JP2.12 CLOUD-TO-GROUND LIGHTNING AND SURFACE RAINFALL DURING THE GREAT FLOOD OF 1993[≠]

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ABSTRACT

Relationships between cloud-to-ground (CG) lightning, as reported by the U. S. National Lightning Detection Network™ (NLDN), and surface rainfall, as reported by NWS Cooperative Observers, have been examined during the Great Flood of 1993. The daily precipitation volume per reported CG flash (CGF) over the Greater Upper Mississippi River Basin (GUMRB) ranged from 4.0 x 10^4 to 4.3 x 10^6 m^3/CGF with a mean and median of 4.6 x 10^5 and 1.9 x 10^5 m^3/CGF, respectively, during June, July, and August, 1993. The monthly rain volume per reported CG flash ranged from 6.3 x 10^4 to 2.1 x 10^5 m^3/CGF with an overall mean of 1.8 x 10^5 m^3/CGF. Similar ratios were found for the Upper Mississippi River Basin (UMRB) that is imbedded within the GUMRB. For the entire summer season, there were about 6.5 x 10^{11} cubic meters of rainfall over the GUMRB and there were 3.6 x 10^6 CGF reported by the NLDN, which gives an overall seasonal mean of 1.8 x 10^5 m^3/CGF. If we correct the lightning counts for an imperfect NLDN detection efficiency, we estimate that there were actually about 5.4 x 10^6 CG flashes over the GUMRB, and therefore, the actual seasonal mean rain volume was about 1.3 x 10^5 m^3 per CGF. The above values are remarkably similar to the summer mean of 1.1 x 10^5 m^3/CGF obtained by Petersen and Rutledge (1998) over the mid-continental U.S. and are consistent with other studies on daily and storm scales. The above ratios are larger than, but still consistent with, an estimate of the excess stream volume per excess (reported) CG flash from the UMRB, 6.8 x 10^4 m^3/CGF, based on streamflow measurements at Keokuk, IA.

1. INTRODUCTION

The Great Flood of 1993 was "one of the worst natural disasters in recent history" (Kunkel et al., 1995); it affected 30% of the Mississippi River Basin, killed 52 people, and caused over $18 billion in property damage. Numerous levees failed, 14 rivers had record water levels and overflowed their banks, and 536 counties were declared federal disaster areas (Williams, 1994; Kunkel et al., 1995; Changnon, 1996).

During the Fall of 1992, almost continuous rainfall produced extremely high values of soil moisture over

[≠] This paper has been submitted to Monthly Weather Review.
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the central U.S., and this was followed by additional moisture from winter rain and snow. In March 1993, just prior to the Great Flood, the soil moisture over most of the Midwest and Central Plains was at maximum capacity (Rodenhuis, 1996). Although there was above average rainfall that spring, the primary cause of the heavy precipitation and flooding during the summer of 1993 was a strongly arched, midlatitude jet that persisted over the central U.S. for several months. This feature was associated with an unusually strong and persistent anticyclone over the southeastern U.S. that impeded zonal flow and drew warm, moist air from the Gulf of Mexico (northwestward) into the Greater Upper Mississippi River Basin (GUMRB). Large mesoscale convective complexes (MCCs) and mesoscale convective systems (MCS), that are typically associated with very heavy and persistent rainfall as well as intense lightning (Maddox et al., 1986), developed along the anticyclonic side of the midlatitude jet and produced torrential rainfall over the already saturated soil (Brackenridge, 1994; Anderson et al., 1998; NWS, 1994). On 17 June 1993 (UTC), for example, a plume of water vapor was drawn up from the Gulf of Mexico, interacted with a jet streak near the northern U.S. border, and produced a MCS over Minnesota. This system merged with other convective storms and eventually became a back-building MCS that produced heavy rainfall and flash floods, and the outflow triggered new storms and almost continuous rainfall over the entire region. The results were 5-7 inches of rain over southern Minnesota (Scofield and Achutuni, 1994), and more than 100,000 cloud-to-ground (CG) lightning flashes in the region (see Figure 1). The path of the MCS over southern Minnesota and Wisconsin, and the other storms over the GUMRB, is clearly evident in the pattern of the lightning data that are shown in Figure 1.

Because of the magnitude of the Great Flood disaster, a wealth of information has been collected on the synoptic patterns and dynamics of the flood-producing storms and the climatology of the region, as well as other hydrological and agricultural data (e.g. Brackenridge et al., 1994; Changnon, 1996; Walker et al., 1994; Guttman et al., 1994; Williams, 1994; Kunkel, 1995; NWS, 1994). However, to the best of our knowledge, until now no one has analyzed the cloud-to-ground (CG) lightning that occurred during the Great Flood or examined the relationships between that lightning and the associated rain volume and streamflow.

Tables 1a and 1b summarize several studies that have compared lightning and rainfall on various scales of space and time in a variety of geographical locations. Note that there have been both rain gauge (Table 1a) and radar (Table 1b) measurements of precipitation and that the scales have ranged from isolated cells, to large

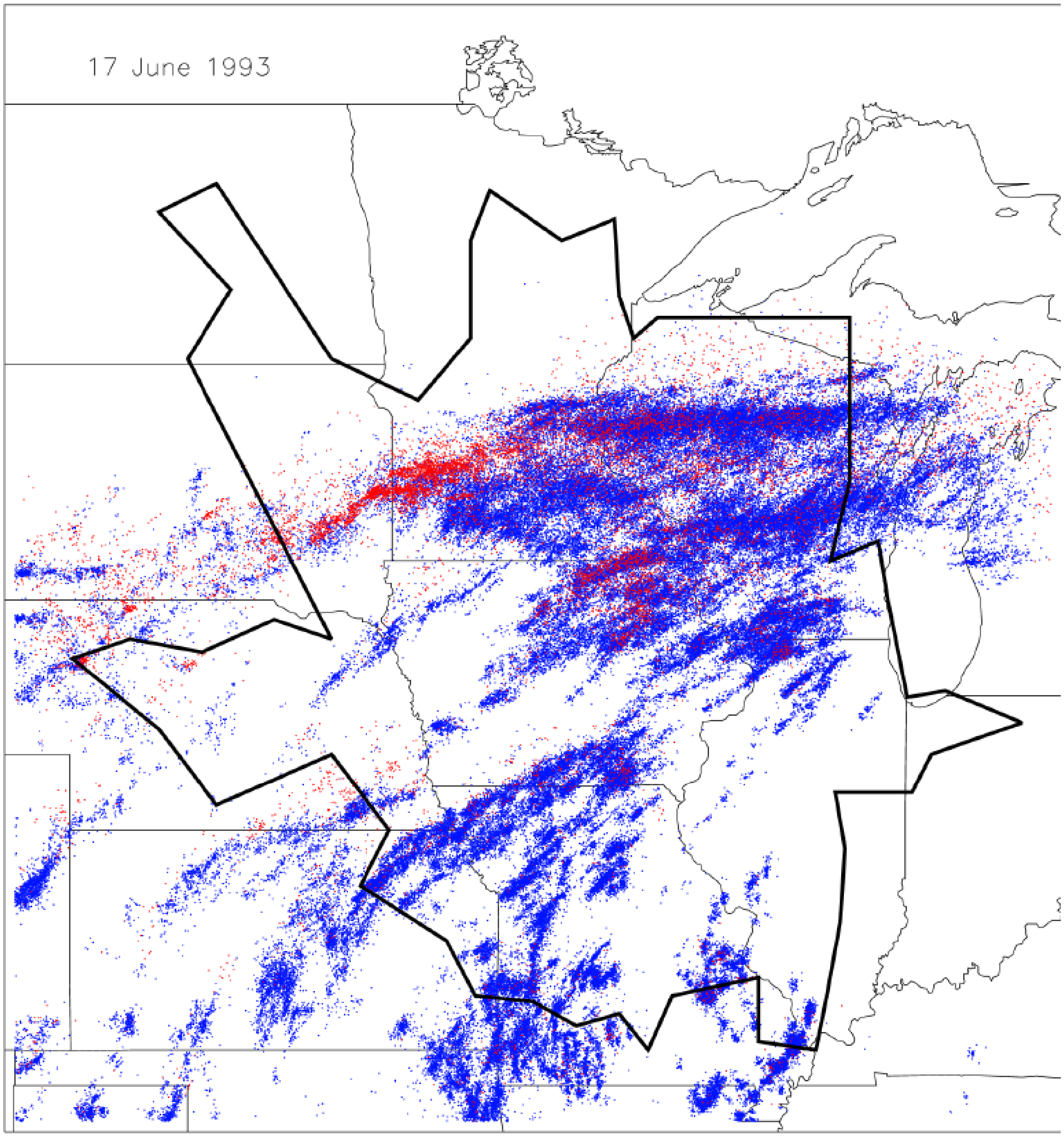

Fig. 1. Positive (red) and Negative (blue) CG Flashes that the NLDN reported on 17 June 1993 (UTC). The total number of flashes in this plot is 156,188, and the number over the GUMRB is 118,475.

Table 1a. Studies based on rain gage measurements of precipitation.

Study using Rain Gages	Location	Precipitation volume per CG flash (m^3/CGF)	Comments
Isolated Thunderstorms			
Battan [1965]	Arizona	3.0×10^4	Summer season
Piepgrass et al. [1982]	Florida	2.0×10^4	2 isolated storms
Gungle & Krider [2000]	Florida	3.0×10^4	9 isolated storms
MCSs and Large Storm Systems			
Holle et al. [1994]	Central U.S.	2.9×10^5	MCS
Peterson & Rutledge [1998]	Central U.S.	1.1×10^5	Summer season
Soriano et al. [2001]	Iberian Peninsula	1.2×10^5 2.1×10^5	Semiarid (summer) Humid (summer)
Present	GUMRB	4.6×10^5 (3.2×10^5)*	Daily mean
Present	GUMRB	1.8×10^5 (1.3×10^5)*	Seasonal mean

*Values in parentheses have been corrected for NLDN flash detection efficiency

Table 1b. Studies based on radar measurements of precipitation.

Study using Radar	Location	Precipitation volume per CG flash (m^3/CGF)	Comments
Isolated Thunderstorms			
Buechler et al. [1990]	Southeastern U.S.	3.8×10^4	21 isolated storms
Tapia et al. [1998]	Florida	4.3×10^4	22 isolated storms
Soula et al. [1998]	Spain	3.1×10^4	1 storm causing a flash flood
Soula & Chauzy [2001]	France	7.2×10^4	4 isolated storms
Seity et al. [2001]	France	6.8×10^4	21 isolated storms over land and ocean
MCSs and Large Storm Systems			
Williams et al. [1992]	Darwin, Australia	5.0×10^5 5.0×10^6	Continental regime Monsoon regime
Holle et al. [1994]	Central U.S.	7.7×10^5	MCS

MCCs, to daily and seasonal averages. Given the high degree of uncertainty in radar estimates of precipitation (Woodley et al., 1975; Zawadzki, 1975; Wilson and Brandes, 1979; Austin, 1987; Joss and Waldvogel, 1990; Anagnostou et al., 1999), the rain gauge and radar studies are listed in separate tables. Although some studies (Petersen et al., 1999; Lang et al., 2000) have found anomalously low CG flash rates associated with intense rainfall, and as a result, a large rain volume per CG flash (CGF), the values of rain volume per CGF in Table 1 range from 2.0 x 10^4 to 5.0 x 10^6 m^3/CGF, and values over the central U. S. are of the order of 10^5 m^3/CGF. Tables 1a and 1b have also been subdivided by storm type; isolated storms appear to have rain volumes of the order of a few times 10^4 m^3/CGF, and larger systems are typically an order of magnitude larger. At this point, we should note that the lightning counts used for many of the studies in Tables 1a and 1b were not corrected for the imperfect detection efficiency (DE) of the lightning detection systems. This point will be considered further below, but to facilitate comparisons with the prior literature, in the following we will give both the reported flash counts and an estimate of the true counts based on a study of the NLDN DE in 1993.

2. DATA

The Greater Upper Mississippi River Basin (GUMRB), as defined by Kunkel et al. (1994), is outlined in Figure 2 and includes the Illinois River Basin and part of the Missouri River Basin. The Upper Mississippi River Basin (UMRB) covers an area upstream of Keokuk, Iowa, and is entirely enclosed within the GUMRB. The total area of the GUMRB is 1.3 x 10^{12} m^2, and the area of the UMRB is 5.3 x 10^{11} m^2.

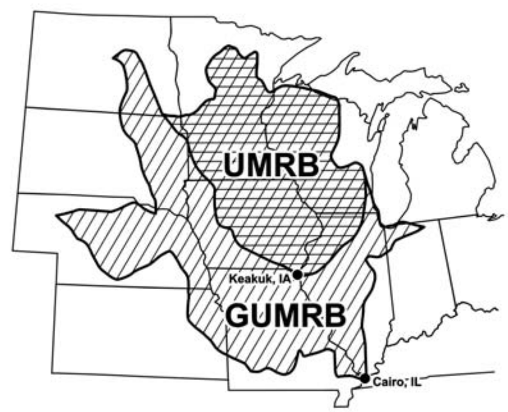

Figure 2. Outline of the Greater Upper Mississippi River Basin (GUMRB) (outer boundary) and the Upper Mississippi River Basin (UMRB) (inner boundary) [adapted from Kunkel et al., 1994].

a. Cloud-to-Ground Lightning

Data reported by the U.S. National Lightning Detection Network™ (NLDN) (Cummins et al., 1998a,b) have been used to quantify how much cloud-to-ground lightning occurred over the GUMRB during the summers of 1992, 1993, and 1994. Figure 3 shows the daily counts of positive

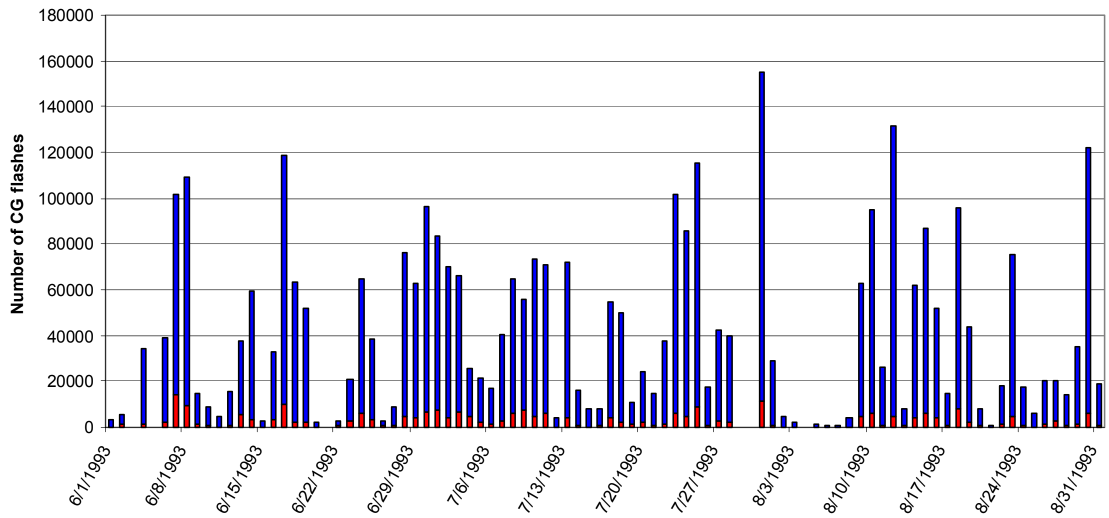

Figure 3. Daily counts of positive (red) and negative (blue) cloud-to-ground lightning over the GUMRB in 1993.

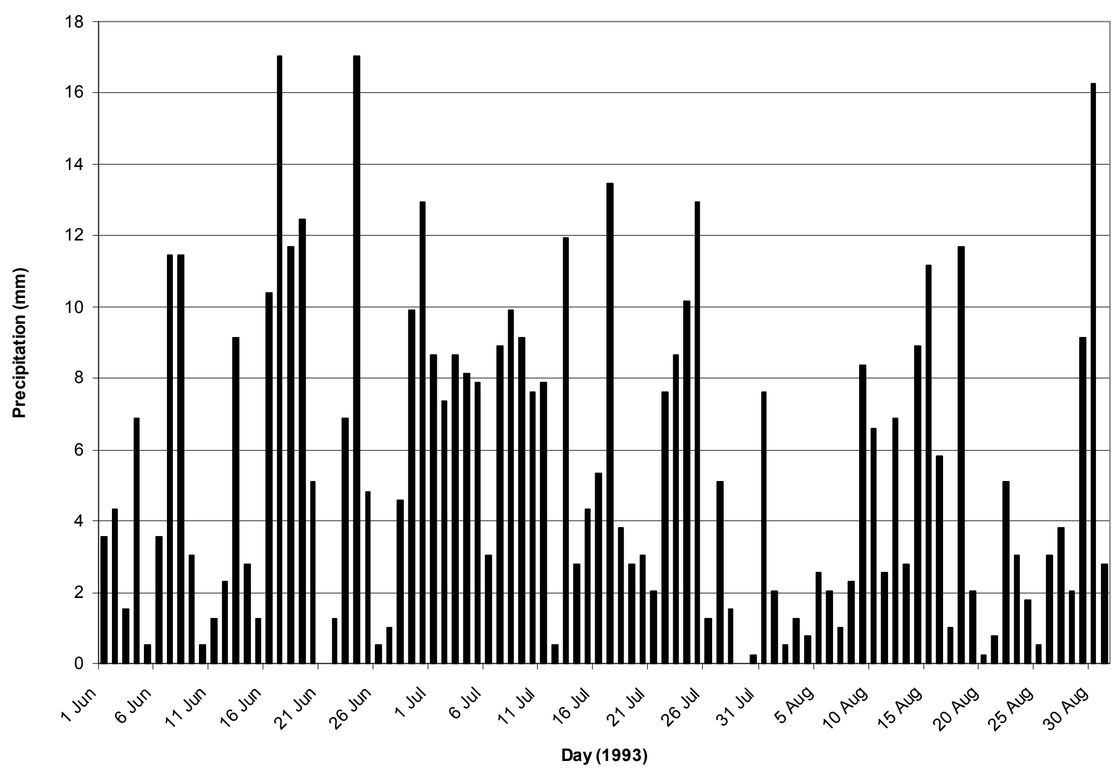

Figure 4. Area-average, daily precipitation depth over the GUMRB (courtesy of K. E. Kunkel 2001, personal communication).

and negative CG flashes that the NLDN reported over the GUMRB during the summer of 1993. Positive flashes transfer positive charge to ground and negative flashes transfer negative charge to ground. We have restricted the positive counts to only those flashes that have an estimated peak current greater than or equal to 15 kA in order to eliminate a small percentage of cloud discharges (Cummins et al., 1998b; Idone et al., 1998a). The overall ratio of positive to negative flashes over the GUMRB is 7.7% and is similar to the lightning climatologies that have been discussed previously by Orville and Silver (1997), Zajac and Rutledge (2001) and Orville and Huffines (2001).

The monthly counts of CG flashes that the NLDN reported over the GUMRB are given in Table 2a, and those over the UMRB are given in Table 2b. We have estimated the excess lightning counts that occurred during the Great Flood by subtracting the average of the monthly counts in 1992 and 1994 from the corresponding count in 1993. We are only using two years to estimate the average in 1993 because the NLDN configuration and performance were improved in 1995 (Cummins et al., 1998b). Note that the NLDN reported a total of 3.6×10^6 CG flashes over the GUMRB in June, July, and August, and that 2.1×10^6 of these reports were above the seasonal average.

The lightning counts given in the upper portions of Tables 2a and 2b have been taken from an NLDN database that is maintained by Vaisala-GAI Inc. (formerly Global Atmospherics Inc.) in Tucson, AZ, and no corrections have been made for the imperfect flash detection efficiency (DE) of the NLDN. Cummins et al. (1998b) have estimated that in 1993 the flash DE of the NLDN was 65-80%. Idone et al. (1998a,b) measured the flash DE of the NLDN near Albany, NY in 1993, using a network of digital video cameras, and they obtained a value of 67%. If we assume that the NLDN flash DE over the GUMRB was also about 67% as a worst case, then we can multiply the raw NLDN flash counts by a factor of 1.5 to estimate the true number of CGFs that actually occurred. The corrected counts are given in the lower portions of Tables 2a and 2b. Note that after this correction there were actually about 5.4×10^6 CG flashes over the GUMRB during the summer of 1993, which was about 3.1×10^6 CG flashes above the seasonal average. For the UMRB sub-basin, the counts of reported (actual) CG flashes were 1.4×10^6 (2.1×10^6) and the excess counts were 7.9×10^5 (1.2×10^6).

Table 2a.

Counts of Cloud-to-Ground (CG) Lightning Flashes in the Greater Upper Mississippi River Basin (GUMRB).

Monthly Counts of CG flashes	1992 x 10^5	1993 x 10^5	1994 x 10^5	Excess Counts in 1993 x 10^5
June	1.7	10.8	7.7	6.1
July	6.7	14.5	7.7	7.2
August	1.5	10.8	5.5	7.3
Total	9.9	36.1	20.9	20.6
Corrected Counts	x 10^5	x 10^5	x 10^5	x 10^5
June	2.5	16.1	11.5	9.1
July	10.0	21.6	11.5	10.7
August	2.2	16.1	8.2	10.9
Total	14.2	53.8	31.1	30.7

Table 2b.

Counts of Cloud-to-Ground Lightning Flashes in the Upper Mississippi River Basin (UMRB).

Monthly Counts of CG Flashes	1992 x 10^5	1993 x 10^5	1994 x 10^5	Excess Counts in 1993 x 10^5
June	0.81	4.7	3.0	2.8
July	1.9	4.6	3.7	1.8
August	0.40	4.6	2.1	3.3
Total	3.1	13.9	8.8	7.9
Corrected Counts	x 10^5	x 10^5	x 10^5	x 10^5
June	1.2	7.0	4.5	4.2
July	2.8	6.8	5.5	2.7
August	0.60	6.8	3.1	4.9
Total	4.6	20.7	13.1	11.8

b. Precipitation

Two datasets have been used to estimate the daily and monthly rain volumes that fell over the GUMRB: (1) the daily, basin average rain depths provided by Kunkel et al. (1994) and Kunkel (2001, personal communication). These depths are based on summary-of-the-day rain gauge readings reported by National Weather Service (NWS) Cooperative Observers around 5 pm LST. The observer network has an overall spatial resolution of approximately one gauge per 1000 km^2. (2) Kunkel et al. (1994) have published monthly precipitation amounts over the UMRB and GUMRB from July 1992 through October 1993 together with climatological averages based on area-weighted, gauge measurements in each climate division. The climatological data that are archived at the National Climatic Data Center (NCDC) are based on approximately 10 to 20 standard rain gauges within each climate division, an area of roughly 20,000 km^2 (Redmond 2001, personal communication; Changnon, 1996). These two datasets, although different, give similar values during the summer of 1993. Although we have not undertaken a detailed statistical analysis (Bras and Rodriguez-Iturbe, 1993), the large spatial scales of both the storms and the basins suggest that the errors in these measurements are minimal (Huff and Shipp, 1969; Zawadzki, 1973; Drufuca and Zawadzki, 1975; Seed and Austin, 1990; Ungersbock et al., 2001).

Figure 4 shows the daily average rain depth over the GUMRB from June 1 to August 31, 1993, based on the NWS Cooperative Observer reports (Kunkel 2001, personal communication). Note that there were several periodic episodes of intense rainfall and that the intervals between them were not long enough to reduce the soil moisture significantly (Kunkel, 1996).

Table 3 gives the climatological average precipitation depth and the associated rain volume, together with the excess rainfall that occurred over the GUMRB and the UMRB during the months of June, July, and August of 1993. Note that the total volume over the GUMRB was 3.9×10^{11} m^3, and that the excess was about 2.8 $\times 10^{11}$ m^3.

c. Streamflow

Streamflows in the Mississippi River and its various tributaries are measured by the United States Geological Survey (USGS) at a number of sites along the rivers. Because the soil in the GUMRB was almost completely saturated by late spring, most of the summer rain over this area became runoff, and therefore, the integrated streamflow was a large fraction of the rain

Table 3. Climatological average (CA) and excess (E) precipitation depths and the associated rain volumes during the summer of 1993.

	GUMRB		UMRB		
1993	Precipitation Depth (mm)	Rain Volume (m^3)	Precipitation Depth (mm)	Rain Volume (m^3)	Streamflow Volume at Keokuk, IA (m^3)
June					
CA	103	1.2×10^{11}	103	5.5×10^{10}	6.9×10^{9}
E	70	9.2×10^{10}	85	4.5×10^{10}	8.8×10^{9}
July					
CA	96	1.3×10^{11}	99	5.3×10^{10}	5.5×10^{9}
E	107	1.4×10^{11}	107	5.7×10^{10}	2.4×10^{10}
August					
CA	89	1.4×10^{11}	98	5.2×10^{10}	3.7×10^{9}
E	35	4.6×10^{10}	35	2.7×10^{10}	1.3×10^{10}
Summer					
Average	288	3.9×10^{11}	300	1.6×10^{11}	1.6×10^{10}
Excess	212	2.8×10^{11}	227	1.1×10^{10}	4.6×10^{10}

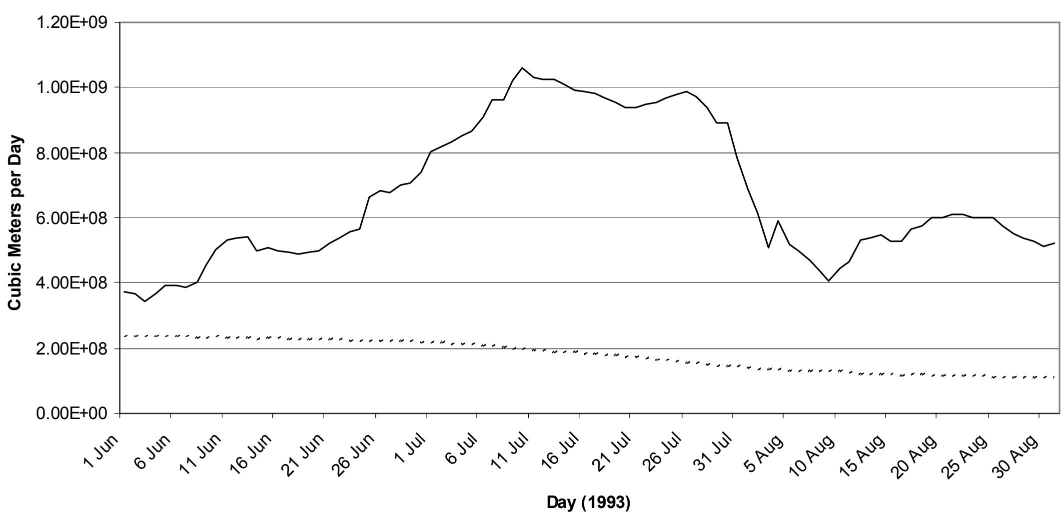

Figure 5. Mississippi stream volume per day as measured at Keokuk, IA during the summer of 1993.

The solid curve shows daily values, and the dashed curve is the climatological average.

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volume that fell over the basin. The USGS site at Keokuk, IA is located at the southern tip of the UMRB (Fig. 1). Values of the monthly stream volume at Keokuk during June, July, and August, 1993 and the climatological means (based on daily statistics from 1878 through 2000) are given in Figure 5. The right column in Table 3 shows the average and the excess stream volumes during June, July, and August, 1993. Note that the monthly stream volumes in Table 3 are about a factor of two lower than, but still consistent with, the monthly rain volumes over the UMRB. We expect lower values of streamflow because there will necessarily be some soil evaporation and absorption (Linsley et al., 1982), and also because many levees failed in the UMRB and caused stream overflows and standing water outside the riverbeds (Williams, 1994; Kunkel et al., 1995; Changnon, 1996).

3. RESULTS

a. Daily Precipitation Volume per CG Flash

Because there was little rain or lightning on June 5, June 6, June 21, and July 29, these days have been omitted from our dataset. Figure 6 shows the remaining daily precipitation volumes plotted as a function of the daily counts of CG flashes (uncorrected); the solid line shows the best linear fit to these data (R^2=0.561), and the slope of this line corresponds to 1.1 x 10^5 m^3 of rainfall per CG flash. The daily ratios necessarily include all forms of precipitation, i.e. stratiform as well as convective rainfall, and the values range from 4.0 x 10^4 to 4.3 x 10^6 m^3/CGF, with a mean and median of 4.6 x 10^5 ± 8.3 x 10^5 m^3/CGF and 1.9 x 10^5 m^3/CGF, respectively. Figure 7 shows the daily precipitation volume per CGF on a logarithmic scale. The 36 solid dots in Figure 7 indicate the days that produced more than 40,000 CG flashes over the GUMRB, days when we expect that the production of rainfall was dominated by deep convection. Note that the values of precipitation volume per CGF on those days with the most lightning range from 5.3 x 10^4 to 3.4 x 10^5 m^3/CGF, with a mean and median of 1.6 x 10^5 ± 7.3 x 10^4 and 1.6 x 10^5 m^3/CGF, respectively.

Williams et al. (1992) have examined the daily precipitation volume and CG lightning during two wet seasons over a large region near Darwin, Australia. The average rain volume per CG flash was 5.0 x 10^5 m^3/CGF in deep continental convection and 5.0 x 10^6 m^3/CGF in the monsoon regime that contained both 'hot tower' convective precipitation and stratiform rain. They attribute this difference to the differences in convective energy, and clearly the continental convection produced more lightning per unit volume of rain. Holle et al. (1994) have also reported 2.9 x 10^5

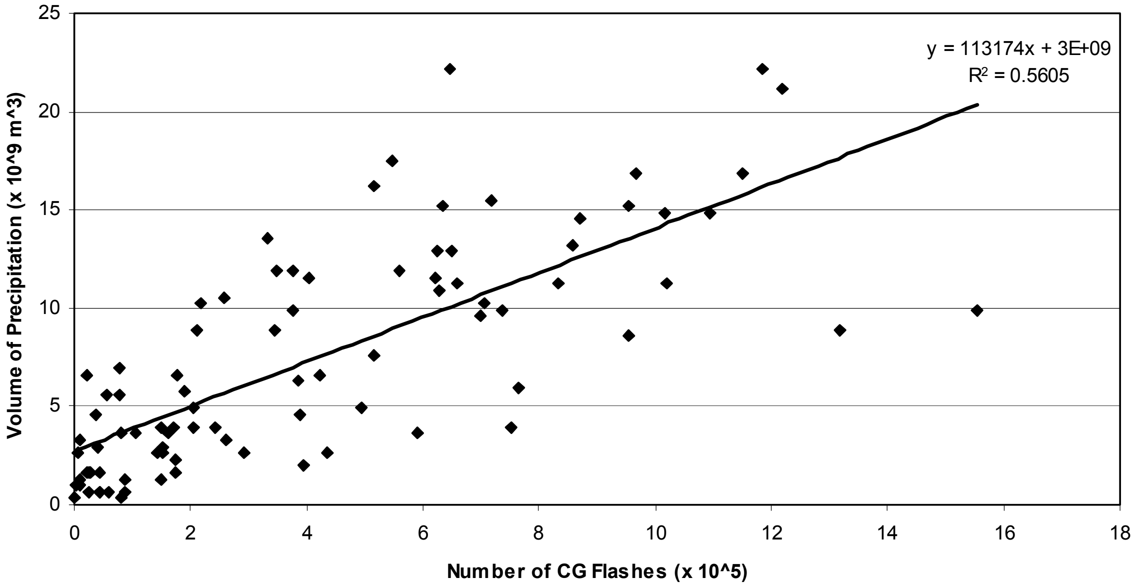

Figure 6. Daily rain volume vs. daily counts of CG flashes over the GUMRB.

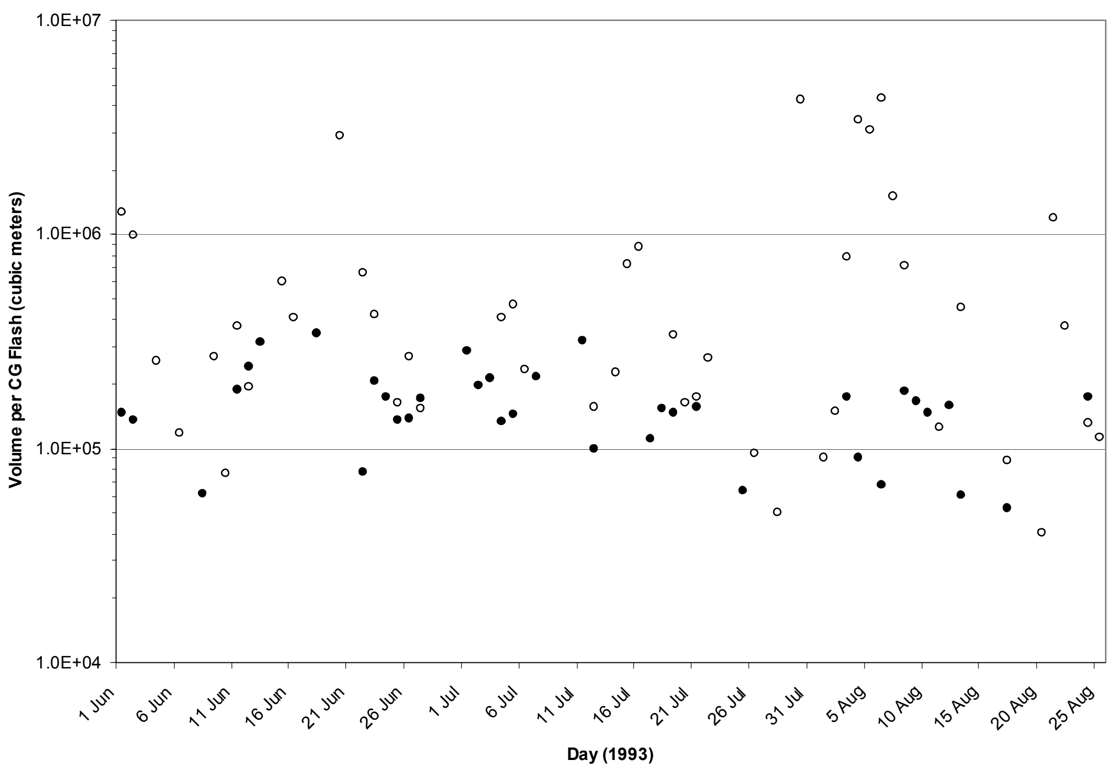

Figure 7. Daily rain volume per CG flash over the GUMRB. Days with more than 40,000 CG flashes are plotted as solid dots.

m^3/CGF for a persistent MCS that occurred over the central U.S.

After correcting for the imperfect NLDN flash detection efficiency (as discussed above), the mean and median daily precipitation volume *per actual CG flash* was $3.2 \times 10^5 \pm 5.6 \times 10^5$ m^3/CGF and 1.3×10^5 m^3/CGF, respectively, over the GUMRB. These values are also consistent with the previous measurements listed in Tables 1a and 1b.

Note in Figures 3 and 4 that there appears to be a 5-7 day periodicity in the lightning counts and rainfall, and in Figure 7 there is a similar periodicity in the rain volume to CGF ratio. This periodicity is similar to the time required for synoptic features to move across the entire Midwest, and MCCs tend to occur during these synoptic scale disturbances. During the summer of 1993, however, the presence of the persistent, blocking anticyclone may have compressed the spatial scale and caused a similar variations over the GUMRB (Maddox 2002, personal communication).

b. Flash Polarity and Multiplicity

If we restrict the daily lightning counts to just the CG flashes that transfer positive charge to ground, we obtain a precipitation volumes *per positive CG flash* (PCGF) that range from 8.8×10^5 to 6.6×10^7 m^3/PCGF with a mean of $5.7 \times 10^6 \pm 8.9 \times 10^6$ m^3/PCGF and a median of 3.0×10^6 m^3/PCGF. These ratios are about a factor of ten larger than the average precipitation volume per negative CG flash (5.2×10^5 m^3/CGF), and they are similar to the results of Soula and Chauzy (2001) who found that the precipitation volume per (negative) flash was about 1.0×10^4 m^3/CGF, i.e. when no positive flashes were present, and 4.11×10^5 m^3/CGF when over half the flashes were positive.

The precipitation volume *per (detected) return stroke* was computed by summing the NLDN multiplicity reports for all flashes and then dividing the precipitation volume by the total number of strokes. The values range from 1.1×10^4 to 2.3×10^6 m^3 per stroke, with a mean and median of $2.0 \times 10^5 \pm 4.2 \times 10^5$ m^3 per stroke and 6.4×10^4 m^3 per stroke, respectively. Assuming that the NLDN *stroke* DE was 47% (Idone et al., 1998a), the corrected mean and median values are $9.5 \times 10^4 \pm 2.0 \times 10^5$ m^3 per stroke and 3.0×10^4 m^3 per stroke, respectively. Seity et al. (2001) found a mean value of 4.2×10^4 m^3 per stroke for 21 storms in France.

c. Monthly Precipitation Volume per CG Flash

Table 4 summarizes the monthly average (and excess) rain volume per reported (and actual) CG

Table 4. Rainfall volume per CG flash over the Greater Upper Mississippi River Basin (GUMRB), 1993.

Rainfall Volume per Reported CG Flash	Average (m^3/CGF)	Excess (m^3/CGF)
June	2.5×10^5	1.5×10^5
July	1.7×10^5	1.9×10^5
August	3.9×10^5	6.3×10^4
Average	2.7×10^5	1.3×10^5
Rainfall Volume per Corrected CG Flash	Average (m^3/CGF)	Excess (m^3/CGF)
June	1.7×10^5	1.0×10^5
July	1.2×10^5	1.3×10^5
August	2.7×10^5	4.2×10^4
Average	1.7×10^5	9.1×10^4

Table 5. Excess streamflow volume per excess (reported) CG flash in 1993.

UMRB	Reported (m^3/CGF)
June	3.1×10^4
July	1.3×10^5
August	3.9×10^4
Average	6.8×10^4
	Corrected (m^3/CGF)
June	2.1×10^4
July	8.9×10^4
August	2.7×10^4
Average	4.6×10^4

flash for June, July, and August 1993 over the GUMRB. The reported (and actual) values range from 1.7×10^5 to 3.9×10^5 (1.2×10^5 to 2.7×10^5) m^3/CGF, with an overall mean of $2.7 \times 10^5 \pm 1.1 \times 10^5$ ($1.7 \times 10^5 \pm 7.6 \times 10^4$) m^3/CGF.

The *excess* precipitation volumes per reported (and corrected) *excess* CG counts in Table 4 range from 6.3×10^4 to 1.9×10^5 (4.2×10^4 to 1.3×10^5) m^3/CGF, with an overall mean of $1.3 \times 10^5 \pm 6.5 \times 10^4$ ($9.1 \times 10^4 \pm 4.5 \times 10^4$) m^3/CGF. These ratios are about 50% of the monthly ratios, which implies that the excess rain volume was produced by a greater proportion of deep convection.

Petersen and Rutledge (1998) examined the average rain volume per CGF over a large (approximately 10^{11} m^2) region that included part of the GUMRB during the summer of 1994. Their value of the seasonal mean rain volume, 1.1×10^5 m^3/CGF (uncorrected), is in good agreement with our (corrected) seasonal mean of 1.3×10^5 m^3/CGF. Soriano et al. (2001) have also examined the monthly convective precipitation volume per CG flash over selected portions of the Iberian Peninsula (approximately 10^2 km^2 each) during the summers of 1992, 1993, and 1994. They obtained a seasonal mean of 1.2×10^5 m^3/CGF over the semiarid region of the peninsula, and 2.1×10^5 m^3/CGF over the humid region; both of these values are similar to our values over the GUMRB.

Results similar to those in Table 4 were also found over just the UMRB sub-region of the GUMRB. The excess monthly rain volume per reported CG flash over the UMRB ranged from 8.1×10^4 to 2.1×10^5 m^3/CGF, with an overall mean of $1.5 \times 10^5 \pm 6.5 \times 10^4$ m^3/CGF.

d. Excess Streamflow Volume per Excess CG Flash in the UMRB

The excess stream volume per CG flash over the UMRB has been computed by dividing the excess stream volume at Keokuk, Iowa (see Table 3 and Figure 5) by the excess number of CG flashes that the NLDN reported over the UMRB (Table 2b). The results are shown in Table 5. Note that the excess stream volume per excess (reported) CGF was about 6.8×10^4 m^3/CGF, which is lower than but still within a factor of 2 of the excess rain volume per reported flash that was discussed in the preceding paragraph (1.5×10^5 m^3/CGF). Table 5 also shows that the excess stream volume per (corrected) CG flash was 4.6×10^4 m^3/CGF.

4. SUMMARY

There appears to have been a regular, reproducible relation between the daily rain volumes and the corresponding counts of CG lightning during the Great Flood of 1993, and similar relations have been found between the average and excess monthly rain volumes and CG lightning, and between the excess stream volume and the excess CG flashes over the UMRB. Our values for the rain volume per CG flash are consistent with prior estimates made on large storms in the Upper Midwest and elsewhere. Altogether, the NLDN reported 3.6 x 10^6 CG flashes over the GUMRB during June, July, and August, 1993, and there were 6.5 x 10^{11} cubic meters of rainfall; the overall rain volume per (reported) CG flash was 1.8 x 10^5 m^3/CGF during the Great Flood. If we correct the NLDN counts for an imperfect network detection efficiency, the actual rain volume per CG flash averaged about 1.3 x 10^5 m^3/CGF. From these analyses, it is clear that reports of CG lightning can possibly be useful for estimating the locations and amounts of convective rainfall in large, mesoscale convective systems and for forecasting and analyzing the associated flood events.

Acknowledgements. One of the authors (NMK) has submitted this research in partial fulfillment of the requirements for an MS degree in Atmospheric Sciences at The University of Arizona. The authors are grateful to Dr. Kenneth E. Kunkel for providing the daily precipitation amounts and to John Cramer and Dr. Kenneth L. Cummins of Vaisala-GAI Inc. (formerly Global Atmospherics Inc.) for providing the NLDN data.

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