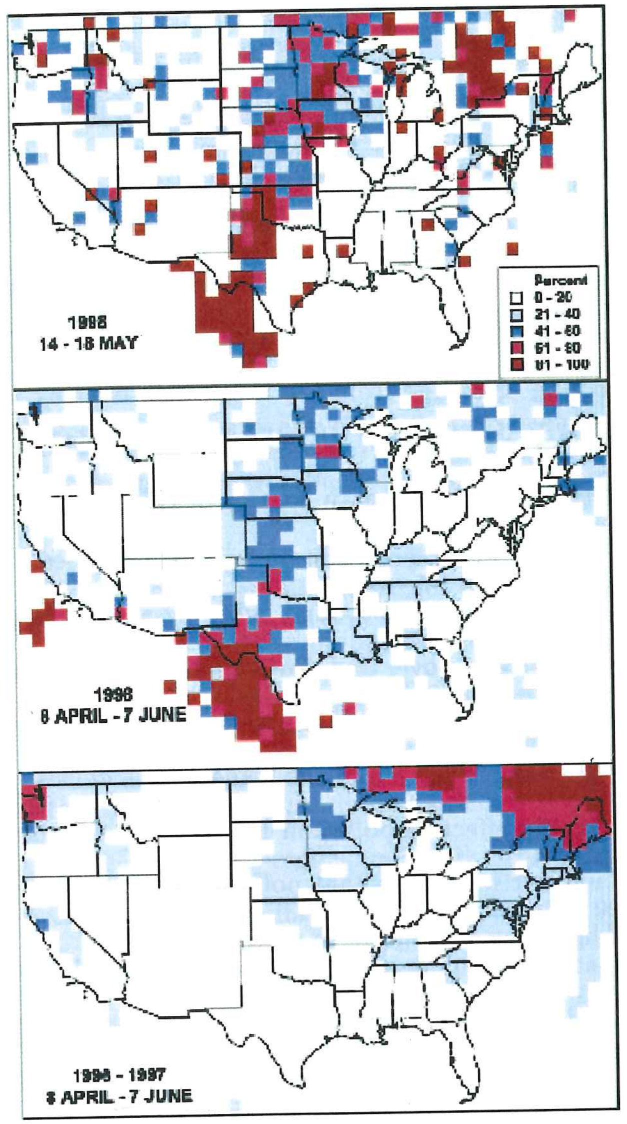


Figure 1.6: (Top) +CG% from May 14-18, 1998. (Middle) +CG% during April 8 - June 7, 1998. (Bottom) +CG% averaged for the period of April 8 - June 7 1996 and 1997. Grid cells are 100km by 100km in all cases. From *Lyons et al.* [1998].

comparing lightning in May 1998 with climatological values derived from May 1995-1997 and 1999. +CG% was found to increase by a factor of two. Median peak current decreased for -CG's, but increased by over 20 kA in the southern plains during the smoke event for

+CG's. Mean multiplicity, the number of strokes per lightning flash, was found to have an insignificant change for +CG's, but decreased from 2.8 to 1.0-1.4 strokes per flash for -CG's in a region including Texas, Oklahoma, Louisiana, and Kansas. It was suggested that these changes were somehow caused by the anomalously large smoke production in Central America and Southern Mexico coupled with strong northward transport.

Several other papers deserve mention here. *Latham* [1991] found that a cloud formed by the plume of a prescribed fire in western Ontario produced exclusively +CG flashes. He attributed this to advection of charge from the fire, which is likely to be quite substantial at such close proximity (less than 9 km). *Vonnegut et al.* [1995] discuss several additional storms in close proximity to forest-fires with +CG% of 25 to 50%.

Additionally, the effects of urban pollution on lightning has been noted on several occasions. *Westcott* [1995] analyzed cloud-to-ground lightning around 16 central U.S. cities. She found an enhancement of lightning over and downwind of many of these cities on the order of 40-85%. *Orville et al.* [2001] analyzed cloud-to-ground lightning data around Houston, Texas for the period 1989-2000. They found the highest flash densities to be near the urban areas of Houston. While the effect of pollution is likely to be important in both of these studies, it is presently unclear how important pollution is relative to the urban heat island in the enhancement of lightning proximate to cities.

1.4.2 Positive Cloud-to-Ground Lightning

Orville and Silver [1997] reported the annual +CG% to be less than 10% in the contiguous United States. However, +CG% varies considerably with season and geographical location, with maxima in the winter season, temporally, and, geographically, on the West Coast, Northeast, and Midwest in the years 1992-1995. Some types of storms tend to produce elevated +CG% and have been the source of considerable study.

The first of these studies were conducted on winter thunderstorms. *Takeuti et al.* [1973] found that most of the winter thunderstorms in Hokuriku produced ground flashes of positive polarity, in contrast with what was observed in summer. Later, *Brook et al.* [1982] found +CG% in these storms to increase with wind shear and formulated the idea of the "tilted dipole" to explain this. In this scenario, the upper positive charge center of a thunderstorm is displaced horizontally from the lower negative. This would theoretically allow discharges from the upper positive charge center to ground. Upon further investigation of winter storms in Norway, *Takeuti et al.* [1985] deduced that wind shear is not as important as the location of the -10°C isotherm, with +CG% increasing with as the -10°C decreased in altitude. Finally, *Kitagawa and Michimoto* [1994] found that winter storms frequently form a brief tripole structure with positive charge closest to the ground before forming a positive monopole. The lower positive charge of the tripole was hypothesized to arise from positively charged graupel below the -10° isotherm while the monopole occurred after graupel fallout, leaving only the positively charged ice crystals. Either of these charge centers are potential sources of +CG's.

Further studies of +CG's have focused on mesoscale convective systems (MCS's). These are large precipitation systems which are commonly found in the high plains region of the central United States. *Rutledge and MacGorman* [1988] found that most of the +CG's struck in the stratiform region which was located behind a leading line of convection. They suggested that the stratiform region was comprised of small, positively charged ice particles advected from the top of the convective region, much like the tilted dipole idea of *Brook et al.* [1982]. Furthermore, modeling studies by *Rutledge et al.* [1990] based upon a non-inductive ice-ice collisional charging mechanism predicted significant charge generation in the stratiform region leading to an inverted dipole charge structure (negative charge above positive charge), which could also lead to +CG's.

Finally, several studies have focused on certain types of severe thunderstorms which tend to produce +CG's. *Reap and MacGorman* [1989] found that, while strong wind shear was not a sufficient condition to produce a high +CG%, the presence of severe weather (tornadoes, hail, and strong wind) correlated well with the presence of +CG's. *Bluestein and MacGorman* [1998] and *Perez et al.* [1997] suggest that some, but not all, tornado-producing storms switch from producing +CG's to -CG's with tornadogenesis. *Stolzenburg* [1994] indicates that a high +CG%, high +CG flashrate, and a high density of +CG's is coincident with large hail formation, presumably due to large concentrations of liquid water causing the graupel to charge positively.

It is important to consider that most of these potential causes of +CG's are not well understood. Wind shear seems intuitively important for creating a tilted dipole, but several studies seem to downplay its importance. Furthermore, it is difficult to imagine why a tilted dipole would produce a storm which is composed almost exclusively of +CG's as the lower negative charge region should be producing -CG's. +CG's associated with MCS's are also poorly understood. While the strokes hit the ground in the stratiform region, it should be noted that the origin of the lightning stroke is not known and may actually start in the convective region. Furthermore, electric-field soundings by *Marshall and Rust* [1993] found two types of vertical electrical structures in the stratiform region, both having negative charge at the lowest layer, apparently contradicting *Rutledge et al.* [1990]. Finally, the occurrence of +CG's with severe weather is only at the observational stage, without a firm understanding of the processes involved.

1.5 This Study

In this study, we first extend the climatology used in *Murray et al.* [2000] to include May 2000. We also include the level of significance of the anomalies. Furthermore, we extend the study to include the fire season of the year 2000.

In addition to looking at smoke, we felt it important to look for other anomalies during the fire seasons, to see if there exists a different explanation for the lightning observed in May 1998. We examine surface temperature, precipitation, and stability and discuss what effects each of these could have on thunderstorms.

Finally, we investigate the effects of changing CCN concentrations in a thunderstorm, utilizing the 1.5 dimensional model of *Solomon and Baker* [1998]. This model is also modified to incorporate a simplified version of the anomalous charging pattern associated with chemical impurities in the cloud as discussed by *Jayaratne et al.* [1983].

Chapter 2

DATA AND ANALYSIS

We used a number of data sources to try to ascertain what effect, if any, the May 1998 and August 2000 forest fires had on downwind clouds. In addition to looking for anomalies in lightning and smoke, we also looked at surface temperature, precipitation, and convective available potential energy for the relevant regions to try to determine which parameters might have contributed most importantly to the lightning anomalies.

2.1 Smoke Plume

2.1.1 May 1998

Total Ozone Mapping Spectrometer

In order to determine the spatial and temporal extent of the smoke plumes, we used the Total Ozone Mapping Spectrometer (TOMS), onboard the Earth Probe platform, which was launched on July 2, 1996. Although originally intended to provide estimates of total column ozone, it can also detect UV-absorbing aerosols and was the only instrument active during both May 1998 and August 2000 which could detect aerosols over both water and land. This is accomplished by comparing the measured spectral contrast of two bands of backscattered UV radiation to the modeled spectral contrast:

$$\Delta N_\lambda = -100\{\log_{10}[(\frac{I_{340}}{I_{380}})_{meas}] - \log_{10}[(\frac{I_{340}}{I_{380}})_{calc}]\} \tag{2.1}$$

where I_{340} is the backscattered radiance at λ=340 nm and I_{380} is the backscattered radiance at λ=380 nm. The resulting N-value is used as a non-dimensional proxy for aerosol optical depth, called the TOMS aerosol index. The aerosol index is roughly linearly proportional to optical depth. For nadir view, overhead sun, and aerosol effective radius of 0.1 μm, an aerosol index of 0.54 corresponds with an optical depth of 0.1 and an aerosol index of 2.06

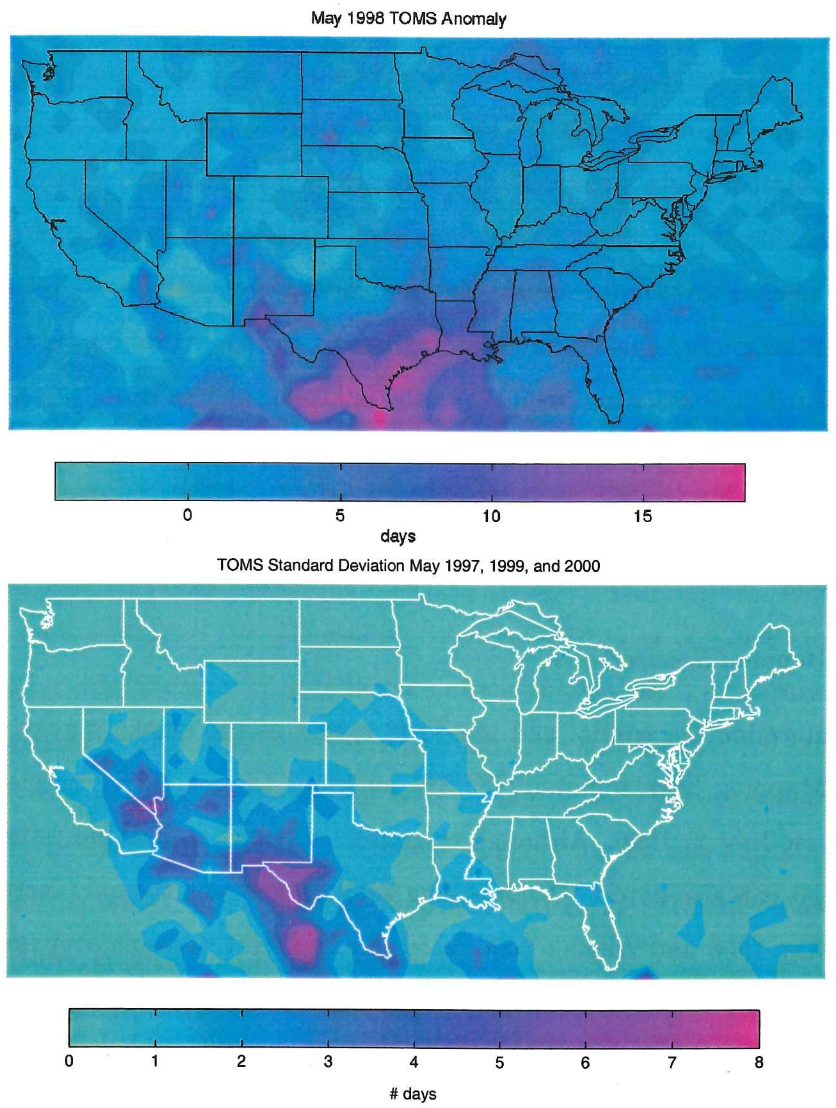


Figure 2.1: (top) May 1998 anomaly of number of days when TOMS aerosol index exceeded 0.7. (bottom) Standard deviation of number of days when TOMS aerosol index exceeded 0.7 for May 1997, 1999, and 2000. See text.

corresponds with an optical depth of 1.0.

To minimize the effect of noise and nonabsorbing aerosols on detecting UV-absorbing smoke particles, only N-values greater than 0.7 were utilized in this study. It is also worthwhile to note that the TOMS cannot detect aerosols below about 1 km because the signal is weak relative to ground noise. For more information on using the TOMS for detecting UV-absorbing aerosols, see *Herman et al.* [1997] and *Torres et al.* [1998].

The TOMS level 2 aerosol product is distributed on a 1° latitude by 1.25° longitude grid. Each grid cell is observed by the satellite about once per day. For each month and each grid cell, the number of days for which the aerosol index exceeded 0.7 (roughly corresponding to an optical deth of around 0.2) were counted to determine a number of "smoke days." We were then able to find the anomaly of smoke days in May 1998 and August 2000 by subtracting the average number of smoke days in May and August from the number of smoke days in May 1998 and August 2000, respectively. The average for May was based upon May 1997, 1999, and 2000, while the average for August was based upon August 1996-1999. These results, along with the standard deviation of smoke days, are plotted in figures 2.1 and 2.3. While we lose the limited amount of information on the optical thickness of the plume with these plots, they give us a good idea of the persistence of the smoke plume.

In May 1998, there is a clear anomaly over southern Texas, Lousiana, and northern Mexico. The smoke plume did extend farther north than this, covering the Central United States up to Canada, but only for several days around May 14-15 and thus does not show up in figure 2.1. Figure 2.3 shows a very clear plume extending east from Central Idaho, the region of highest fire intensity during August 2000, all the way to at least Minnesota.

Airplane Observations

Peppler et al. [2000] published an extensive paper detailing observations of the smoke plume from the Atmospheric Radiation Measurement program Southern Great Plains Cloud and Radiation Testbed (ARM SGP CART site), in Oklahoma and Kansas, as well as observations from several satellites. Lidar observations showed a distinct aerosol layer around 1 km AGL. The University of North Dakota Citation also made several flights during the month of May 1998, measuring condensation nuclei (CN) concentrations, which are shown in figure 2.2. CN concentrations were measured with a TSI 3760, which counts essentially all particles from about 0.01 to 3.0 μm in diameter. There is a very thick concentration of CN in the lowest kilometer which decreases with altitude, extending to about 6 km AGL.

2.1.2 August 2000

Total Ozone Mapping Spectrometer

Analysis was performed as in section 2.1.1. Figure 2.3 shows a very clear plume extending east from Central Idaho, the region of highest fire intensity during August 2000, to at least Minnesota.

Other Observations

The Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin, Madison compiled a number of useful images of the forest fires of August 2000 and their associated smoke pall. Figure 2.4 shows the smoke plume from fires on August 8, 2000 from the Geostationary Operational Environmental Satellite-8 (GOES-8). The smoke plume extends eastward into Wisconsin and Illinois. This smoke plume was evident in WSR-88D radar on August 9 in Wisconsin, Iowa, and Illinois. Cloud-free regions exhibited reflectivities of 10-15 dBZ at an altitude of 3-4.5 km AGL [*http://cimms.ssec.wisc.edu*, 2001].

Figure 2.5 shows wildfire locations from the CIMMS GOES-10 Automated Biomass Burning Algorithm (ABBA) [*Prins et al.*, 1998] for the week of August 22-27. The fires are concentrated in central Idaho, but are also present in significant quantities in northern Oregon and southern Washington and also in western Montana. Fires in Idaho include the 155,500 acre Valley Complex and the 33,500 acre Mussigbrod Complex. The Measurements Of Pollution In The Troposphere (MOPITT) instrument aboard NASA's Terra spacecraft also detected large concentrations of CO downwind of the fires . The location of the maximum of this concentration is noted in figure 2.5.

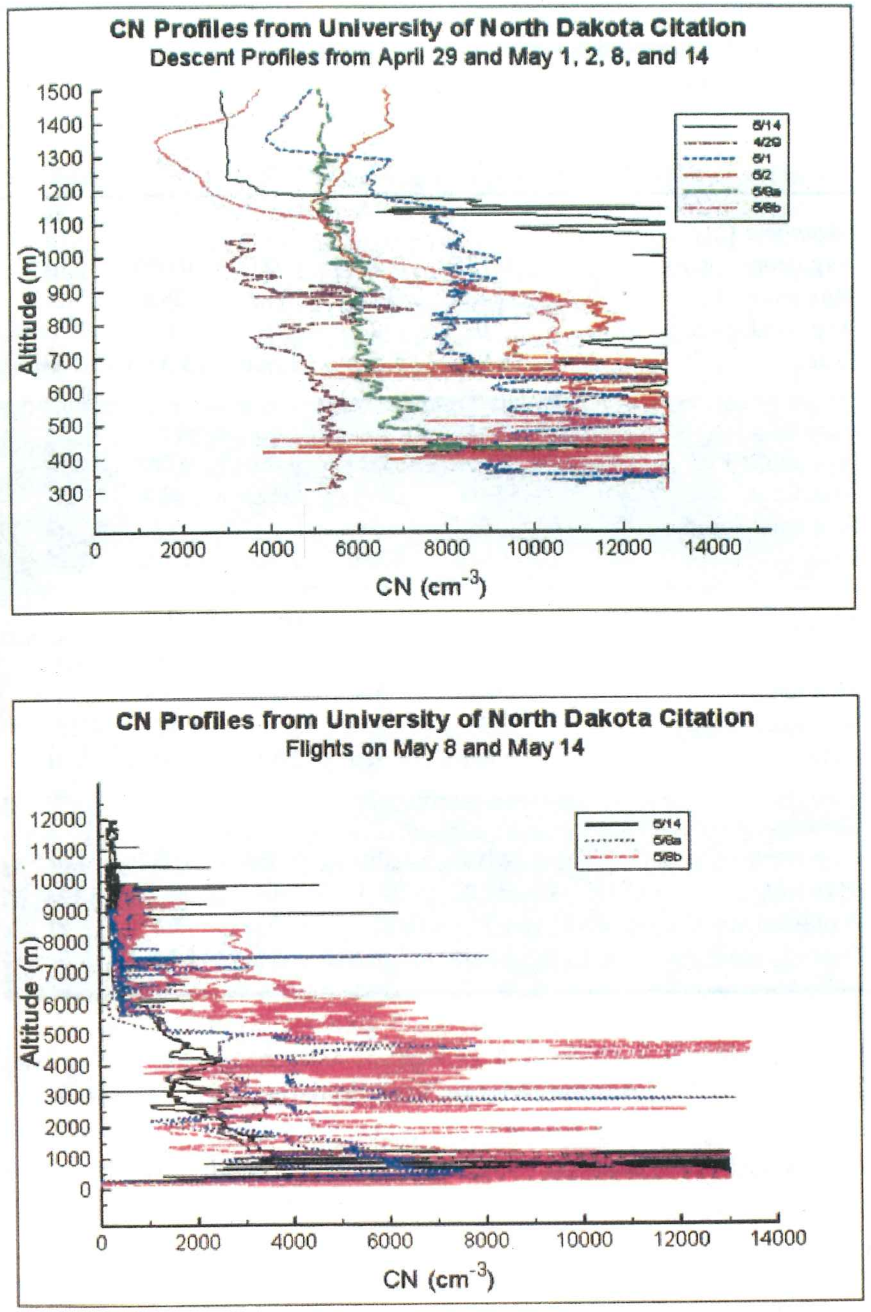


Figure 2.2: (top) Condensation nuclei profiles from the University of North Dakota Citation in the lowest 1500 m and (bottom) for the full altitude range for three flights. The flights were conducted in the ARM SGP CART site. Note that the CN detector saturates at 13000 CN (cm^{-3}). From *Peppler et al.* [2000].

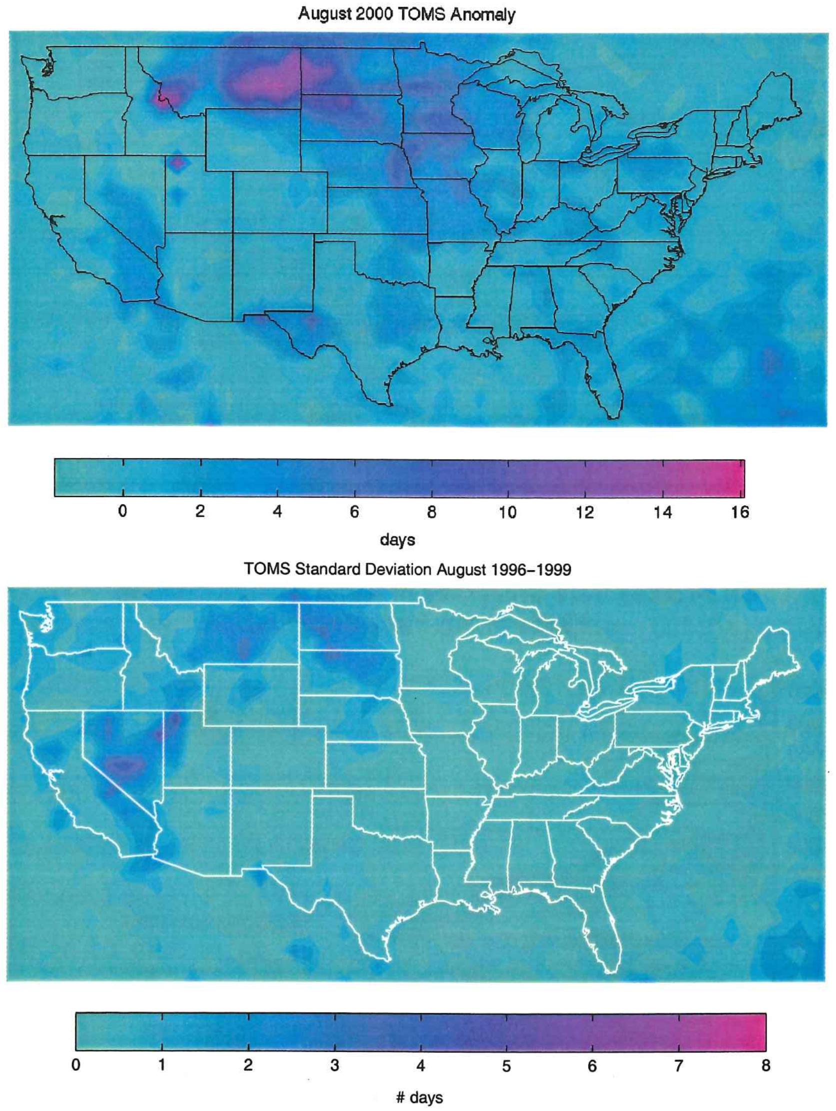


Figure 2.3: (top) August 2000 anomaly of number of days when TOMS aerosol index exceeded 0.7. (bottom) Standard deviation of number of days when TOMS aerosol index exceeded 0.7 for August 1996-1999.

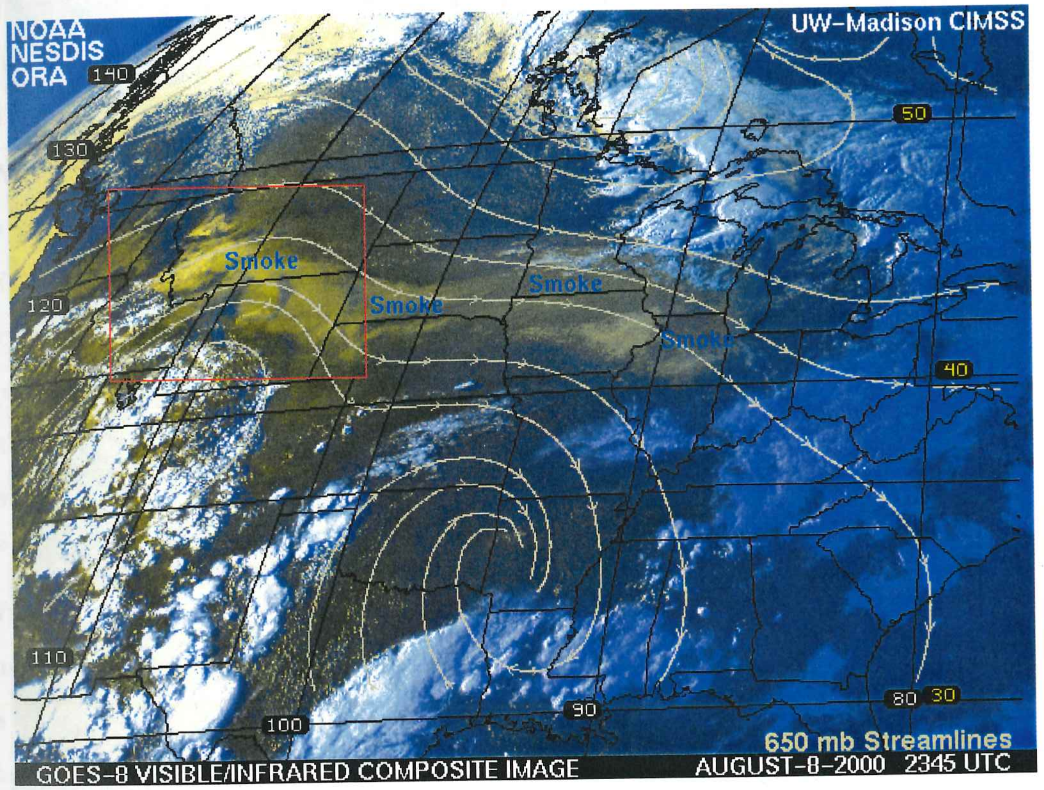


Figure 2.4: Smoke plume from forest fires in Idaho and western Montana on August 8, 2000 along with 650 mb streamlines. From *http://cimms.ssec.wisc.edu* [2001]

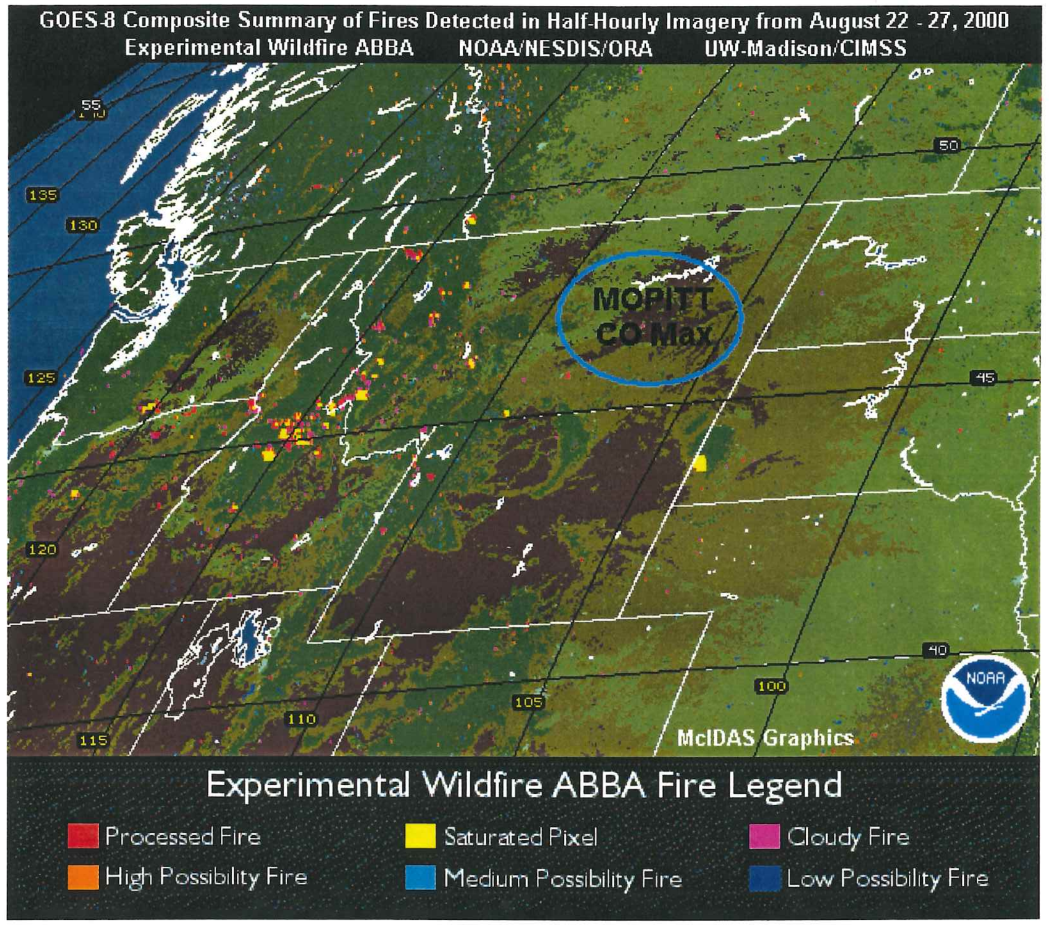


Figure 2.5: Composite of GOES-10 Wildfire ABBA fire observations from the week 22-27 August 2000. Also depicted is the area of maximum CO from MOPITT. From *http://cimms.ssec.wisc.edu* [2001].

2.2 *National Lightning Detection Network*

The National Lightning Detection Network (NLDN) is a network of 106 sensors throughout the continental United States which detect cloud-to-ground (CG) lightning [*Cummins et al.*, 1998]. Along with time and location, the NLDN also records polarity, peak current, and multiplicity (number of strokes) of each flash. Our analysis of the NLDN data follows that of *Murray et al.* [2000] very closely, but we extended the study to include August 2000 and to include the extra year (2000) of lightning data available at the time of our study. Additionally, we made an attempt to illustrate the uncertainty in these analyses.

We examined the years of 1995 through 2000 for the months of May and August. The NLDN began operation in 1989, but a network upgrade in 1994 [*Cummins et al.*, 1998] makes it difficult to use the older data for trend analysis. The network upgrade increased flash detection efficiency substantially and altered the algorithms for calculating peak current and stroke multiplicity significantly. In this study, all positive flashes with peak currents less than 10kA were eliminated to minimize contamination from intracloud lightning, as in *Murray et al.* [2000]. The data were gridded on the same grid as the TOMS: 1° latitude by 1.25° longitude.

We made anomaly maps of total lightning, percentage of positive CG lightning (+CG%), mean peak current for each polarity, and mean multiplicity for each polarity for both May 1998 and August 2000. Anomaly maps were created by subtracting the average value of each of these items for all years except the one of interest from the value for the year of interest. For example, +CG% was computed for each grid cell for the month of May in the years 1995 through 2000. To make the anomaly map for May 1998, we first averaged all these values for the years 1995, 1996, 1997, 1999, and 2000. This was then subtracted from the May 1998 +CG% grid. We also calculated the significance level of the anomaly. This number indicates the probability that the May 1998 value is the climatological mean value. Thus, a significance level close to zero indicates that the May 1998 value is anomalous to a nearly 100% confidence interval and is statistically quite significant. Conversely, a significance level close to 1 indicates that the May 1998 value is statistically indistinguishable from the mean value. The anomaly maps, along with maps of the significance level are shown in figures 2.6

through 2.20. In all cases, black areas indicate areas of missing data. Also note that data outside of the continental United States is outside of the network and should be viewed with some skepticism.

2.2.1 May 1998

Total Cloud-to-Ground Lightning

The total CG lightning anomaly is shown in figure 2.6. There is a clear decrease across the southern portion of the United States. CG flashes in portions of the southern central US were up to 12,000 flashes below the average per grid cell.

In the lower figure of 2.6, it is clear that much of the decrease in CG lightning activity in Eastern Texas and Kansas as well as the increase in activity in Southern Indiana is statistically very significant.

Figure 2.7 shows total CG lightning in the area with anomalous aerosols for the month of May 1998. Many areas of Texas, Kansas, and Nebraska had very small amounts of total lightning, and were among the areas with the most anomalous lightning.

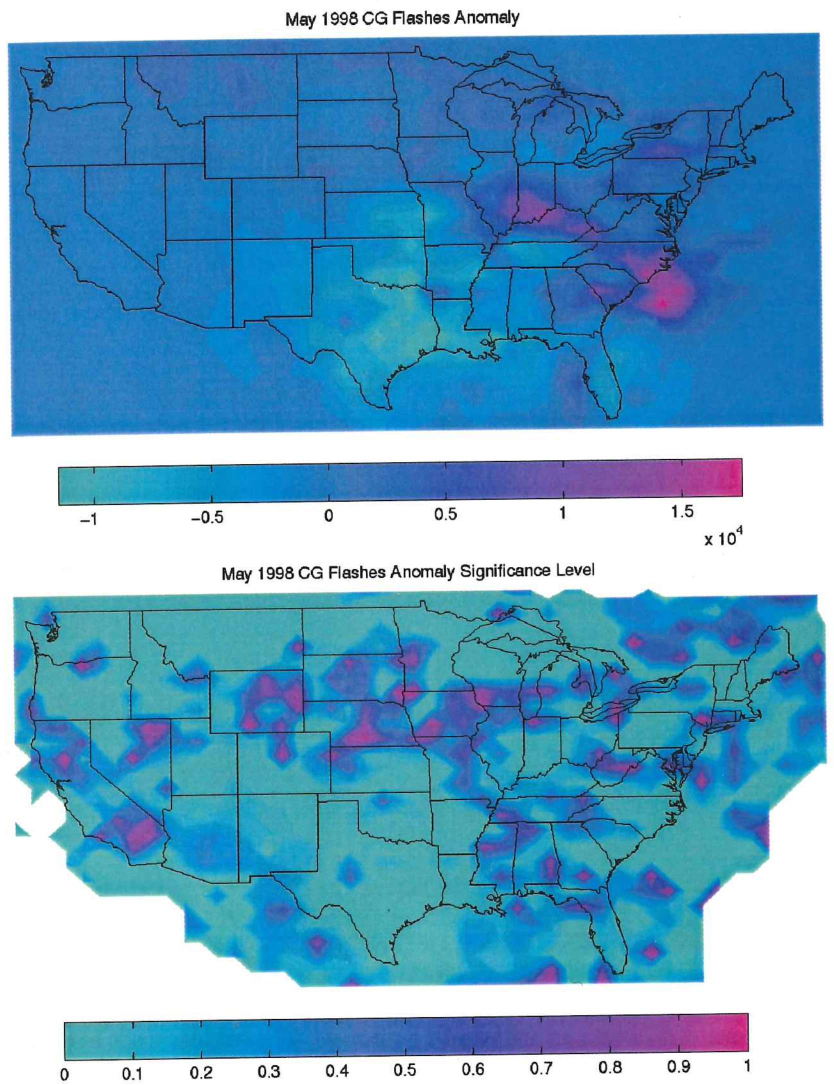
+CG%

Figure 2.8 shows the +CG% anomaly for May 1998. A clearly evident plume extends from Texas northward to Minnesota. In Central and Western Texas, there was an increase of more than 50%, with a very high confidence level. In other regions of the country, the anomaly did not stray far from zero, with the exception of the very northern regions, where lightning frequency is low and detection is poor, making these data somewhat unreliable.

As an addendum to this, we found it interesting to explore whether the anomaly in +CG% is actually due to increased +CG activity in 1998 or whether it is an artifact of decreased total lightning that year. We accomplished this with a simple formulation:

$$+CG\%^{*}_{anomaly} = \frac{N(+CG's_{May1998})}{N(CG's_{average})} \times 100 - +CG\%_{average} \tag{2.2}$$

where N(+CG's$_{May1998}$) is the number of +CG's per grid cell in May 1998, N(CG's$_{average}$) is the average number of total CG's per grid cell for the month of May over the years 1995-1997 and 1999-2000, and +CG%$_{average}$ is the average +CG% in each grid cell for month of


May 1998 CG Flashes Anomaly

May 1998 CG Flashes Anomaly Significance Level

Figure 2.6: (top) Total cloud-to-ground lightning anomaly for May 1998. (bottom) Significance level of the anomaly (see text).

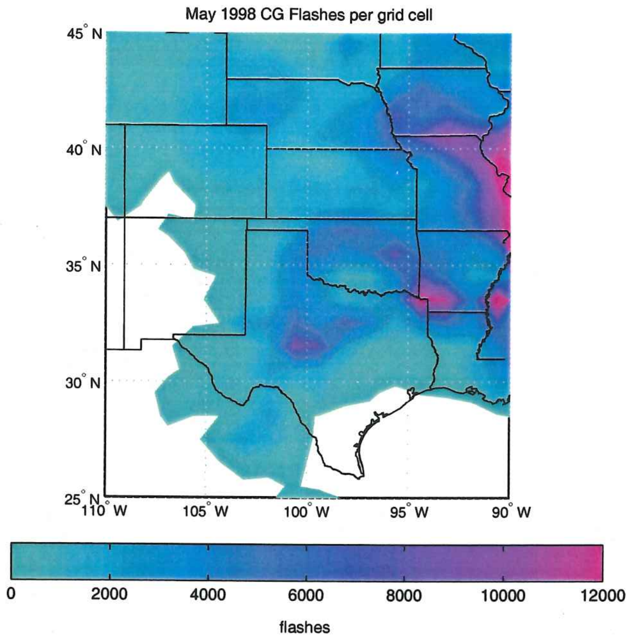


Figure 2.7: May 1998 CG flashes per 1° latitude by 1.25° longitude grid cell.

May over these same years. These results are displayed in figure 2.9. Although the anomaly is somewhat muted, it is still present. Thus, the anomaly in +CG% is not likely to be attributable to a dearth of total CG lightning.

Mean Peak Current

Anomaly maps for mean -CG peak current and mean +CG peak current are shown in figures 2.10 and 2.11. Mean -CG peak currents decreased over Texas by about 10 kA in some areas. The Northern US also has some decrease and the Western US saw a significant increase, exceeding 15 kA in some areas, but both of these areas are not as statistically significant as the Texan anomaly.

Positive flashes, shown in figure 2.11 show a substantial increase in mean peak current, exceeding 20 kA in parts of Texas with a signficance level very close to zero. This is clearly a major anomaly.

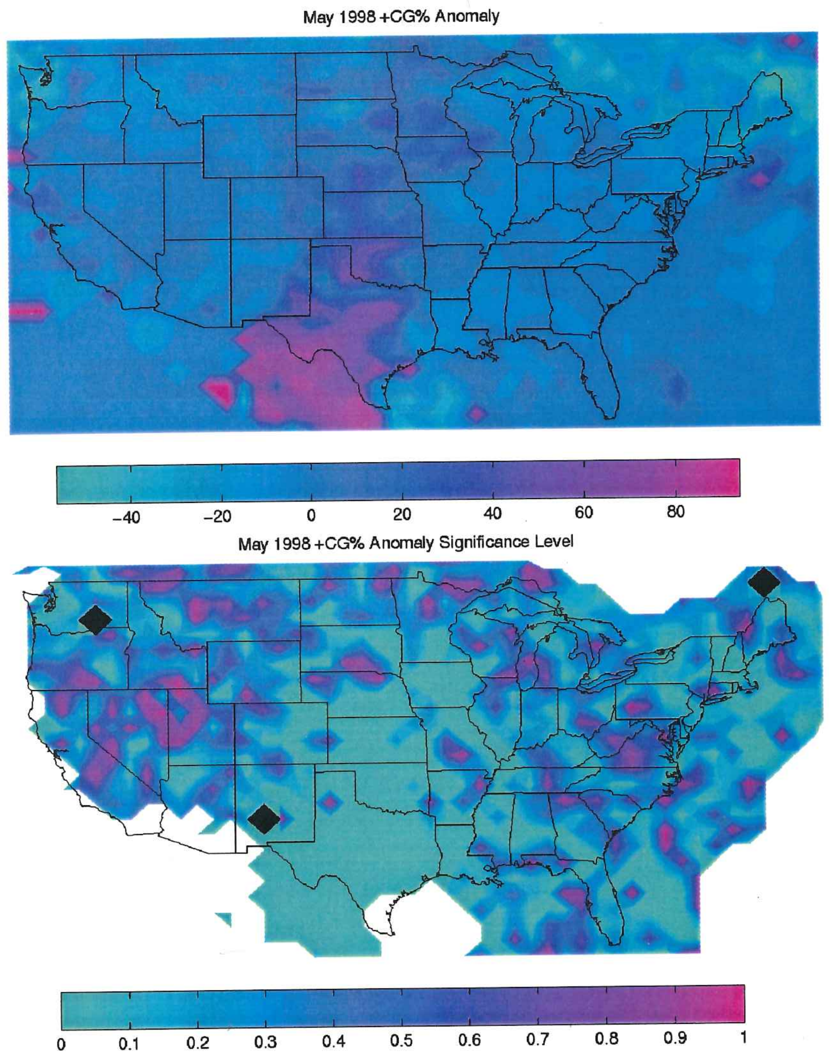


Figure 2.8: (top) May 1998 anomaly of percent of total cloud-to-ground lightning which lowered positive charge to ground (+CG%). (bottom) Significance level of the anomaly. In all figures, dark areas indicate missing data.

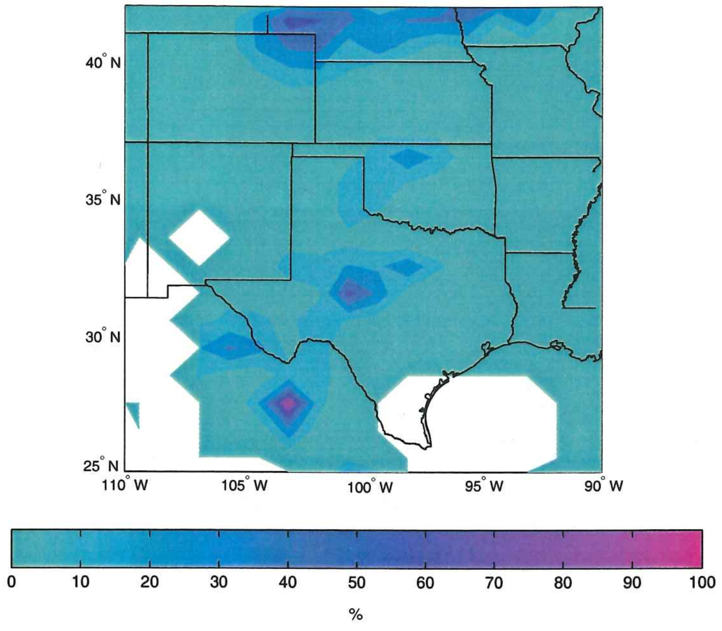


Figure 2.9: Anomaly of +CG% for May 1998 recalculated using average number of CG's instead of May 1998 number of CG's (see text).

Mean Multiplicity

Anomalies in mean multiplicity, or number of strokes in a flash, are presented in figures 2.12 and 2.13 for -CG flashes and +CG flashes, respectively. -CG flashes show a clear decrease in multiplicity over Central Texas and in regions of Oklahoma and Kansas. Mean multiplicity decreased by up to 1.5 strokes per flash. Northern Montana had the opposite anomaly, with increases of 1.5 strokes per flash. Both anomalies are statistically quite significant. +CG mean multiplicity, on the other hand, was quite spotty. +CG flashes seldom have more than one stroke [*Beasley*, 1985] and therefore we would not expect to see much variation. *Mazur and Ruhnke* [1993] attrubute the lack of multiple return strokes in +CG lighting to the low speed of propagation of positive leaders compared to the speed of negative leaders.

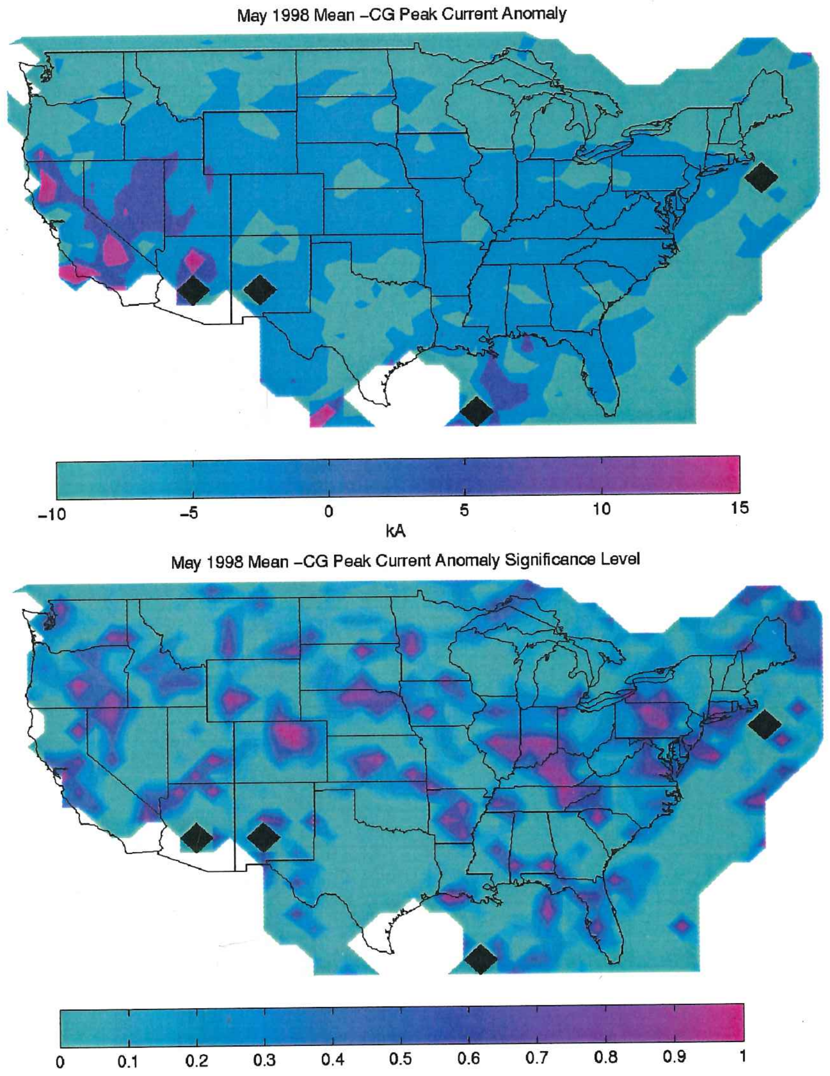


Figure 2.10: (top) May 1998 mean negative cloud-to-ground peak current anomaly. (bottom) Significance level of the anomaly.

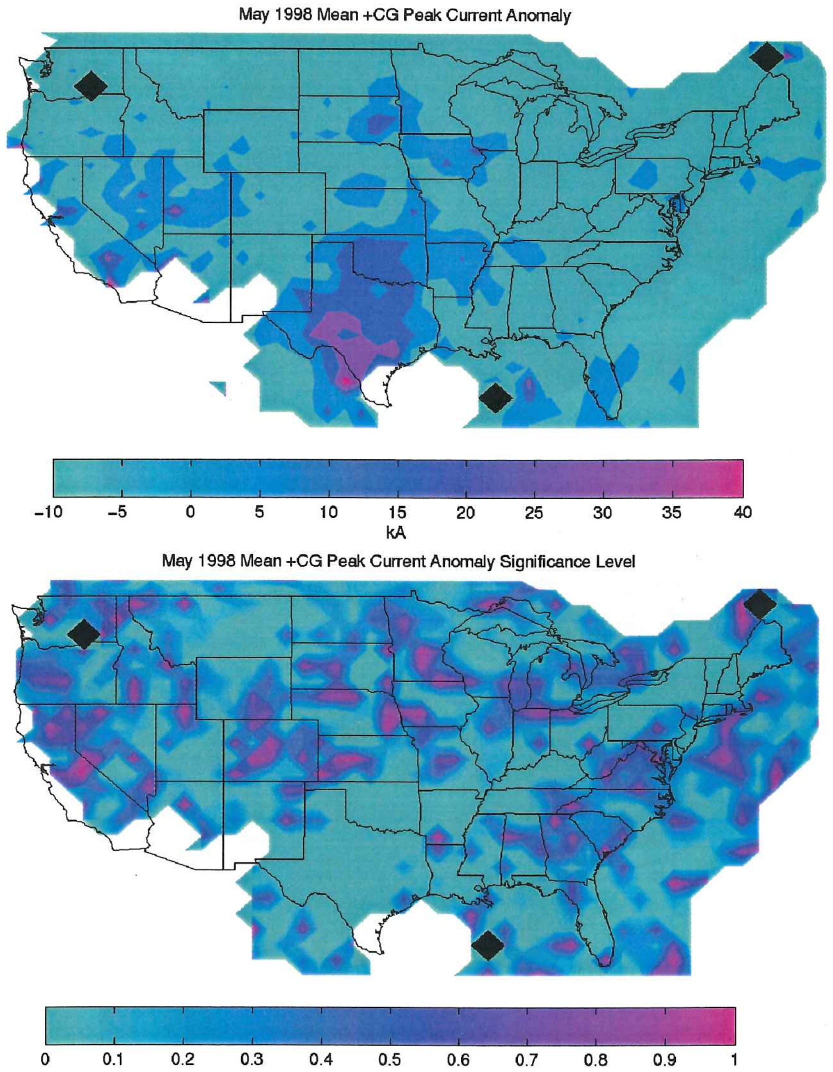


Figure 2.11: (top) May 1998 mean positive cloud-to-ground peak current anomaly. (bottom) Significance level of the anomaly.

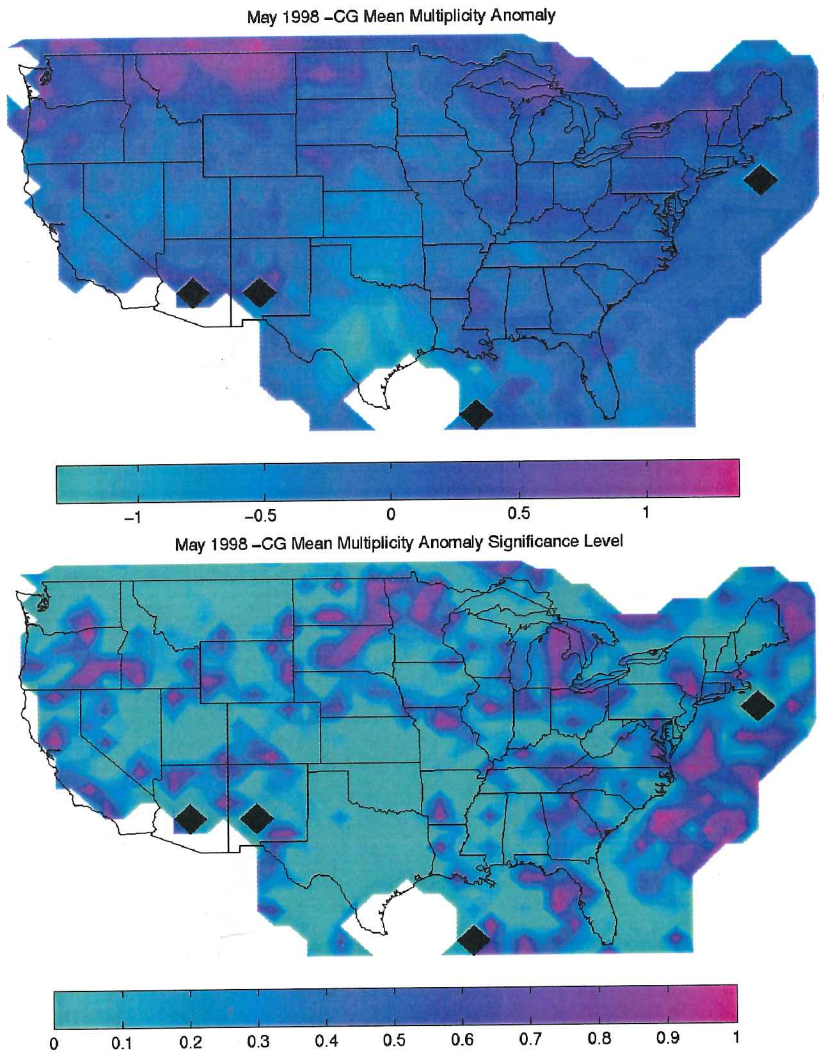
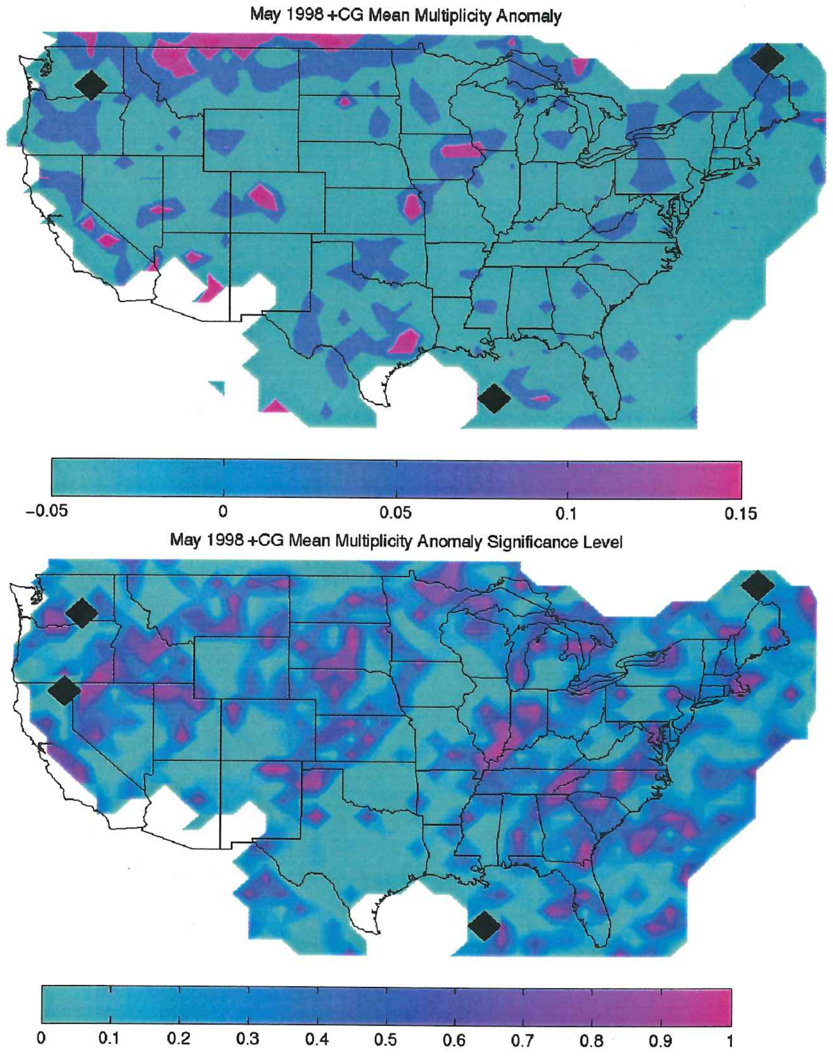


Figure 2.12: (top) May 1998 negative cloud-to-ground mean multiplicity anomaly. (bottom) Significance level of the anomaly.


May 1998 +CG Mean Multiplicity Anomaly

May 1998 +CG Mean Multiplicity Anomaly Significance Level

Figure 2.13: (top) May 1998 positive cloud-to-ground mean multiplicity anomaly. (bottom) Significance level of the anomaly.

May 1998 Lightning Summary

The Southern Plains had very anomalous lightning in May 1998. Total CG lightning decreased by up to 12,000 flashes per grid cell below the mean. +CG's were especially potent: +CG% increased by more than 50% and +CG mean peak current increased by more than 20 kA in some areas of the Plains. -CG's, conversely, were somewhat bridled: -CG mean peak currents decreased by about 10 kA and mean multiplicity decreased by up to 1.5 strokes per flash.

2.2.2 August 2000

The analysis for lightning events in August 2000 follows that of May 1998. According to the TOMS, the smoke was almost as persistent over the Northern United States in August 2000 as it was over Texas in May 1998, but, as you will see, lightning was not nearly as anomalous.

Total Cloud-to-Ground Lightning

Total CG lightning activity, as indicated in figure 2.14, decreased over much of the Central United States and, to a lesser extent, over Montana and Wyoming. There were pockets of increased activity, most notably in Indiana, Illinois, Kentucky, and Missouri and in eastern Arizona.

Total CG lightning for the month of August 2000 in the area with anomalous aerosol coverage is shown in figure 2.15. There was little lightning directly over the fires, but substantial amounts of lightning occurred to the East, downwind of the fires.

+CG%

August 2000 +CG% anomaly is illustrated in figure 2.16. There is a small, but striking anomaly over western Montana and eastern Idaho. This is very close to the forest fires during this period. The anomaly is of approximately the same magnitude and significance level, but much smaller geographically than the anomaly in May 1998 in the Central United States. Regions in Minnesota and Wisconsin also show some evidence of increased +CG%.

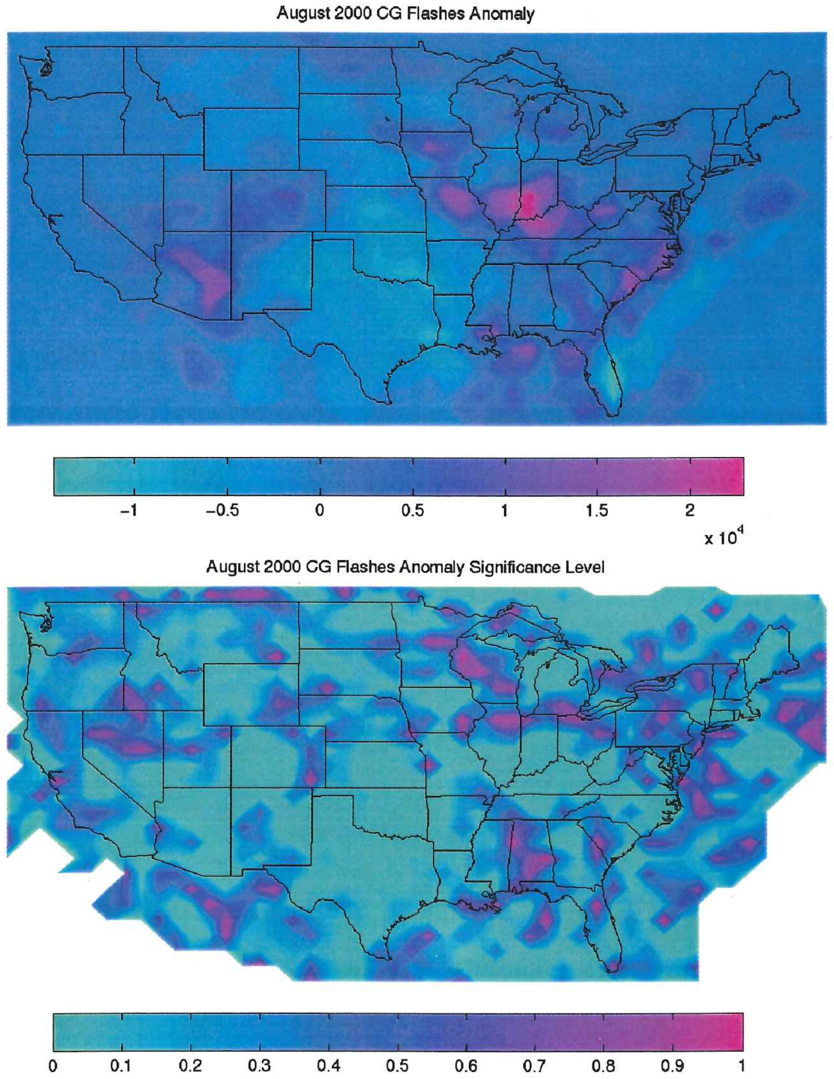


Figure 2.14: (top) Total cloud-to-ground lightning anomaly for August 2000. (bottom) Significance level of the anomaly.

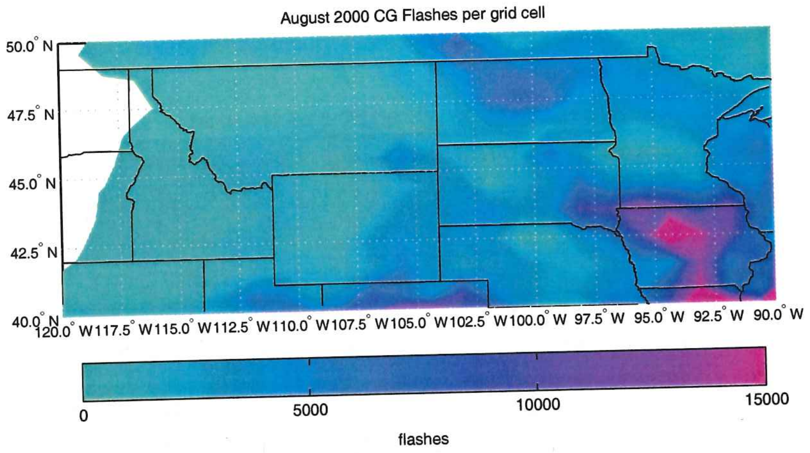


Figure 2.15: August 2000 CG flashes per 1° latitude by 1.25° longitude grid cell.

Mean Peak Current

Mean peak current anomalies for both polarities are shown in figures 2.17 and 2.18. Mean -CG peak currents are increased slightly in some regions of the Central United States and decreased slightly along the Canadian border. Mean +CG peak currents follow a similar pattern, as opposed to May 1998 when mean -CG peak currents decreased and mean +CG peak currents increased. There is one small spot in southwestern Idaho with an increase of mean peak current of about 25 kA, which is close to the fires, but it is highly localized.

Mean Multiplicity

Figures 2.19 and 2.20 show mean multiplicity anomalies for each polarity. -CG mean multiplicity is increased by about 0.5-1 in much of the Midwest, Pennsylvania, and New York and also in Montana. These are statistically significant anomalies. Once again, the +CG mean multiplicity anomaly is very scattered and quite small.

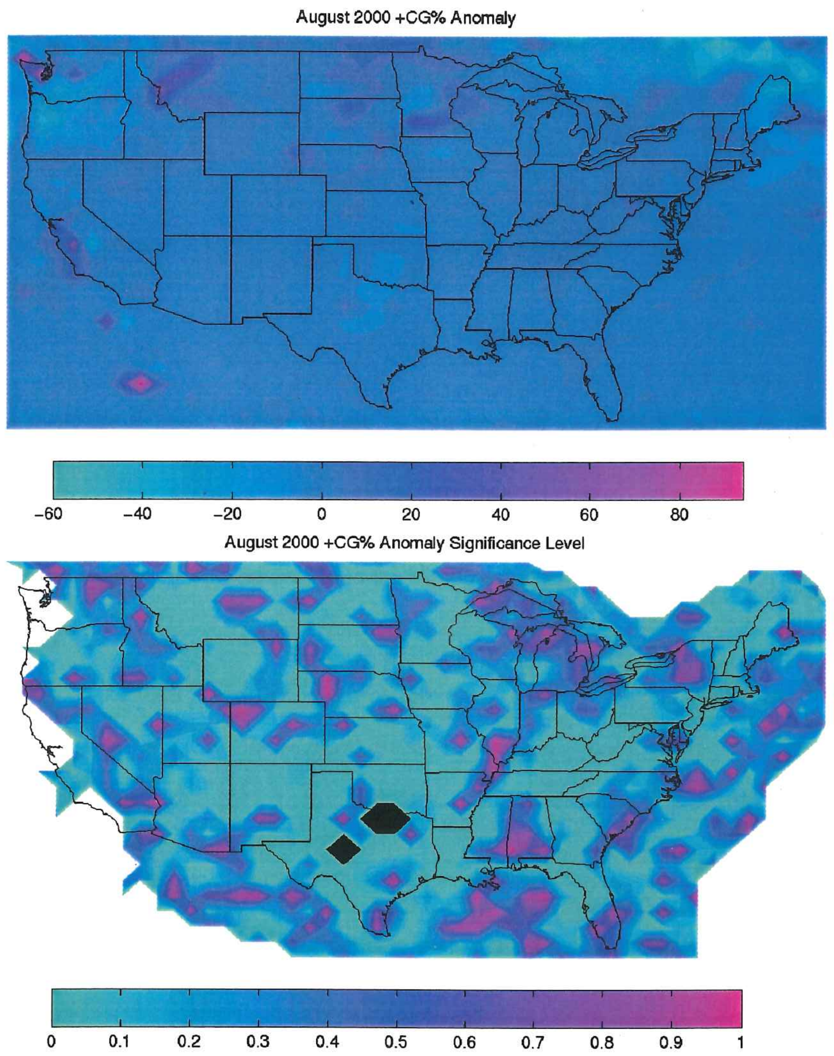


Figure 2.16: (top) August 2000 percent of total cloud-to-ground lightning which lowered positive charge to ground (+CG%). (bottom) Significance level of the anomaly.

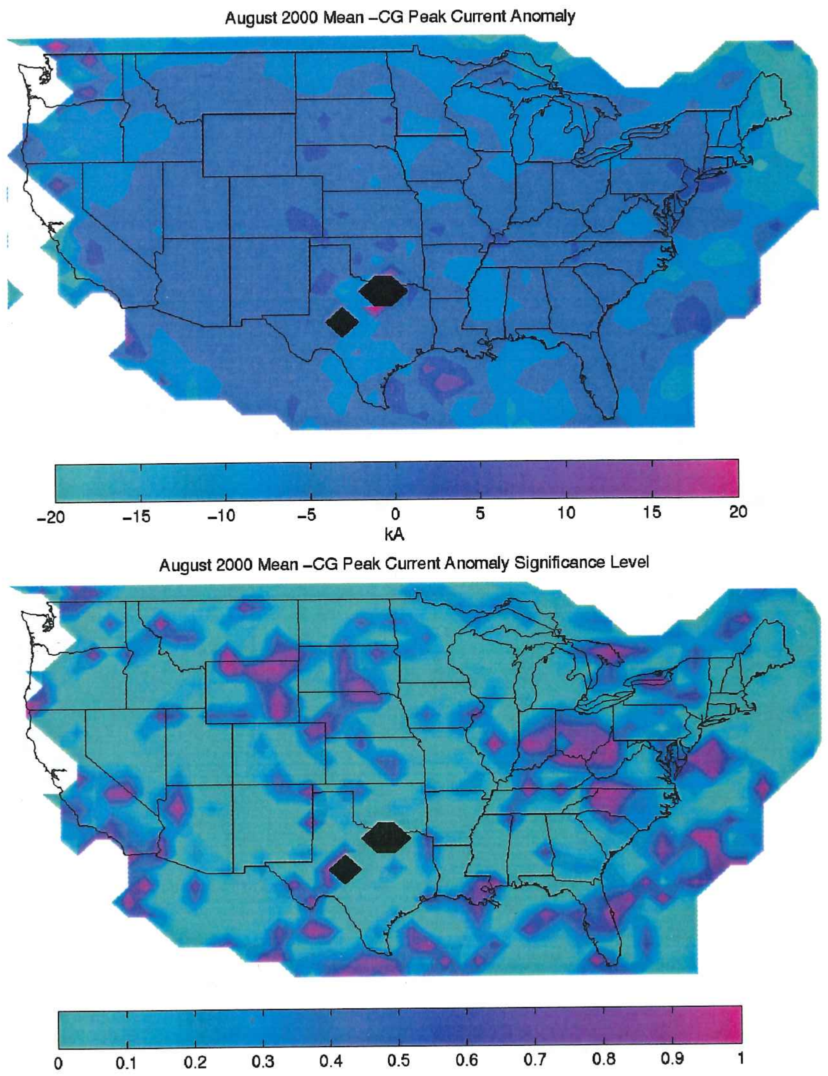


Figure 2.17: (top) August 2000 mean negative cloud-to-ground peak current anomaly. (bottom) Significance level of the anomaly.

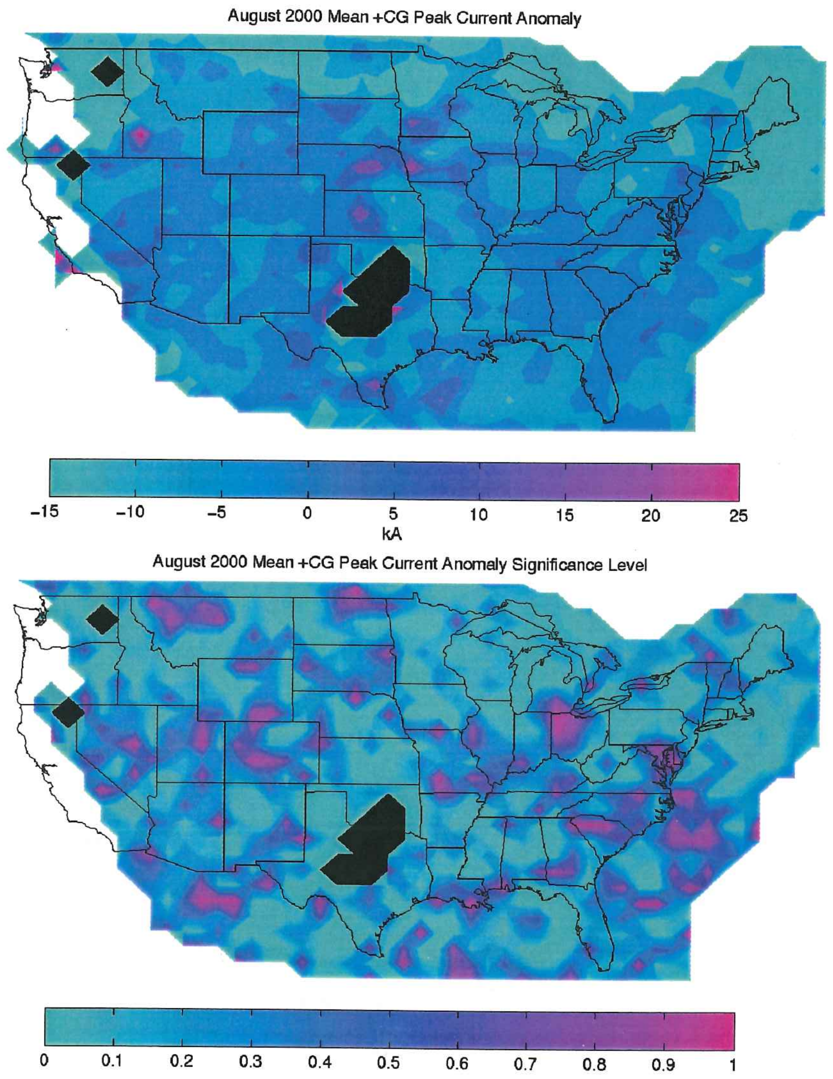


Figure 2.18: (top) August 2000 mean positive cloud-to-ground peak current anomaly. (bottom) Significance level of the anomaly.

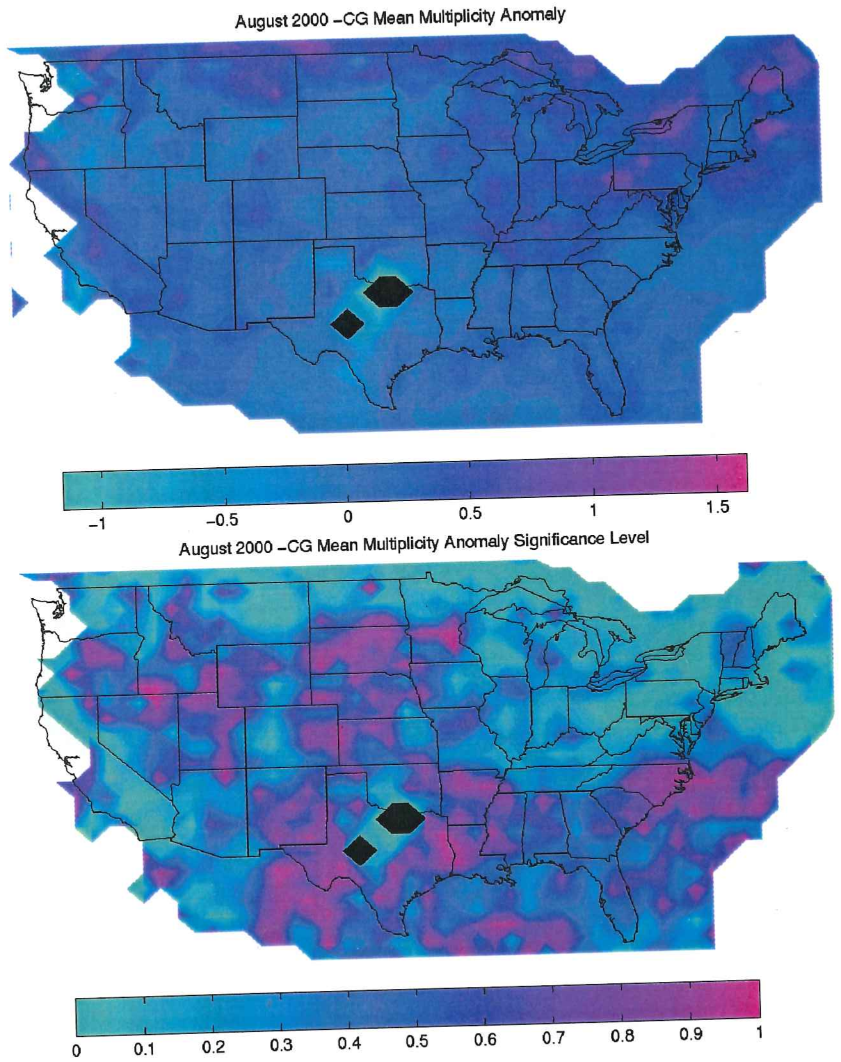


Figure 2.19: (top) August 2000 negative cloud-to-ground mean multiplicity anomaly. (bottom) Significance level of the anomaly.

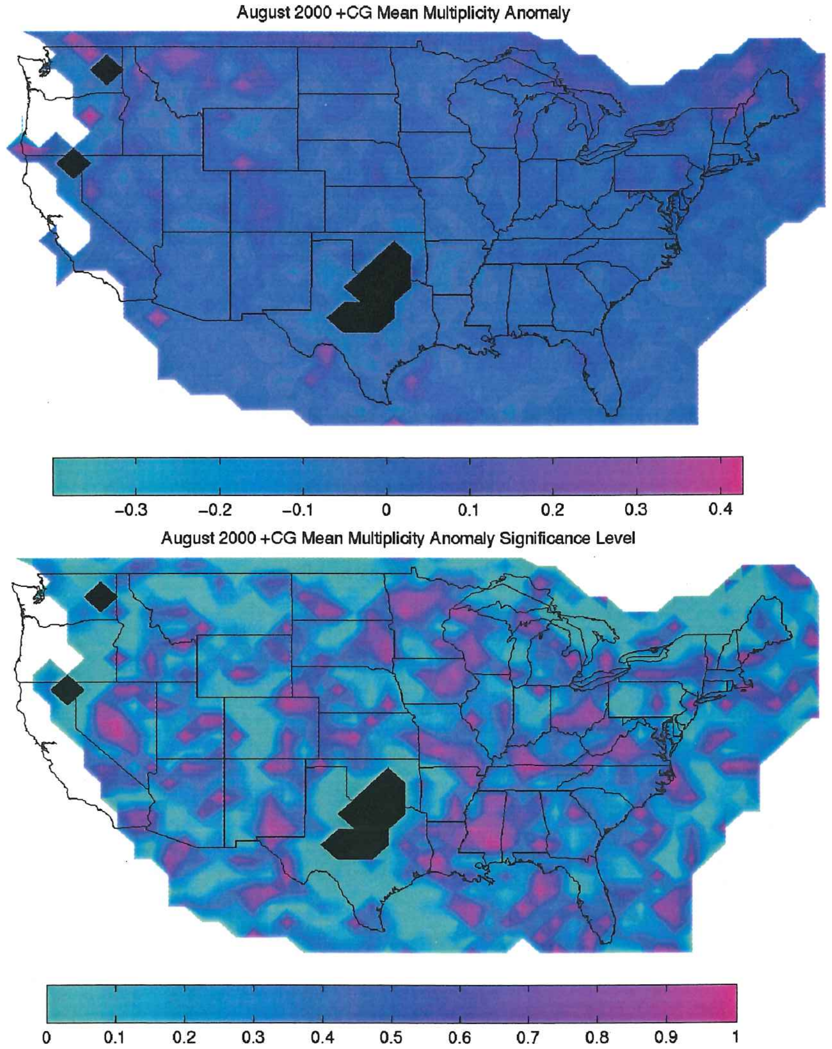


Figure 2.20: (top) August 2000 positive cloud-to-ground mean multiplicity anomaly. (bottom) Significance level of the anomaly.

August 2000 Lightning Summary

In contrast to May 1998, lightning was not particularly anomalous in August 2000. A small +CG% anomaly was present near the fires in Idaho and Montana, but this is the only obvious anomaly.

2.3 Radiosondes

To better understand the environments of the months of May 1998 and August 2000, we used radiosonde data, freely available from the University of Wyoming Department of Atmospheric Science [*http://weather.uwyo.edu/upperair/sounding.html*, 2001]. We analyzed twice-daily weather station soundings at the locations marked in figure 2.21 for the months of May and August, spanning the years of 1990 through 2001. Each sounding had an associated Convective Available Potential Energy (CAPE), calculated by the University of Wyoming as:

$$CAPE = g \sum_{z=LFCV}^{EQLV} \Delta z \frac{(TP - TE)}{TE} \tag{2.3}$$

where g is the acceleration due to gravity; LFCV is the level of free convection; EQLV is the equilibrium level (the level at which a parcel is raised, dry adiabatically below the lifting condensation level and moist adiabatically above the lifting condensation level, above which the temperature of the environment is the same as the temperature of the parcel); Δz is the incremental depth; TP is the temperature of a parcel from the lowest 500m of the environment raised dry adiabatically to the lifting condensation level, then moist adiabatically to the LFCV; and TE is the temperature of the environment. Higher values of CAPE imply a possibility of more vigorous convection.

CAPE values were averaged over the entire month for each station in each year. The average values were then gridded in a 2.5° by 2.5° grid. We then compared this gridded CAPE for the month of May 1998 to the average of the gridded CAPE for the month of May in the years 1990 through 1997 and 1999 through 2001. We analyzed August 2000 in a similar manner. The results of both comparisons are illustrated in figures 2.22 and 2.23. In May 1998, there are two large positive anomalies: one in the central Midwest and

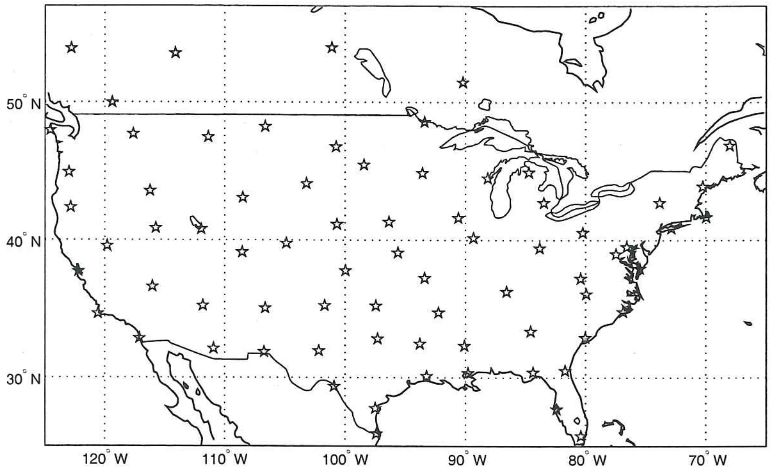
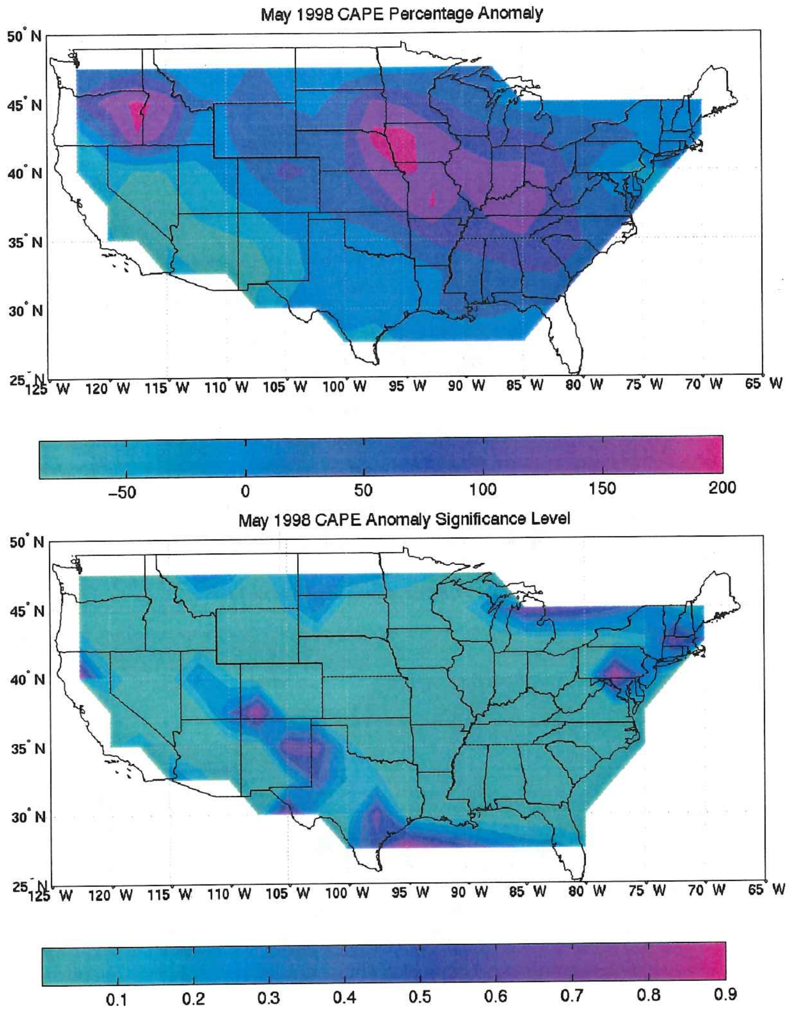


Figure 2.21: Locations of soundings used for CAPE analysis.

one in eastern Oregon and western Idaho. Both of these anomalies are statistically quite significant. The anomaly in the Midwest is coincident with a portion of the percentage of cloud to ground lightning anomaly, but the northwestern CAPE anomaly is not. In August 2000, the anomalies were much less pronounced. CAPE values are slightly elevated over the northern Great Plains and central Midwest, but the anomalies in the Plains are statistically insignificant.

2.4 *Precipitation*

Precipitation anomalies (departure from 1900-1990 mean) are presented in figure 2.24. The anomalies are derived from raingauge data provided by the National Climatic Data Center. May 1998 was clearly an anomalous month. New Mexico, Texas, and Lousiana had a record dry month while precipitation on the west coast was much above normal to record wettest in Oregon. In August 2000, much of the country, especially the Northwest, had below normal precipitation. Texas, Oklahoma, and Arkansas reported record dry months.


May 1998 CAPE Percentage Anomaly

May 1998 CAPE Anomaly Significance Level

Figure 2.22: (top) The percentage change in CAPE between May 1998 and the mean CAPE for the month of May in the years 1990 through 1997 and 1999 through 2001 derived from twice daily soundings. (bottom) Significance level of the anomaly.

2.5 *Surface Temperature*

Surface temperature anomalies (departure from 1900-1990 mean) are shown in figure 2.25. The anomalies are determined by meteorological station data and are provided by the National Climatic Data Center. May 1998 was also clearly an anomalous month for surface temperatures. Much of the Great Plains and the Northeast was much warmer than average,

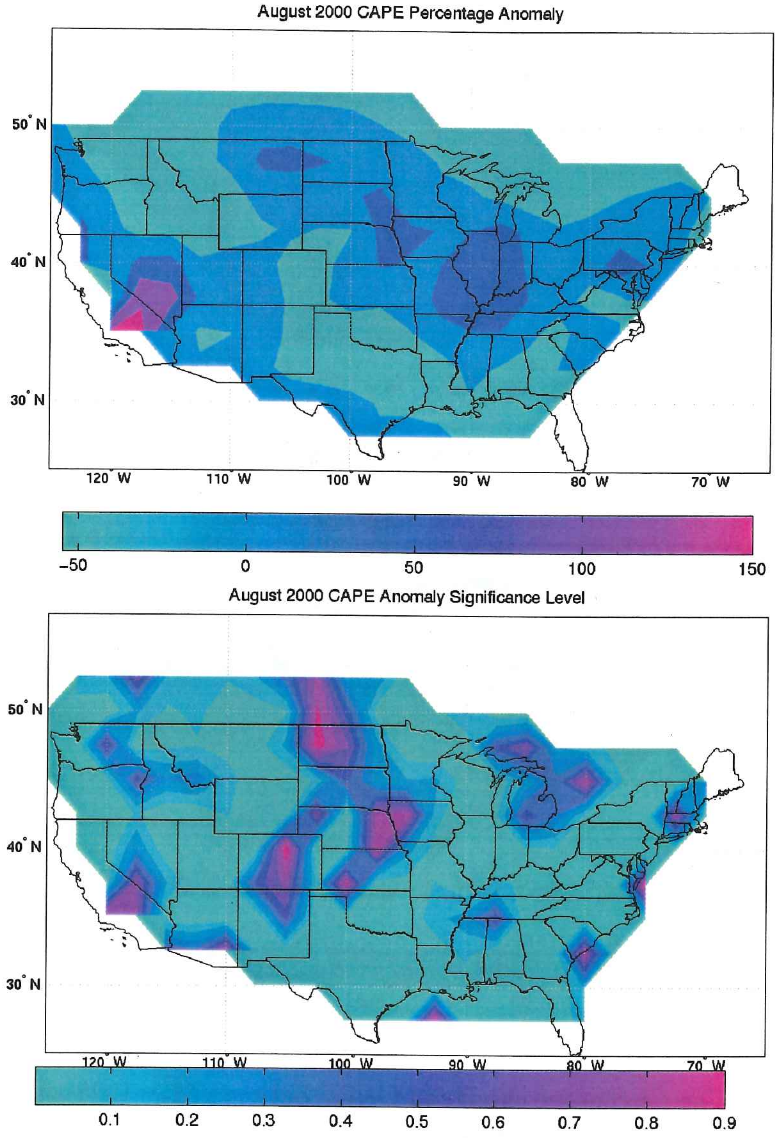


Figure 2.23: Same as figure 2.22, except comparing August 2000 with August 1990 through 1999 and 2001.

while the West Coast was quite cool. In August 2000, much of the Northeast was cooler than normal, while temperatures in Kansas were up to 3°C warmer than normal. Near the fires in the Northwest, temperatures were elevated slightly.

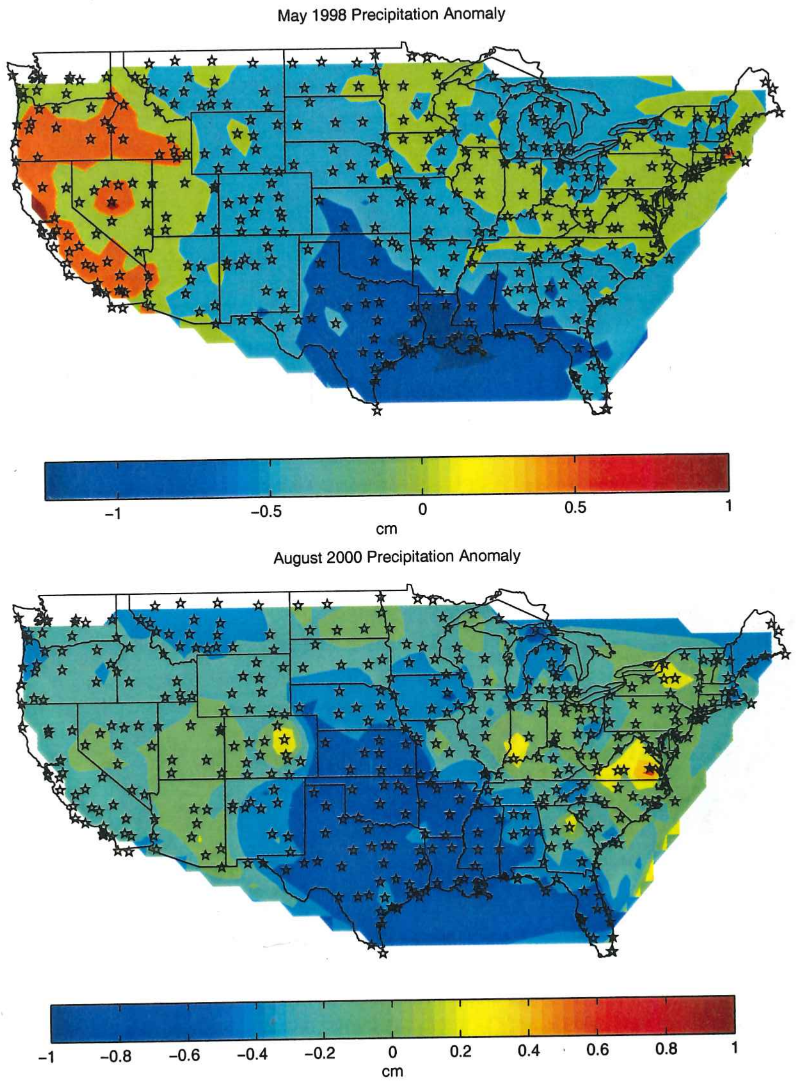


Figure 2.24: (top) May 1998 precipitation anomaly. Stars indicate station locations. (bottom) August 2000 precipitation anomaly.

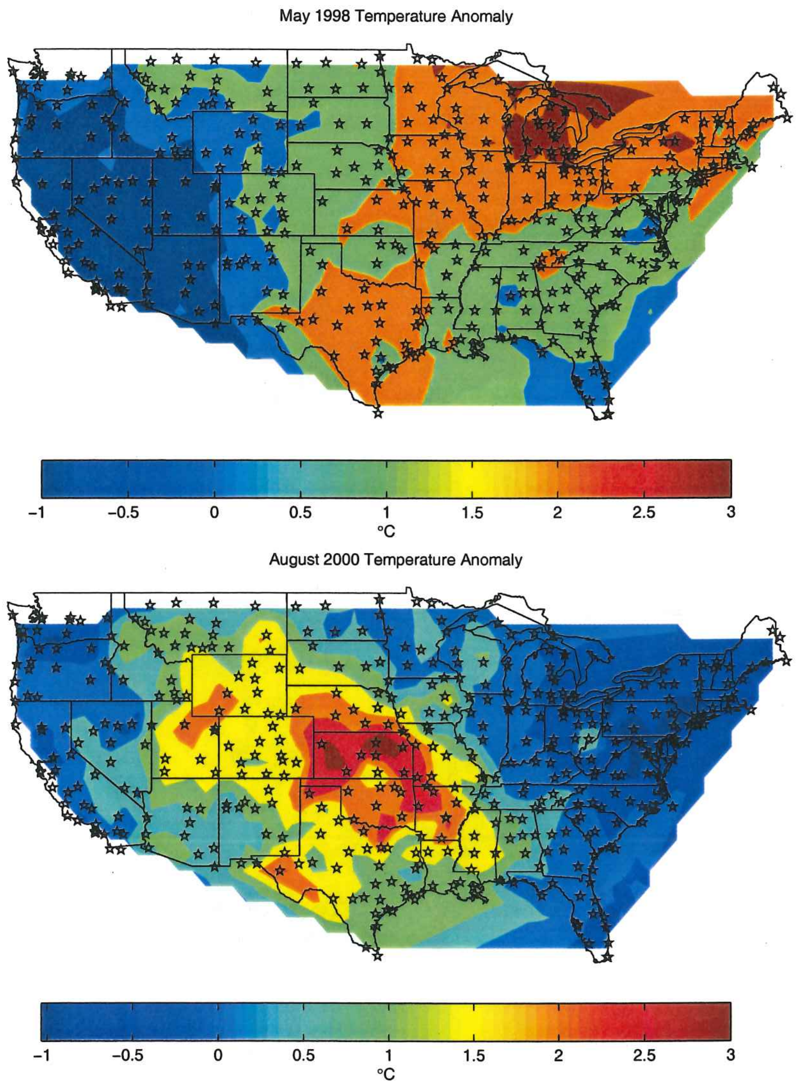


Figure 2.25: (top) May 1998 surface temperature anomaly. Stars indicate station locations. (bottom) August 2000 surface temperature anomaly.

2.6 *Discussion*

2.6.1 *May 1998*

In May 1998, portions of the Central United States, and especially Texas, saw very anomalous lightning. Total CG flashes were reduced, but, in some areas, the vast majority of flashes were +CG's with very high peak currents. Peak currents and mean multiplicities of -CG's were substantially lowered over the same regions.

This was clearly an anomalous month, but not just for the lightning and the smoke. The Texas Climatic Bulletin for May 1998 states:

> The preliminary temperature and precipitation ranks produced by the Climate Prediction Center help to place May conditions for regions of the United States into perspective. These ranks compare this year's weather conditions to the previous conditions observed over the last 102 years, with "preliminary" meaning that the data from cooperative stations have not been incorporated into the ranking. Texas is included within a region including Kansas, Oklahoma, Arkansas, Louisiana and Mississippi. *May 1998 has been ranked as both the warmest and the driest May that this region has ever seen.* [Italics added] [*Griffiths and Belcher*, 1998] See figures 2.24 and 2.25.

These persistent warm, dry conditions could have substantial effects on thunderstorm dynamics and microphysics. In a warm, dry environment, cloudbase is likely to be quite high, which could have several effects: 1) Fewer flashes are likely to hit the ground due to the increased distance between the charging zones and ground. 2) Those flashes which do hit the ground are likely to deposit more charge to ground because the amount of charge in the charge center of the thunderstorm required to reach the breakdown field between the earth and the charge center must increase in order to compensate for the greater distance.

Of course, this does not explain why peak current and mean multiplicity decreased for -CG flashes. If, however, there is little net negative charge in the region of the cloud producing the -CGs, growth of the positive leader associated with the -CG will be inhibited in the cloud. This could prevent subsequent return strokes, thereby decreasing the total amount of charge lowered to ground.

2.6.2 August 2000

The most striking feature of the August 2000 lightning anomaly maps is the lack of any substantial anomaly. Although the TOMS anomaly is nearly as strong in the Northern United States as it was in Texas in May 1998, there seemed to have been little effect on the lightning. It is possible that the aerosols were carried to altitudes too high to affect thunderstorms, but their detection by radar as far east as Illinois at the 3-4.5 km level casts some doubt on this hypothesis.

Figures 2.7 and 2.15 show the total amount of CG lightning for May 1998 and August 2000. It is clear that in August 2000 there were not copious amounts of lightning in close proximity to the fires, but the plume extended eastward into areas with relatively high flash densities. These densities are certainly commensurate to those in May 1998 which produced anomalous lightning. Therefore, it is unlikely that the lack of anomalous lightning in August 2000 was due to a lack of total lightning.

Chapter 3

1.5 DIMENSIONAL THUNDERSTORM MODEL

3.1 The model

In order to better understand the effect of forest fires on thunderstorms, we employed the 1.5 dimensional thunderstorm model described in *Solomon and Baker* [1998]. For initialization, the model takes an environmental sounding, which includes vertical profiles of temperature and dewpoint, along with user-input parameters such as cloudbase, storm duration, storm radius, cloudbase updraft velocity, and cloud condensation nuclei concentration. The model itself consists of three regions - inner cloud, outer cloud, and cloud-free environment. Explicit microphysics are calculated in each cloud region for the duration of the storm. Charging is accomplished through the non-inductive charge transfer mechanism of *Saunders et al.* [1991] (see figure 1.2). When this charging process produces electric fields exceeding a user determined threshold (set to 200 kV/m for this study), lightning is initiated.

While this model is clearly incapable of reproducing the true dynamics of a thunderstorm, it can yield valuable insight into the microphysical processes.

3.2 Modeled thunderstorm day: May 1998

We chose to examine a day when the smoke plume from Central America was near its peak and there was a significant anomaly in the percent of positive cloud-to-ground lightning: May 15, 1998. Figure 3.1 shows the percent of positive cloud-to-ground lightning on May 15, 1998; note the exceptionally high values in northern Texas and western Oklahoma. Figure 3.2 gives a measure of the particulate matter in Amarillo, TX during the month of May. There is a spike in particle mass near May 15. The sounding for May 15, 1998 0Z in Amarillo, TX is shown in figure 3.3. The sounding is required as input for the model. Cloudbase was chosen to be the lifting condensation level, 580 mbar.

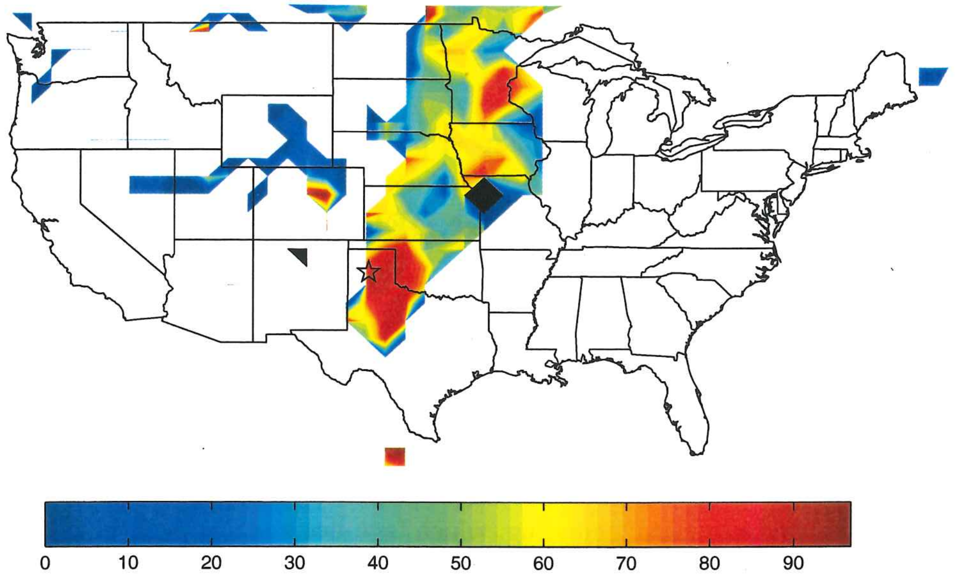


Figure 3.1: Contours of percent of positive cloud-to-ground lightning for May 15, 1998. Grid size is 1.25° longitude by 1° latitude. The lone star marks Amarillo, TX

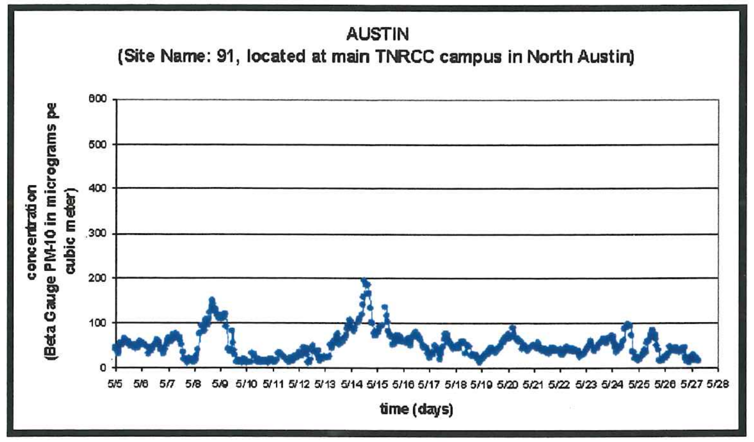


Figure 3.2: PM10 (Total Mass of Particulate Matter less than 10 microns in radius) in Austin, Tx. Note peak near May 15. From *http://capita.wustl.edu/Central America/Resources/Data/Data.html* [1998].

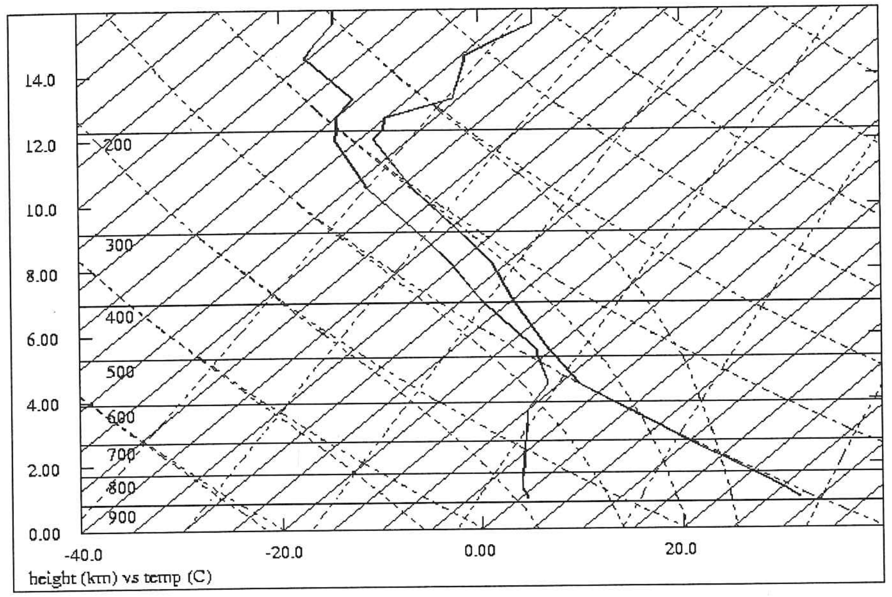


Figure 3.3: 0Z Sounding for May 15, 1998 in Amarillo, TX. The curve on the right is temperature and the curve on the left is dewpoint, both in °C. From *http://weather.uwyo.edu/upperair/sounding.html* [2001].

3.3 *Effect of varying CCN concentration*

Both *Lyons et al.* [1998] and *Murray et al.* [2000] suggested that heightened concentrations of CCN may have been a factor in the anomalous lightning observed in May 1998. To investigate this hypothesis, we utilized the 1.5 dimensional thunderstorm model for the day described above, varying CCN concentrations from the relatively clean 500 CCN/cm^3 to the turbid 15,000 CCN/cm^3. Figure 3.4 shows the effect of varying CCN on peak total (CG's + intracloud flashes) flashrate, +CG%, and total number of CG's (both +CG's and -CG's). It is quite obvious that, at least in our model, there is no clear correlation between these three parameters and CCN concentration.

It is interesting to note that most of the model runs which produced CG lightning produced exclusively +CG's. To help explain this behavior, observe figure 3.5, which illustrates some aspects of the model output when initialized with 500 CCN/cm^3. Around 2000 s after model initiation, there is a clear upper positive and lower negative electric field which persists for the duration of the storm. However, there is also a strong lower positive electric field caused by positive charge below the main charge centers of the storm.

The causes of this lower positive charge center are twofold: 1) As noted in chapter one, when collisions occur between graupel particles and ice crystals in an environment with substantial amounts of liquid water, the graupel will tend to charge positively. Due to the very dry sounding, cloudbase was above the altitude of the freezing level (cloudbase temperature=-5°C), allowing water condensing out of the rising air to comingle with ice. This increased the liquid water content sufficiently for the graupel to charge positively in ice crystal-graupel collisions. Therefore, part of the lower positive charge center is due to positively charged graupel. 2) Intracloud lightning deposits positive charge in this region. Intracloud lightning is initiated in the peak of the of the negative electric field, which corresponds to the area between the main positive and negative charge centers in the cloud. The lightning channel extends just beyond the lower negative charge center and deposits positive charge.

The +CG's were eventually created about 4000 s after model initiation when the lower positive charge center grew strong enough to initialize lightning. This result is reasonably archetypal of this series of model runs. The storms were fairly weak in terms of updraft velocity and graupel production, largely because of the lack of moisture. This favored the production of a lower positive charge region in several ways: 1) Large graupel did not form. The downward motion of large, negatively charged, precipitating graupel particles would act to reduce or eliminate the lower positive charge region, by contaminating it with negative charge, or by pushing it to the ground. 2) A weak updraft generally means weak charging. Although graupel initially charged positively, this only persisted for about the first 1000 s of the model run when there was an updraft at cloudbase which was actively condensing water. Had the charging mechanism been more active after this point, the production of negative charge on graupel may have destroyed the lower positive region. These modeled

storms were strong enough to create lightning, but not so strong that they destroyed the lower positive charge center.

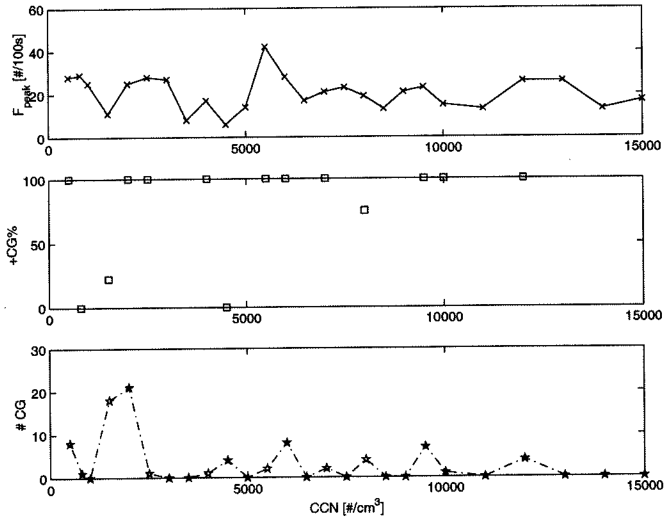


Figure 3.4: (top) Peak Flashrate (flashes/100s) vs. CCN concentration, (middle) Percent of positive cloud-to-ground lightning vs. CCN concentration, and (bottom) Total Number of cloud-to-ground flashes in each 6500s model run.

3.4 Increasing the relative humidity of the sounding.

The exceptionally dry conditions in the central U.S. during May 1998 may have had a significant impact upon lightning. In an effort to understand this effect, we modified the sounding used in the previous section by increasing the relative humidity (RH) in the entire sounding by 5%. RH is defined as:

$$RH = 100\frac{q_s(T_d, p)}{q_s(T, p)} \tag{3.1}$$

where q_s is the saturation mixing ratio with respect to water, T_d is the dewpoint, T is temperature, and p is pressure. Increasing the humidity lowered cloudbase to 605 mbar and increased the mixing ratio of vapor at cloudbase to 5.5 g/kg. The modified sounding is shown in figure 3.6.

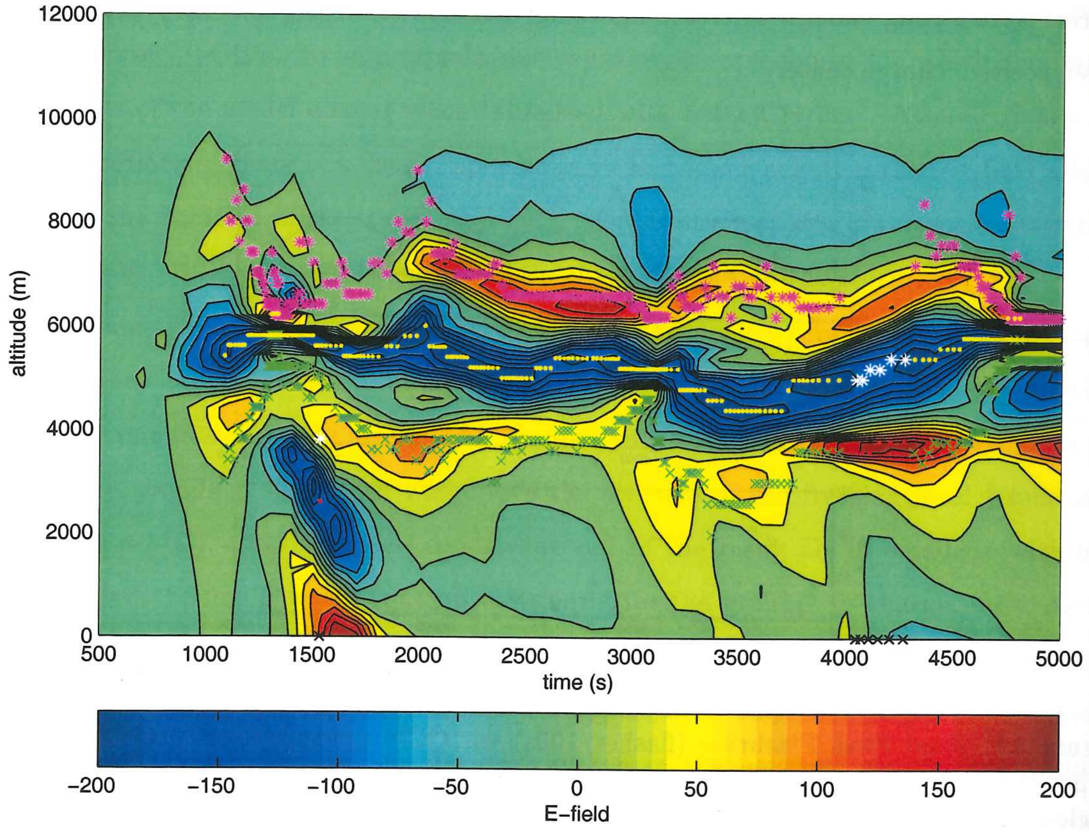


Figure 3.5: Electric field and lightning output for model run initialized with 500 CCN/cm^3. Contours are electric field. The positive direction of the electric field is up, and the direction of the electric field is the direction which a positive test charge would move while under the influence of the field. Pink $*$'s indicate the top of intracloud lightning channels, yellow dots are initiation points of intracloud lightning channels, and green x's are the bottom of intracloud lightning channels. White $*$'s, red dots and black x's are the same, but for +CG's.

The model was rerun using this modified sounding, again varying CCN concentrations between 500 and 15000 CCN/cm^3. The effect of CCN on flashrate, +CG%, and total number of CG's is presented in figure 3.7. Again, it is clear that CCN concentration does not affect any of these in a straightforward manner. However, it is interesting to note that the +CG% is significantly lower than with the unmodified sounding. The mean +CG% for the unmodified sounding was 78% with a standard deviation of 39% compared to a mean

of 60% with a standard deviation of 31% for the more humid sounding.

In order to help explain the lower +CG%, let us again look at the electric field profile and resultant lightning from one of these model runs. Figure 3.5 shows the results for a model run initialized with the modified sounding and a CCN concentration of 500/cm^3. Comparing this to the model run with the unmodified sounding, it is obviously much more difficult to pick out the main charge regions. This storm was much more vigorous because of the added moisture. Charge production was significantly increased due to the greater abundance of ice particles and increased updrafts, leading to enhanced lightning. The copious amounts of lightning served to redisribute charge throughout and below the cloud, creating a rather ugly charge distribution.

This fractionation of the charge centers made it impossible to produce the coherent lower positive region we saw in less humid case. Intracloud lightning initiated almost concurrently from both positive and negative electric field maxima, driving opposite charges around the cloud. As a result, the charge regions were quickly eroded and moved elsewhere in the cloud. This model run did produce some +CG's from about 1900 s to 2300 s after model initiation. Large precipitation which had taken on a positive charge from earlier intracloud lightning was close to the ground. This positive charge above the ground was not strong enough to initiate lightning, but when a lightning channel pushed its way to ground from above this region, the small positive charge center was able to push down a bit of positive charge. However, since the positive charge center was not being adequately replenished, it quickly died out and and the storm began producing -CG's exclusively.

Table 3.1: Comparison of charge lowered to ground averaged over all model runs for the modified (increased relative humidity) and unmodified soundings. All entries are in Coulombs.

	-CG			+CG		
	Mean	Median	Standard Deviation	Mean	Median	Standard Deviation
Unmodified Sounding	-3.75	-3.79	2.06	6.85	5.91	5.64
Modified Sounding	-4.96	-2.86	4.84	4.28	4.26	2.50

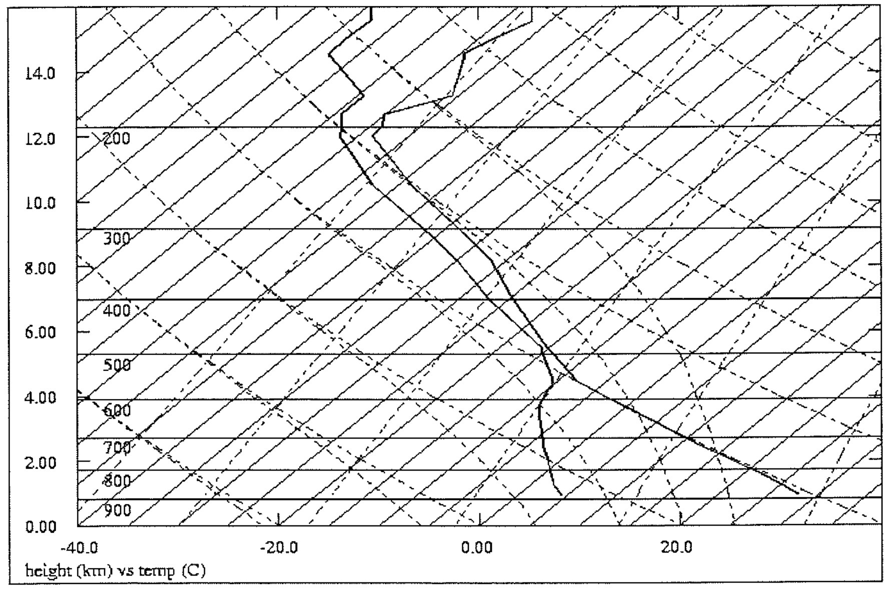


Figure 3.6: May 15, 1998 0Z Amarillo, TX sounding with relative humidity increased by 5%. Curve on the right is temperature and curve on the left is dewpoint; both are in °C

In chapter 2 we found that, in addition to the anomaly in +CG% in May 1998, there were also anomalies in mean peak currents. +CG peak currents were much stronger and -CG peak currents much weaker than average. While, in our modeling study, we did not find charge to ground to change significantly with variations in CCN, they did change modestly with the relative humidity change, albeit with considerable scatter. Table 3.1 shows the results of this analysis. Changing from a drier environment to a more humid one, mean -CG charge to ground became more negative (although the median changed in the opposite direction), while both mean and median +CG charge to ground decreased.

As we saw in these two cases, lightning did not initiate from a strong lower positive charge center in the moister case as it did in the dry case. In the drier case, lightning went straight from a strong positive charge center to ground, which may explain the increased charge to ground from the +CG's in the drier storms. There were too few -CG's in the dry model runs to be able to draw any firm conclusions on the effect that moisture had on their charge to ground, besides the obvious effect of almost eliminating them entirely.

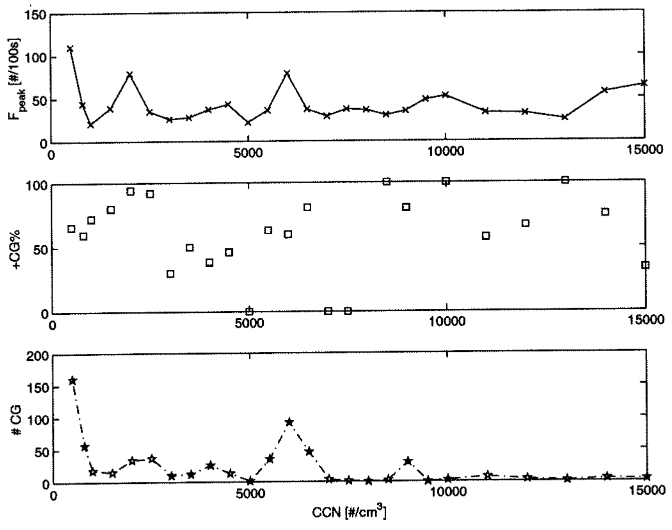


Figure 3.7: Same as figure 3.4, but for the modified sounding.

The thunderstorm model used in this study does not include a parameterization of CG multiplicity, making multiplicity comparisons between the dry and humid cases impossible.

3.5 Chemistry effects

Although still poorly understood, there is evidence to suggest that collisional charging of a polluted storm may be significantly altered. The study of *Jayaratne et al.* [1983] discussed earlier describes the anomalous charging which can take place in the presence of pollutants. The magnitude and sign of the charge transferred to the graupel particle during a collision with an ice crystal is usually determined by three algorithms based on *Saunders et al.* [1991]: size dependence, velocity dependence, and environmental dependence (temperature and liquid water content). In order to approximate the anomalous charging discussed in *Jayaratne et al.* [1983], the environmental dependence was replaced by a constant, q_{cpc},

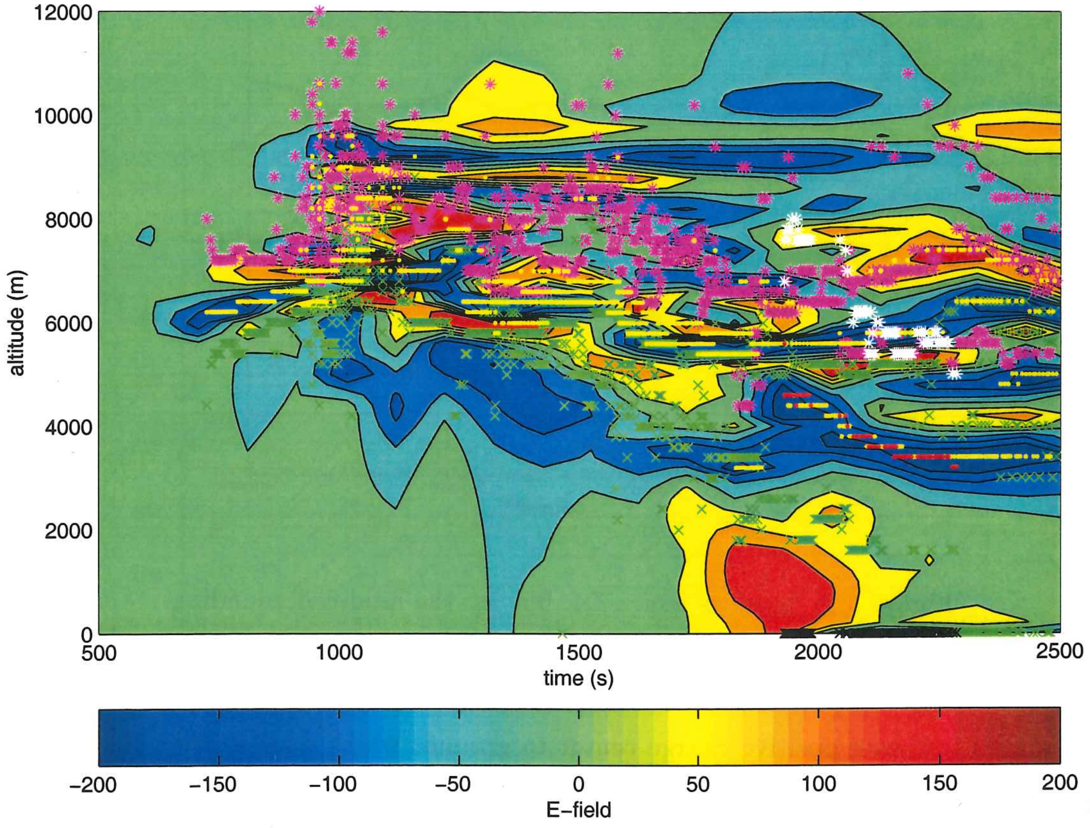


Figure 3.8: Same as figure 3.5, but for the modified sounding. Additionally, this model run had -CG's which are displayed the same as intracloud flashes, except the lower extent of the lightning channel reaches ground.

while the size and velocity dependence were untouched. The model was run with four different values of q_{cpc}: 2 fC and 5 fC per collision (to simulate charging in a cloud with traces of$(NH_4)_2SO_4$) and -2 fC and -5 fC per collision (to simulate charging in a cloud with traces of NaCl). For each value of q_{cpc}, the model was initialized once with 500 CCN/cm^3 and once with 12,000 CCN/cm^3.

Figure 3.9 shows the results of several of these model runs, initialized with 500 CCN/cm^3. The model run with q_{cpc}=-5 looks very similar to the unmodified run, except that the charge centers never grew strong enough to produce any CG's. q_{cpc} in the unmodified case varied between -35 and 15 fC, significantly larger than the q_{cpc} produced by any of the polluted

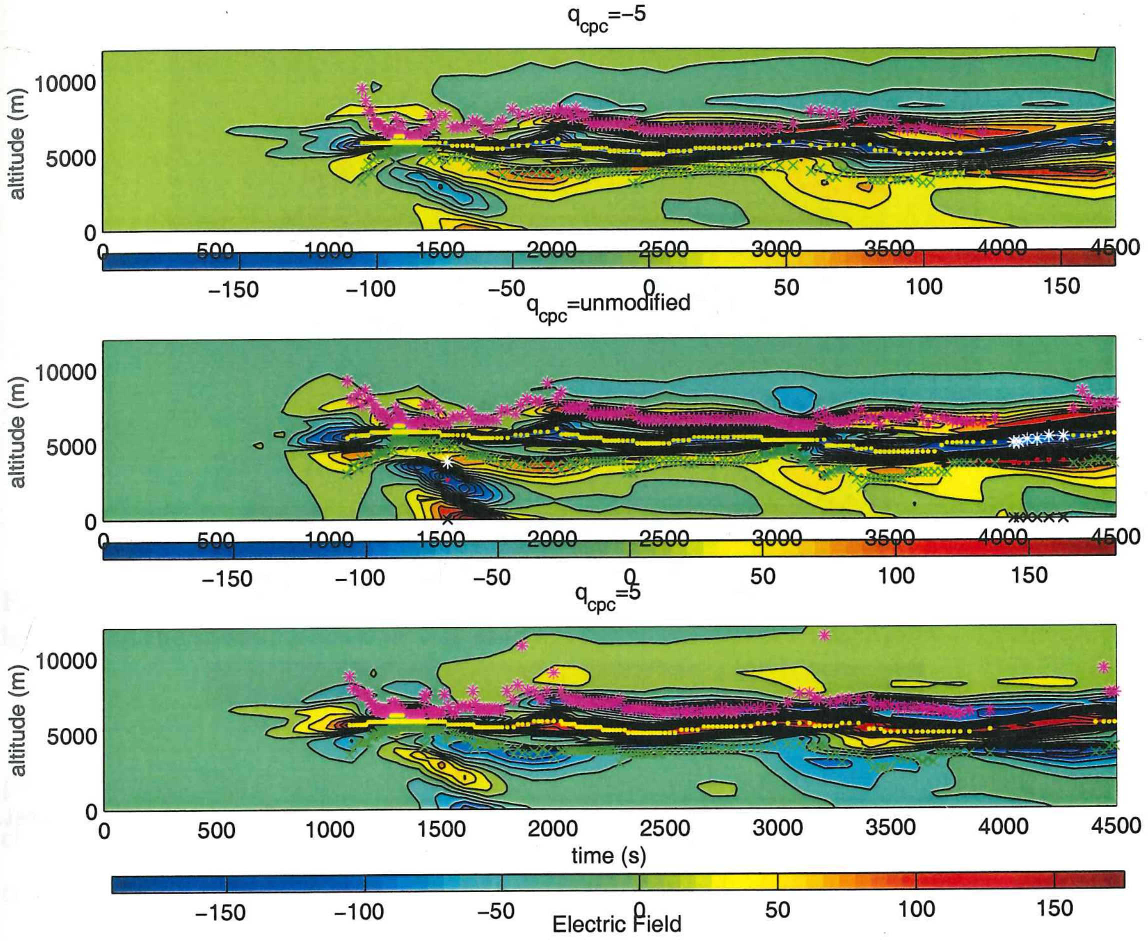


Figure 3.9: Comparison of model runs altered to take into account the effect of pollutants in the charging zone. (top) q_{cpc}=-5 fC to simulate charging in a cloud with traces of $(NH_4)_2SO_4$ (middle) Unaltered charging (bottom) q_{cpc}=5 fC to simulate charging in a cloud with traces of NaCl. All three were initialized with 500 CCN/cm^3. The notation in the figures is akin to 3.5.

samples in *Jayaratne et al.* [1983]. When q_{cpc} was set to 5 fC, the cloud again failed to produce CG's. It did, however, produce an interesting, but not unexpected, negative, positive, negative charge structure. This charge structure would be extremely unlikely to produce +CG's due to the strong negative electric field close to the ground. The model runs initialized with 12,000 CCN/cm^3 were very similar to these ones. The model runs with q_{cpc}=±2 fC had even weaker charge centers and did not produce CG's.

3.6 *Modeled thunderstorm day: August 2000*

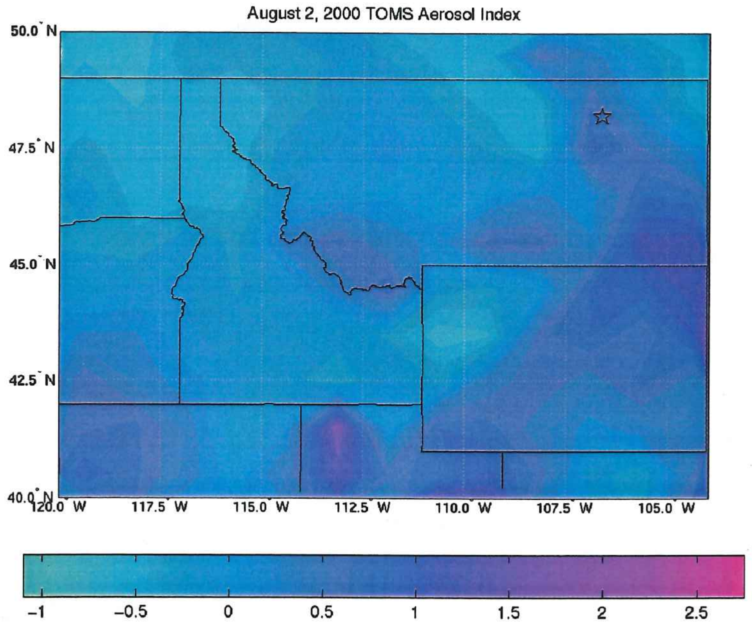


Figure 3.10: TOMS Aerosol Index for August 2, 2000 near the forest fires in the Northwest. The star indicates the location of the sounding used in this study.

We also performed a simulation of a storm in Montana during the August 2000 fires. Figure 3.10 shows the location of the smoke as detected by the TOMS on August 2, 2000 as well as the location of the sounding used to initialize the model. The lightning distribution for this day is presented in figure 3.11. There was a small amount of CG lightning observed near the location of the sounding. The storms in this area produced low +CG% (<10%). The model was initialized with the sounding seen in figure 3.12. This sounding was modified by increasing the stability above 200 mbar very slightly to prevent the thunderstorm from escaping the upper bounds of the model, but the effect on the storm should be minimal. We made numerous model runs, changing CCN concentrations from 500 to 15,000 CCN/cm^3. Peak flashrates, +CG%, and total CG lightning for each model run are displayed in figure 3.13. There was little lightning overall and no +CG's in any of the runs (there were only four -CG's). Again, there seems to be no correlation between CCN concentrations and +CG% or peak flashrate. The storms produced a classic dipole with positive charge overlying negative charge. They did not create a substantial lower positive charge center, due to minimal intra-cloud lightning moving charge within the storm. The lack of a lower positive charge center explains the dearth of +CG's. The CG's which did occur in these model runs initiated from the peak of the main negative electric field.

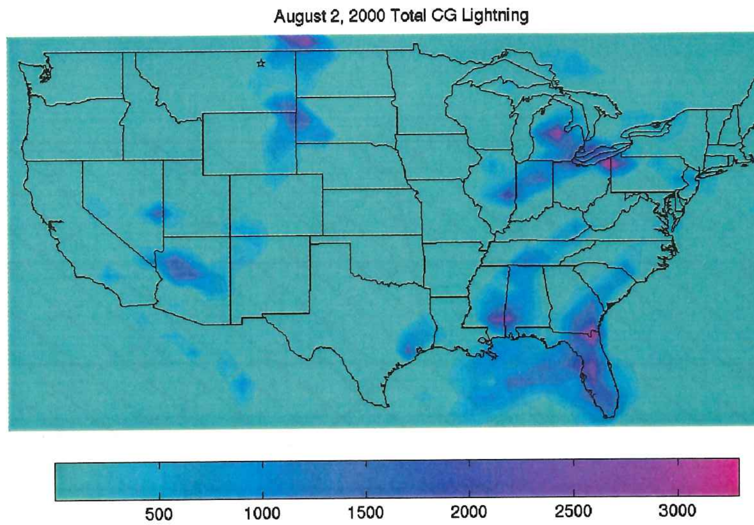


Figure 3.11: Total CG lightning per grid cell for August 2, 2000. The star indicates the location of the sounding used in this study.

3.7 *Discussion*

Our model was unable to reproduce the anomalies of May 1998 by simply adding CCN to the cloud: CG flashrates, strength of CG flashes, and +CG% were not affected by CCN in a coherent fashion. However, when the sounding was made slightly more humid, mean +CG% dropped and flashrates increased. It is, at the very least, intriguing to think that the anomalies observed in May 1998 may have been caused by the exceptionally dry conditions alone.

When the model was modified to take into account the effect of pollutants in the charging zone, the results were somewhat inconclusive. The charging was too weak to produce any

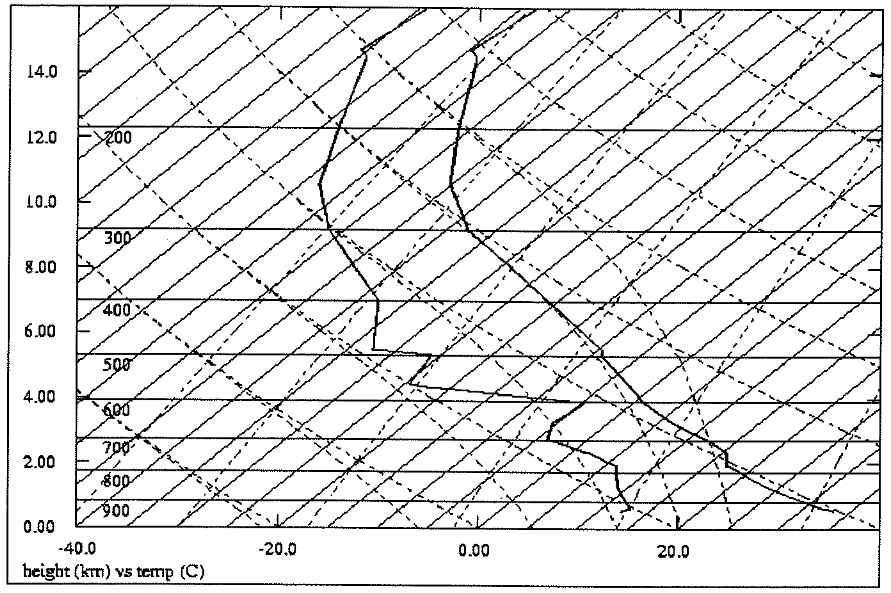


Figure 3.12: 0Z Sounding for August 2, 2000 in Glasgow, MT. The curve on the right is temperature and the curve on the left is dewpoint, both in °C. From *http://weather.uwyo.edu/upperair/sounding.html* [2001].

CG's in our model. With graupel fixed to charge negatively, the charge structure of the storm looked correct to produce +CG's, but it also looked very similar to the unmodified case.

When the model was applied to a thunderstorm in Montana in August 2000, a region frequently covered with smoke, but lacking in anomalous lightning, increasing CCN concentrations once again did not increase +CG%. Although it should be noted that the models produced very low quantities of CG lightning, making the statistics somewhat uncertain.

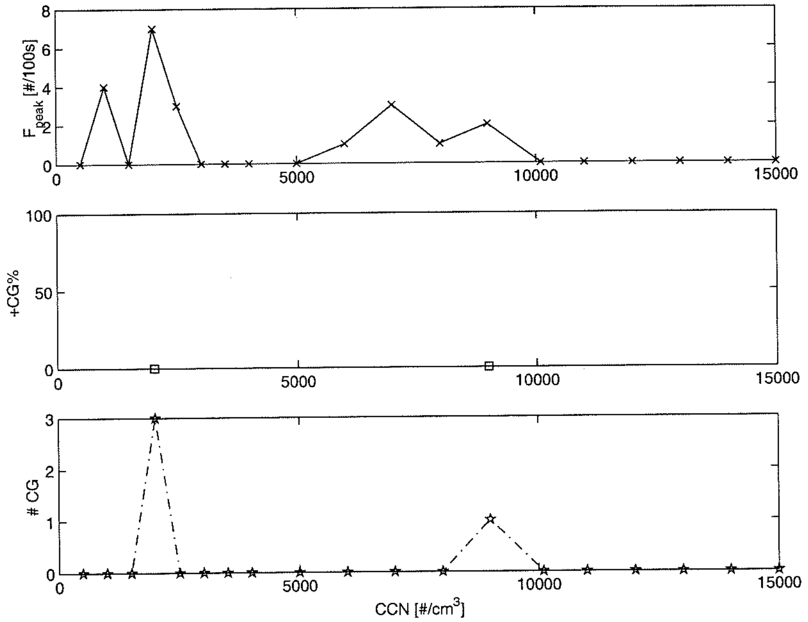


Figure 3.13: Same as figure 3.4, but for August 2, 2000 0Z sounding in Glasgow, MT.

Chapter 4

SUMMARY AND CONCLUSION

The Central Plains region of the United States saw exceptionally anomalous lightning in May 1998 coincident, spatially and temporally, with a large pall of smoke from fires in Mexico and Central America. Total CG flashes were reduced along with the mean peak current and multiplicity of -CG's. +CG% markedly increased along with +CG mean peak current.

The year 2000 was one of the worst fire seasons ever recorded in the United States, with wildfires burning more than double the average number of acres. In August 2000, the TOMS instrument detected a significant smoke anomaly across the Northern U.S. and south into the Midwest, where it was also detected by radar at about 3.5-4 km altitude. Despite the smoke, the lightning anomalies seen in May 1998 were not present in August 2000, even though the total number of CG's were roughly commensurate.

Our modeling studies of May 15, 1998 - a day with a large smoke plume and significant lightning activity over the Central Plains - revealed no correlation between +CG% and CCN concentration. While the 1.5 dimensional model is incapable of reproducing the dynamics of a true thunderstorm, both *Lyons et al.* [1998] and *Murray et al.* [2000] hypothesized the +CG% anomaly was caused by variations in the microphysics of the storms, making our model a useful test.

The Central Plains were in the midst of a drought in May 1998 and, in order to see what effect this might have on lightning, we increased the relative humidity of the sounding by 5%. We found flashrates to increase, +CG% decreased, and, less conclusively due to large amounts of scatter, +CG's lowered less charge to ground. We found that the storms with increased humidity were significantly stronger in terms of flash rate, updraft, and mixing ratio of particles. Thus, the charging mechanism was much stronger and the storm developed a strong lower negative charge center.

Additionally, we tried to add the effects of pollution from the smoke plume, using a charging scheme based upon *Jayaratne et al.* [1983]. However, the charging was too weak to produce any +CG's.

While the modeling results are certainly not definitive, they are suggestive that some of the anomalies in May 1998 may have been caused by the exceptionally dry weather. Interestingly, the anomalies in both temperature and precipitation were not as large in the areas affected by smoke in August 2000, when the lightning anomalies were not observed.

4.1 Recommendations for Future Work

This study has quite possibly provided more questions than answers. The interactions between forest fires and clouds are exceedingly complex and require much more study. My first suggestion would be to look at some of the possible fire effects fires that were not a part of this study. The advection of charge from a fire, over a timescale of several days, should be researched in more detail and this charge should be included in numerical thunderstorm models.

Jayaratne et al. [1983] provide valuable insight into how the ice-ice collisional charging mechanism can be altered significantly with the presence of pollutants. However, their experiments involved only two pollutants. It would, of course, be quite interesting to see what effect, if any, pollution from biomass burning causes on the charging mechanism.

In our simulations of thunderstorms using the sounding of May 15, 1998, we found nearly 100% of CG strokes lowered positive charge to ground. This was dependent upon intracloud lightning depositing positive charge at the bottom of the cloud. While it is known that intracloud flashes usually precede CG flashes by about 5-15 minutes [*MacGorman and Rust*, 1998], a useful study would be to see if storms producing predominately +CG's have a significantly longer lag between initial intracloud lightning onset and the first CG than the lag in storms producing -CG's. This was impossible for our study because only CG lightning data were available, but would be possible with lightning mappers which detect both intracloud and CG lightning.

Finally, it is possible that the smoke from the fires actually inhibited rainfall sufficiently in May 1998 to produce the drought conditions as the work of *Rosenfeld and Lensky* [1998] and *Rosenfeld* [1999] might suggest, perhaps creating a secondary effect of smoke on lightning. Recent satellite advances may make this a feasible research topic.

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