Cloud-to-Ground Lightning in Tropical Cyclones: A Study of Hurricanes Hugo (1989) and Jerry (1989)

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ABSTRACT

Cloud-to-ground lightning characteristics of two Atlantic tropical cyclones of 1989, Hurricanes Hugo and Jerry, are presented. Statistics on the number of flashes, location, polarity, peak currents, and multiplicity (number of strokes per flash) are examined in an 18-h period divided into prelandfall and postlandfall categories. Land-based and aircraft lower fuselage radar data are also analyzed to determine the nature of the precipitation in which lightning is detected. Jerry is found to be more electrically active than Hugo, with 691 flashes detected compared with 33 flashes for Hugo. The majority of these flashes, regardless of the polarity, are located in the right front and right rear quadrants of the hurricanes, almost exclusively in outer convective rainbands. One reason for the large difference in the number of flashes between the two storms is the presence of many convective rainbands in Jerry, compared to only a few in Hugo. More than 20% of the flashes in each storm have a positive polarity. Median negative peak currents of the first return strokes are 49 kA in Hugo and 40 kA in Jerry. Median positive peak currents are 65 kA in Hugo and 52 kA in Jerry. The mean multiplicity of the negative flashes is 1.7 in Hugo and 2.6 in Jerry. Twenty percent of the negative flashes detected in Jerry have a multiplicity of 4 or higher.

1. Introduction

Vertical motions in oceanic convection and in hurricanes are much weaker than in midlatitude storm systems (Zipser and LeMone 1980; Jorgensen et al. 1985). Due to the differences in the vertical velocities, midlatitude mesoscale convective systems (MCSs) might be expected to have more lightning than hurricanes. Goodman and MacGorman (1986) studied mesoscale convective complexes (MCCs), a type of MCS (Hane 1986), in the southern plains and found lightning flash rates of greater than 1000 h^{-1} maintained for several hours. A high cloud-to-ground flash rate was also found by Rutledge and MacGorman (1988) in their investigation of an MCS. Additionally, Keighton et al. (1991) studied cloud-to-ground lightning associated with tornadic storms, as have MacGorman et al. (1989) and MacGorman and Nielsen (1991), and found flash rates from 100 to 900 h^{-1}. We infer that there was an interaction between supercooled water, large ice aggregates, and small ice particles that produced charge separation, in the manner discussed by Dye et al. (1986) and Jayaratne et al. (1983), that resulted in high cloud-to-ground flash rates.

In hurricanes, the above interaction between water phases appears to be lacking. Willoughby et al. (1985) analyzed the results of the Project Stormfury hurricane experiment of the 1960s and 1970s. One of the premises of Stormfury was that strong hurricanes contained enough supercooled water for seeding to be effective in ultimately weakening the eyewall and, in turn, the strongest winds. However, Willoughby et al. (1985) concluded that seeding would be ineffective in hurricanes since there is little supercooled water in the presence of the abundant natural ice above the melting level.

The work of Black and Hallett (1986) determined that a limited amount of supercooled water is present above the melting level, in support of the Willoughby et al. (1985) conclusion. Black and Hallett studied three hurricanes with maximum sustained surface winds greater than 45 m s^{-1}. In each of the hurricanes they found very little supercooled water. Specifically, they noted that supercooled drops were found above the melting level only in convective updrafts stronger than 5 m s^{-1}. Black and Hallett added that not all updrafts greater than 5 m s^{-1} contained appreciable amounts of liquid water. Additionally, less than 5% of the updraft cores found by Jorgensen et al. (1985) had average vertical velocities greater than 5 m s^{-1}.

Based upon the work of Willoughby et al. (1985) and Black and Hallett (1986), it seems the necessary

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microphysical conditions in tropical cyclones may not be sufficient to produce large amounts of cloud-to-ground lightning. Without supercooled water interacting with ice, graupel, and hail there would be a reduced chance for charge separation to occur (e.g., Jayaratne et al. 1983; Saunders and Jayaratne 1986; Baker et al. 1986).

Although there is an abundance of research into the structure of tropical cyclones, there is a lack of research on hurricane electrification. With the exception of the work of Black and Hallett (1986), hurricane cloud physics is also relatively unexplored. The few studies of cloud-to-ground lightning in tropical cyclones are Black et al. (1986), Venne et al. (1989), and Lyons et al. (1989). Black et al. took some of the first steps toward increasing our knowledge of lightning in tropical cyclones with their study of cloud-to-ground lightning in Hurricane Diana (1984). They found lightning strokes to be frequent, prevalent both in the storm's eyewall and in the outer rainbands. The detected lightning appeared to outline some of the curved features of the eyewall as well as the outer rainbands present in Diana. Based on this case study, and other undocumented observations, Black et al. noted that lightning in tropical cyclones may be a more common event than previously acknowledged. Venne et al. (1989) and Lyons et al. (1989) found that lightning was again present in tropical cyclones and was coupled with intense convective activity near the centers of the unnamed tropical storm of 1987 and Hurricane Florence (1988).

These previous studies explored only whether lightning existed in tropical cyclones, its location, and some possible relationships of lightning frequency to intensity change. In this paper we not only report on the existence and location of cloud-to-ground lightning flashes in two tropical cyclones but we also take steps beyond the previous work by analyzing the nature and characteristics of the flashes.

Specifically, we investigate cloud-to-ground lightning flashes in two 1989 hurricanes: Hugo and Jerry. Using a combination of radar reflectivity and lightning data, we examine some of the fundamental questions concerning lightning in tropical cyclones, such as the following:

1) Does cloud-to-ground lightning occur frequently in tropical cyclones?
2) Where is the lightning in tropical cyclones located? In the eyewall? In the rainbands?
3) What is the polarity of the lightning flashes before landfall? After landfall?
4) What are the peak signal strengths, that is, peak currents in the lightning flashes?
5) How many strokes constitute each flash?

Additionally, we infer a relationship between the storm structure and the lightning characteristics of the two storms.

2. Instrumentation and data

Several data sources were used in this study. GeoMet Data Services, Inc., manager of the National Lightning Detection Network (NLDN), provided the lightning data; the National Hurricane Center (NHC) supplied information on the hurricane tracks and intensities. The Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA) provided reflectivity data from the National Weather Service radars recorded during and after the landfall of the two storms. HRD also supplied reflectivity data from the lower fuselage (LF) radar on the NOAA WP-3D (P-3) research aircraft during time periods when the hurricanes were over water.

a. Cloud-to-ground lightning

The NLDN uses gated wideband magnetic direction finders (DFs) (Krider et al. 1976) that provided information on the date, time, latitude, longitude, and multiplicity, or number of strokes per flash, of the cloud-to-ground lightning flash and the polarity and signal strength (peak current) of the first stroke in the lightning flash. The NLDN was developed from a series of smaller networks described by Krider et al. (1980), Mach et al. (1986), and Orville et al. (1983) that were joined and expanded in 1989 to cover the contiguous United States (Orville 1991a). The lightning DFs in the NLDN, with their locations shown in Fig. 1, operate on high gain and have a nominal range of 400 km. Within this range, Orville (1991a) estimates that 70% of the cloud-to-ground flashes are detected. Outside the range of 400 km, lightning is still recorded but with a lower efficiency. The polarity of the flash is recorded

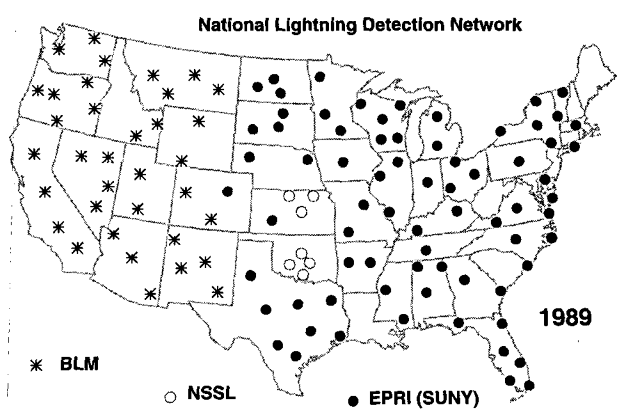


FIG. 1. The locations of 114 magnetic direction finders comprising the National Lightning Detection Network in 1989 with symbols indicating the organizations that own and installed the direction finders. These organizations are the Bureau of Land Management (BLM), the National Severe Storms Laboratory (NSSL), and the Electric Power Research Institute (EPRI) through the State University of New York (SUNY). GeoMet Data Services Inc., Tucson, Arizona, now operates the network with support from the EPRI, adapted from Orville (1991a).

reliably as long as the flash is within 600 km of a direction finder (Brook et al. 1989).

Location accuracy for individual cloud-to-ground lightning flashes is a complicated function of DF azimuthal errors. Detailed discussions of these errors can be found, for example, in Mach et al. (1986) and more recently in Orville (1994). Average errors in flash location have been estimated between 2 and 4 km (Holle and Lopez 1993). We know the location errors in the vicinity of the National Aeronautics and Space Administration (NASA) Kennedy Space Center, Florida, have been evaluated by Maier (1991) and are on the order of 8–10 km. These errors were determined at the edge of the lightning network. Within the continental boundaries, however, we expect to have location errors less than this. In this study, we believe our lightning locations are accurate to within about 5 km.

b. *Hurricane intensity and track*

The NHC final best-track dataset was used to determine the intensity, latitude, and longitude of the two tropical cyclones studied. The best-track dataset contains values of these parameters at 0000, 0600, 1200, and 1800 UTC. When available, radar center positions from land-based and aircraft data at 1-h intervals supplemented the 6-h best-track centers. A storm track for each cyclone was then computed using the spline-fitting method of Willoughby and Chelmow (1982).

c. *Land-based radar*

HRD recorded digitized reflectivity data from the WSR-57 radars at Charleston, South Carolina (Hugo), and at Galveston, Texas (Jerry). The WSR-57 radars are 10 cm in wavelength with 2.0° horizontal and vertical beam widths. Radar data from Hugo were recorded beginning at 0135 UTC 21 September 1989 about 2.5 h prior to landfall and extended through 1225 UTC 22 September. Reflectivity data from Jerry were available from 0000 UTC 16 October just as Jerry made landfall along the Texas coast through 1600 UTC 16 October. The land-based radar data aided in our analysis of the location of lightning flashes relative to the center of the two storms.

d. *Airborne radar*

The LF radar of the P-3 is a 5-cm radar with a horizontal beamwidth of 1.1° and a vertical beamwidth of 4.1° (Jorgensen 1984). Maps of reflectivity in the form of time composites were available from HRD archives for each storm. The composites were created following the procedure of Marks (1985). Data from the LF radar on the P-3 aircraft were used to identify the area of the precipitation associated with each storm and to determine the boundaries of the lightning domain for the two hurricanes. Along with land-based radar maps, the LF radar maps were also used to identify precipitation features associated with cloud-to-ground lightning. We hoped to integrate cloud physics measurements and Doppler radar data from the P-3 tail radar as part of our analysis, but microphysics data were unavailable for either storm, and Doppler radar data were available only for Hugo.

3. Methods of analysis

An 18-h period was selected for the two cyclones to study pre- and postlandfall lightning locations and characteristics. To eliminate subjectivity in determining whether flashes detected by the NLDN were associated with each storm, storm boundaries were established using time composites of radar reflectivity from the P-3 lower fuselage radars. The radar data were also used to identify regions of convection, defined as areas of reflectivity greater than 30 dBZ, similar to the definition used in Rutledge and MacGorman (1988).

For each flash detected by the NLDN within each domain, we analyzed the associated location, polarity, and multiplicity. In addition, we examined the signal strength (peak current) of the first return stroke in each flash using the NLDN calibration of Orville (1991b). We also studied the change in lightning frequency with respect to storm intensity and time. Maps of reflectivity were created from the land-based and aircraft radar data, and 4–8 h of lightning flashes were overlaid in storm-relative coordinates on the reflectivity data. The storm motion during the 4–8-h interval was added or subtracted to the location of each flash and, therefore, the flash locations retained their distance and azimuth relative to the storm center in each of the overlays. Flashes were not plotted with respect to individual cell or rainband movement. As a result, some of the plotted flashes appeared to be located outside of convection, yet radar sweeps near the time of the individual flashes revealed that most of the flashes were contained within convective features.

a. *Times of study*

Hurricane Hugo was studied from 1800 UTC 21 September to 1200 UTC 22 September. Although Hugo first reached hurricane strength at 1800 UTC 13 September, the center of the storm was not within 400 km of the NLDN until 1800 UTC 21 September. At 1800 UTC 21 September, Hurricane Hugo had maximum sustained winds of 62 m s^{-1} that remained at this strength until Hugo made landfall near 0400 UTC 22 September (Case and Mayfield 1990). As documented in the NHC best-track file, Hugo maintained hurricane strength winds for the entire 18 h of study. The path of Hugo during the analysis period (Fig. 2a) shows the storm over land for 8 h. Thus, our analysis period allowed for the investigation of differences between pre- and postlandfall cloud-to-ground lightning.

Jerry was studied from 1800 UTC 15 October to 1200 UTC 16 October. The analysis began at 1800

UTC 15 October when Jerry was upgraded by the NHC to hurricane strength. Hurricane Jerry offers a sharp contrast to Hugo. Over the 18-h period of study beginning at 1800 UTC, Jerry's maximum sustained wind speed increased from 33 m s^{-1} at 1800 UTC to 39 m s^{-1} at 0000 UTC 16 October when it made landfall along the Texas coast (Case and Mayfield 1990). The track of Jerry is seen in Fig. 2b. As in Hugo, our research period allowed for the analysis of pre- and postlandfall lightning characteristics. For Jerry, there were 6 h of data studied before landfall and 12 h after landfall. The postlandfall period included those times when Jerry was at hurricane and tropical storm strengths (Fig. 2b).

b. Domain of study

Based on the analysis of the horizontal extent of precipitation from composites of radar reflectivity data recorded by the P-3 and time-lapse imagery of the flash locations from the NLDN, we estimated that the cloud-to-ground lightning directly associated with Hugo occurred within 250 km of the storm center. This radius appeared to encompass the radar reflectivity in Hugo and was chosen so that all the lightning associated with the precipitation would be included in our study. Only those flashes detected within this domain were considered in this study. In contrast to Hugo, Jerry was a small storm, and all the reflectivity features were contained within a 150-km radius from the storm center. Flashes detected outside 150 km were not included in any of the statistics or computations of the lightning characteristics for Jerry.

TABLE 1. Hurricane lightning flash characteristics.

	Hugo	Jerry
Total flashes (18 h)	33	691
Number prelandfall	23	167
Flashes per hour, prelandfall	2.3	27.8
Number postlandfall	10	524
Flashes per hour, postlandfall	1.3	43.7
Negative flashes	24	547
Positive flashes	9	144
Percentage positive flashes	27	21
Percentage positive prelandfall	30 (7/23)	7 (12/167)
Percentage positive postlandfall	20 (2/10)	25 (132/524)
Median negative peak current (kA)	49	40
Median positive peak current (kA)	65	52
Mean multiplicity (negative flashes)	1.7	2.6
Mean multiplicity prelandfall (negative flashes)	1.5	2.8
Mean multiplicity postlandfall (negative flashes)	2.0	2.5

4. Results

Table 1 presents a summary of the cloud-to-ground lightning that occurred in Hugo and Jerry. The table includes information on the number, polarity, peak current, and multiplicity of the flashes detected for each storm. In addition, Fig. 3 shows the time series of the flash activity of the two tropical cyclones over the

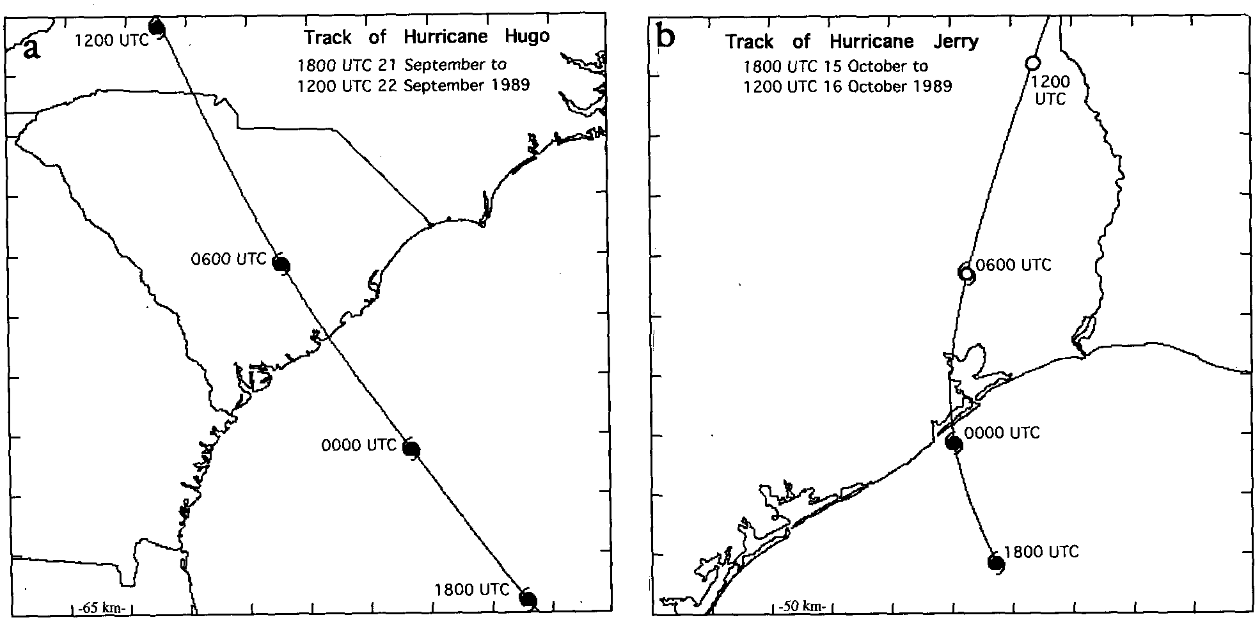


FIG. 2. The tracks of (a) Hurricane Hugo from 1800 UTC 21 September to 1200 UTC 22 September 1989 and (b) Hurricane Jerry from 1800 UTC 15 October to 1200 UTC 16 October 1989. Six-hourly positions are noted by hurricane symbols or circles. Solid and open hurricane symbols indicate when the storms were at hurricane and tropical storm strengths, respectively. The open circle along the track of Jerry at 1200 UTC 16 October indicates tropical depression status. The domains are (a) 650 km × 650 km and (b) 500 km × 500 km.

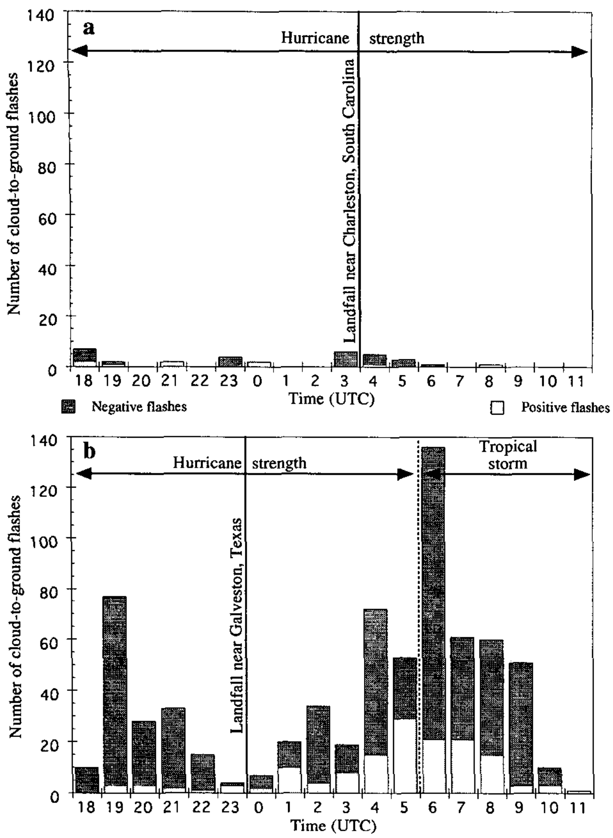


FIG. 3. Histograms of hourly cloud-to-ground lightning rates for (a) Hurricane Hugo from 1800 UTC 21 September to 1200 UTC 22 September 1989, and (b) Hurricane Jerry from 1800 UTC 15 October to 1200 UTC 16 October 1989. Columns with light and dark shading show the number of positive and negative flashes, respectively.

18 h of study. The ordinate in Figs. 3a,b is the same to emphasize the striking difference in the number of flashes that were detected in these two tropical cyclones.

a. Hurricane Hugo

Over the 18 h for which Hugo was studied, only 33 strikes were detected within 250 km of the center (Fig. 3a and Table 1). Land-based and aircraft radar data indicated that the eyewall contained reflectivities from 30 to 40 dBZ, as did isolated areas of the rainband oriented east–west to the southwest of the center and regions of the rainband to the northeast of the center. Figure 4 shows the storm-relative cloud-to-ground lightning flash locations for an 8-h period, 0100–0900 UTC 22 September, plotted onto the reflectivity pattern at 0351 UTC, near the time of landfall. Sixteen cloud-to-ground lightning flashes, 2 positive and 14 negative, were detected over this period. Of the 14 negative flashes, 4 were located in and around the eyewall, and 10 in outer rainbands. Three negative flashes about 220 km east of the storm center appear outside the precipitation features in Fig. 4. These flashes occurred between 0410 and 0430 rather than near 0351 UTC, the time of the radar image in Fig. 4. Analysis of the land-based reflectivity data revealed that the 3 flashes were embedded in a convective cell when they were detected by the NLDN. At 0351 UTC, the cell was located just southwest of the identified cloud-to-ground flashes in Fig. 4 and had not yet rotated counterclockwise to the flash locations near 0420 UTC.

A plot of the 17 flashes detected from 1800 to 0100 UTC (not shown) revealed that 13 of the flashes were in and very near the eyewall, which consisted of reflectivities from 30 to 45 dBZ. Only 4 flashes were located outside the eyewall in isolated regions of convective activity. Seven positive flashes were detected in this period, 6 of which occurred in the eyewall.

Somewhat surprisingly, during the 18-h analysis period cloud-to-ground lightning was not recorded in the extensive rainband oriented east–west approximately 150 km southwest of the eye. While the band was generally stratiform, it did contain some areas of reflectivity greater than 30 dBZ. Nevertheless, what little cloud-to-ground lightning was detected in Hugo was located mainly in the right front and right rear quadrants of the hurricane.

Table 1 shows the lightning characteristics of the flashes in Hugo, beginning with the total number of

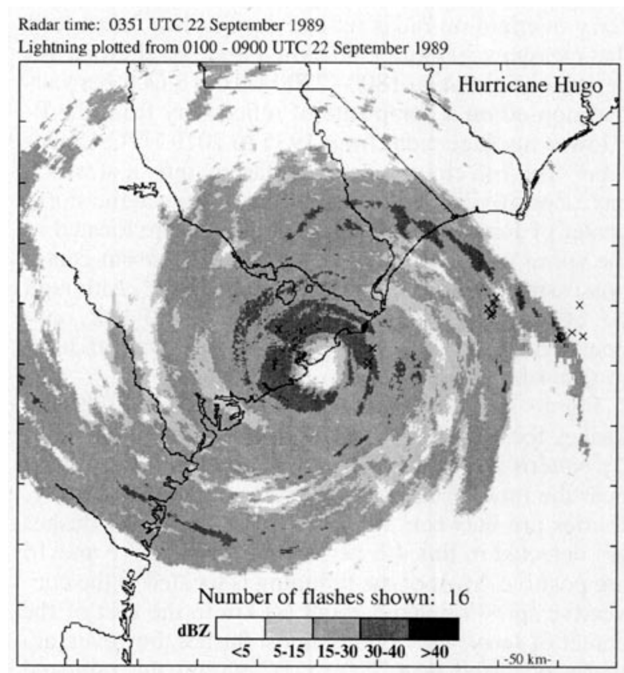


FIG. 4. Horizontal radar reflectivity of Hurricane Hugo from the WSR-57 Charleston radar at 0351 UTC 22 September 1989 as Hugo makes landfall. Lightning flashes to ground (ocean) are shown with crosses for negative charge lowered during the period 0100–0900 UTC. Positive flashes are identified by circles. The lightning locations are plotted relative to the storm center. The domain is 500 km × 500 km.

cloud-to-ground flashes observed over the time of study. Of the 33 flashes recorded in Hugo, 23 occurred before landfall and 10 occurred after landfall. Overall, 27% of the flashes in Hugo lowered positive charge to ground. The percentage of positive flashes was 30% prelandfall (7 out of 23) and 20% postlandfall (2 out of 10).

Median positive peak currents were greater than the median signal strengths associated with the negative flashes detected in Hugo. The mean multiplicity value of the negative flashes was 1.7 (Table 1). The majority of the negative flashes, 14 of 24, had a multiplicity of 1, and there were no flashes with more than 4 return strokes (Fig. 5). Although not shown in Table 1, the mean multiplicity of the positive flashes was 1.0. Orville et al. (1987) and Reap and MacGorman (1989) have shown that 75%–90% of positive flashes have only a single stroke.

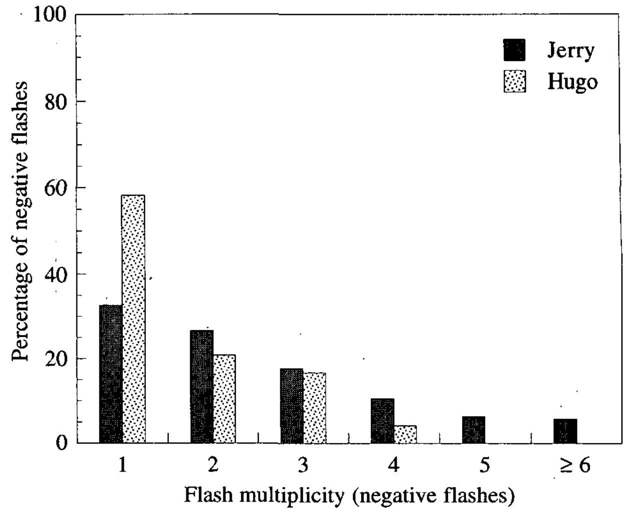


FIG. 5. Percentage of negative flashes as a function of multiplicity in Jerry and Hugo.

b. *Hurricane Jerry*

There were 691 cloud-to-ground lightning flashes identified with Hurricane Jerry over the 18-h period of study. The highest 1-h flash rate occurred between 0600 and 0700 UTC (Fig. 3b) when 136 flashes were detected. This maximum coincided with the time that the NHC downgraded Jerry to a tropical storm (Fig. 3b).

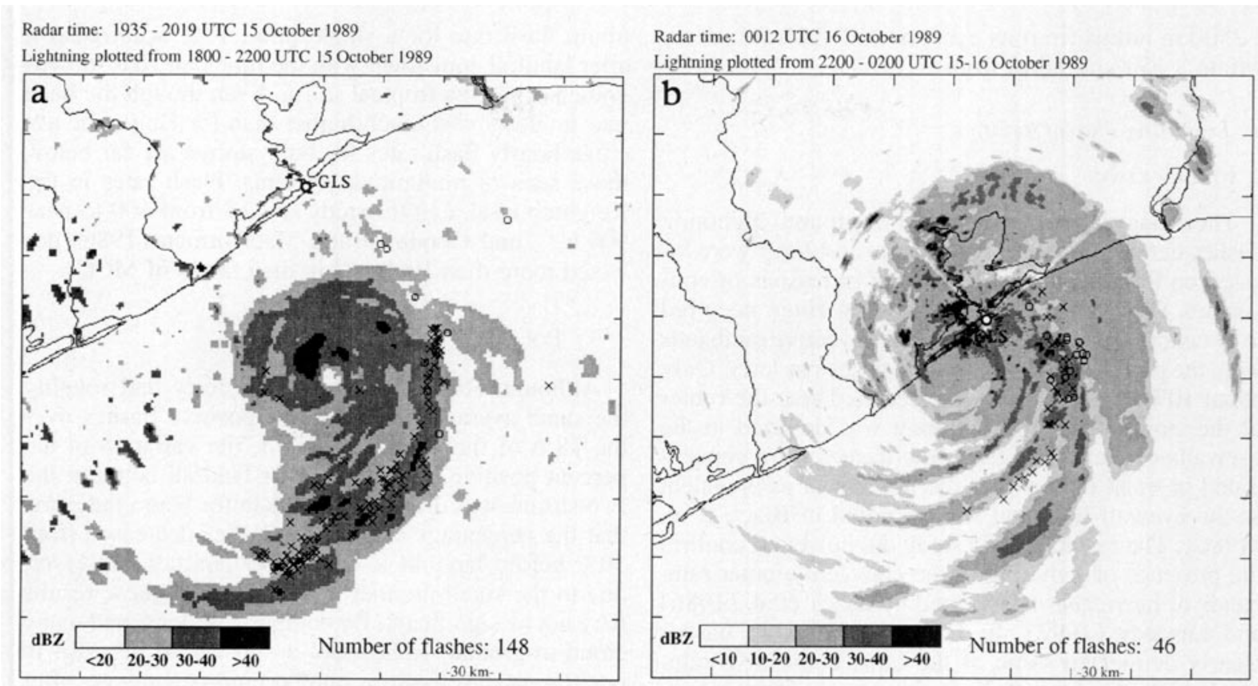
Figures 6a–c show the lightning flash locations for Jerry overlaid on radar reflectivity displays in an area that measures 300 km × 300 km. Figure 6a shows a 4-h period of lightning (1800–2200 UTC 15 October) superimposed on a composite of reflectivity from the P-3 lower fuselage radar from 1935 to 2019 UTC 15 October. The 148 cloud-to-ground flashes, only 8 of which have a positive polarity, are plotted relative to the storm center of Jerry. Almost all of the flashes are located in the spiral rainband east and south of the storm center possessing reflectivities greater than 30 dBZ. Although the eyewall has reflectivities greater than 40 dBZ, only one negative flash is recorded in the eyewall of Jerry in this 4-h period.

Figure 6b shows the cloud-to-ground lightning flashes for 2200–0200 UTC plotted onto the reflectivity pattern for 0012 UTC from Galveston (GLS) radar near the time of landfall. Eyewall and rainband reflectivities are between 30 and 48 dBZ. Only 46 flashes are detected in this 4-h period; 30 are negative and 16 are positive. Most of the lightning is located in the convective spiral rainband about 60 km to the east of the center of Jerry. The southernmost flashes, however, actually occurred near 2200 UTC within the rainband seen just to the east of their plotted location in Fig. 6b. As in Fig. 6a, the majority of the cloud-to-ground flashes are located on the right side of the storm in areas of convective activity.

The 178 cloud-to-ground lightning flashes detected by the NLDN from 0200 to 0600 UTC are plotted in storm-relative coordinates on the GLS radar reflectivity for 0359 UTC in Fig. 6c, nearly 4 h after landfall. Flashes occur in the convective rainband to the north-northeast of the storm center, within scattered convective cells to the northeast of the center and in the northern eyewall of Jerry. Reflectivities are greater than 40 dBZ in the eyewall and northern rainband, and there is abundant convection to the north and east of the eyewall with a broad area of reflectivity greater than 30 dBZ. Thirty-nine and 36 flashes are clustered in the most intense convection of the eyewall and outer rainband, respectively. As in Figs. 6a,b, negative flashes constitute the majority of the identified lightning. However, positive flashes are increasingly detected in this 4-h period (Fig. 3b). Figure 6c confirms the apparent preference for cloud-to-ground lightning to occur in the right front and right rear quadrants of Jerry. Additionally, throughout the 18-h analysis period, cloud-to-ground lightning occurred almost exclusively in convective regions of this tropical cyclone.

Table 1 summarizes the characteristics of the cloud-to-ground lightning in Jerry. Of the 691 flashes in the 18-h analysis period, 167 occurred in the 6 h before landfall at a rate of 27.8 flashes per hour. Most of the lightning in Jerry, 524 flashes, occurred after landfall. In fact, there was a marked increase in the postlandfall hourly flash rate from 27.8 to 43.7 flashes per hour.

The percentage of positive flashes in Jerry was 21%, or 144 out of 691. There was an increase in the percentage of positive flashes between the pre- and postlandfall phases. Before landfall, the percent positive was 7%, and after landfall 25% of the flashes were positive. Multiplicity characteristics of the cloud-to-ground flashes also changed after landfall. Although



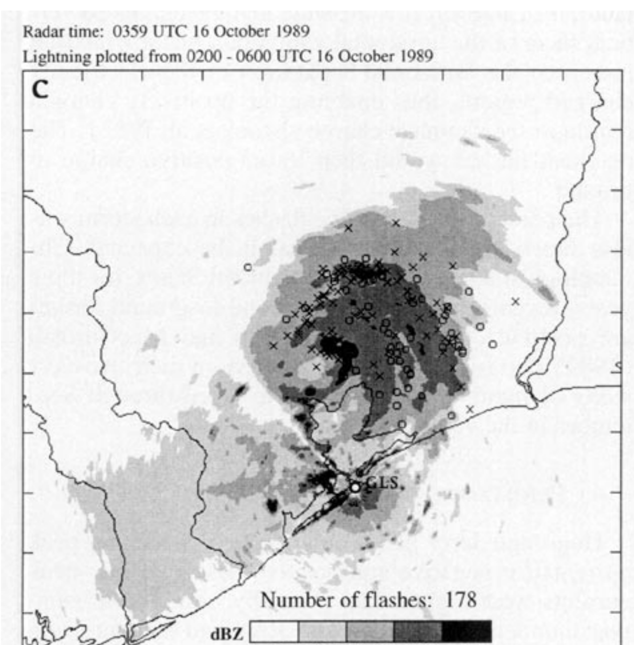


FIG. 6. Horizontal reflectivity and cloud-to-ground lightning flashes in Jerry for prelandfall and postlandfall times. (a) Storm-relative lightning locations for 1800–2200 UTC 15 October plotted on the P-3 lower fuselage composite radar image for 1935–2019 UTC; (b) storm-relative lightning for 2200 UTC 15 October to 0200 UTC 16 October overlaid on the Galveston (GLS) WSR-57 radar reflectivity for 0012 UTC for 16 October; (c) storm-relative lightning for 0200–0600 UTC 16 October plotted on the Galveston radar image for 0359 UTC 16 October. Negative and positive lightning flashes are denoted by crosses and circles, respectively. The domains are 300 km × 300 km. Some of the isolated echoes in (a) are caused by sea clutter and ground return, and the high reflectivities near GLS in (c) are due to ground return.

the differences are not likely to be statistically significant, overall, the mean multiplicity of the negative cloud-to-ground flashes averaged 2.6, with a mean multiplicity of 2.8 prelandfall, decreasing to 2.5 for the postlandfall period. Nearly 60% of the negative flashes had a multiplicity of 1 or 2 (Fig. 5), and the maximum multiplicity of a flash in Jerry was 12. Peak currents for the negative and positive flashes were 40 and 52 kA, respectively.

5. Discussion

Tropical Cyclones Hugo and Jerry were two very different storms. Not only did they differ in their size and intensity but they also had contrasting lightning characteristics. Each cyclone was studied for an 18-h period, including several hours over land, 8 for Hugo and 12 for Jerry. Over the 18-h period of study for each storm, the NLDN recorded 33 flashes in Hugo within a 250-km radius from its eye, and 691 flashes in Jerry within a 150-km radius from its center.

a. Lightning characteristics

1) Location

The majority of the cloud-to-ground lightning flashes detected in Hurricanes Hugo and Jerry were located on the right side of the storm in regions of convection. Over half of the 33 flashes in Hugo occurred in or near the eyewall. In contrast, convective rainbands were the preferred location for the flashes in Jerry. Only about 10% of the flashes were detected near the center of the storm. Although lightning was detected in the eyewalls of Hugo and Jerry, the flashes were concentrated in small regions and did not appear as prevalent as the eyewall lightning strokes noted in Black et al. (1986). The results of this study do, however, confirm the presence of lightning in the convective outer rainbands of hurricanes as reported by Black et al. (1986) and Lascody (1992). In Jerry, the lightning flashes clearly delineated some of the most convective rainbands (Fig. 6).

Rutledge and MacGorman (1988), in their study of a 10–11 June Preliminary Regional Experiment-STORM-Central (PRE-STORM) MCS, found that positive flashes were often located in stratiform precipitation and that negative flashes were located in deep convection. There did not appear to be a preference for positive flashes to occur in the stratiform regions of the two tropical cyclones studied here. Very few of the flashes in either storm were located in areas with reflectivities less than 30 dBZ. Both positive and negative flashes occurred in regions of highest reflectivity, either in the eyewall or in convective rainbands. Based on our results, it appears that cloud-to-ground lightning in tropical cyclones occurs mainly in convection regardless of the polarity of the flash. An explanation for this result may lie in the results of Black and Hallett (1986), who found that supercooled water at upper levels in mature hurricanes existed only in very strong updrafts. These strong updrafts would be limited to convective regions.

2) Flash rates

The cloud-to-ground flash rate for Jerry was more than an order of magnitude higher than for Hugo (Table 1). Hugo showed a slight decrease in the cloud-to-ground flash rate after landfall. Since Hugo was moving within range of more lightning direction finders and thus increasing the likelihood of lightning being detected, we conclude that the observed decrease in cloud-to-ground lightning after landfall is not due to an instrumental effect. In contrast to Hugo, there was an increase in the flash rate between pre- and postlandfall periods in Jerry with the average hourly flash rate increasing from 27.8 to 43.7 flashes per hour. The maximum flash rate for a single hour, 136, occurred 6 h after landfall coincident with the time that NHC downgraded Jerry to a tropical storm. Even though the flash rate for Jerry was much higher than for Hugo, the average hourly flash rates for both storms are far below those seen in midlatitude systems. Flash rates in the Keighton et al. (1991) study ranged from 100 to near 900 h^{-1}, and Goodman and MacGorman (1986) detected more than 1000 h^{-1} in their study of MCCs.

3) Polarity

Although Hurricanes Hugo and Jerry had roughly the same average percentage of positive flashes over the 18 h of the study (Table 1), the variation in the percent positive before and after landfall between the two storms was dramatic. The data for Hugo indicated that the percentage of positive flashes decreased from 30% before landfall to 20% after landfall. However, due to the small number of total flashes, these results may not be significant. By comparison, Jerry had many cloud-to-ground flashes and a substantial increase in positive flashes, both in number and percentage, after landfall (Table 1). It is possible that the enhanced vertical shear of the horizontal wind upon making landfall increased the horizontal separation of the electrically charged regions, thus enabling the positively charged region to see its image charge (Brook et al. 1982). The resultant flashes would then lower positive charge to ground.

The percentage of positive flashes in each storm was also much higher than what might be expected. Climatological analysis across the United States, for three years, reveals that only 4% of cloud-to-ground flashes are positive (Orville 1994). Reap and MacGorman (1989) also found about 4% positive in their two-year study of lightning occurring from April through September in the southern plains.

4) Peak currents

Hugo and Jerry had similar values of median peak currents for negative and positive flashes. These peak currents were higher than normally observed in summer thunderstorms. Hugo and Jerry had median negative peak currents of 49 and 40 kA, respectively. These values compare with 30 kA determined by Orville et al. (1987) for negative flashes using a year of lightning data in the northeastern United States. For positive flashes, Hugo and Jerry had median positive peak currents of 65 and 52 kA, respectively. These values compare with a median of 45 kA for positive flashes determined by Orville et al. (1987).

An explanation for these differences may lie in the highly sheared nature of the hurricane that results from its high horizontal velocities. These high velocities may result in large horizontal extensions of the volume containing the net charge. In other words, the electrical capacitor is larger, resulting in a larger peak current in the stroke to ground.

5) MULTIPLICITY

The multiplicity, or number of strokes in the flash, was different for pre- and postlandfall periods for each storm (Table 1). Hugo's multiplicity increased slightly from 1.5 to 2.0 after making landfall. It is possible that this increase is the result of Hugo coming into the range of more direction finders, and thus, the increased probability of detecting weaker subsequent return strokes resulted in a higher multiplicity. Once again, these results may not be significant since so few flashes occurred in Hugo.

In contrast to Hugo, the mean multiplicity of the negative flashes in Jerry decreases after landfall. We do not believe that the decrease in multiplicity for Jerry in the postlandfall phase is the result of an instrumental effect. This decrease in the multiplicity may be associated with an increase in vertical wind shear due to increased frictional effects while over land. Seasonal observations of thunderstorms show that with an increased sheared environment of storms in winter there is an associated decrease in multiplicity (Orville et al. 1987).

The mean multiplicity of the negative flashes also differed between Hugo and Jerry, with Jerry averaging 2.6 versus 1.7 for Hugo over the 18 h of study. The mean multiplicity values are similar to those found in some midlatitude lightning research. Keighton et al. (1991) found multiplicity values from 2 to 3 in their study of an MCS. In addition, the results from our study are comparable to average values of multiplicity found by Reap and MacGorman (1989). Figure 5 shows the percentage of flashes of different multiplicities for each storm. The percentages are noted in Fig. 5, rather than the number of flashes, to allow easy comparison of the two storms. Nearly 60% of the negative flashes in Hugo had only a single stroke compared to 33% in Jerry, and over 20% of the flashes in Jerry had 4 strokes or more per flash, while only 1 flash in Hugo had a multiplicity of greater than 3.

b. Presence of lightning

The results of this study affirm the hypothesis that hurricanes have less lightning than mesoscale midlatitude systems. Based on this and earlier studies (e.g., Willoughby et al. 1985; Black and Hallett 1986), we assume that only small amounts of supercooled water were available above the melting layer in Hurricanes Hugo and Jerry due to relatively low vertical velocities. Thus, the necessary conditions for electrification were reduced and very little cloud-to-ground lightning occurred relative to MCCs and MCSs. Without cloud physics data or vertical velocity measurements in this study, however, we are forced to infer these differences.

Our results show a positive correlation between convection, especially in outer convective rainbands, and the frequency and occurrence of cloud-to-ground lightning. We found that the majority of the lightning detected by the NLDN occurred in regions of relatively high reflectivity in rainbands. Although Hugo was a very strong hurricane in terms of its minimum central pressure and its maximum sustained wind speed, radar reflectivity from Charleston shows that the majority of reflectivities fall below 30 dBZ outside the eyewall, indicating weakly convective or stratiform rainbands. However, eyewall reflectivities in Hugo were 30–40 dBZ. Just over half of the flashes in Hugo were detected near the eyewall.

In contrast to Hugo, Jerry was a small, weak hurricane that contained several intense rainbands that persisted after landfall. As in Hugo, cloud-to-ground lightning was detected in the eyewall of Jerry; however, there were many more flashes in the outer rainbands. Unlike the stratiform rainbands of Hugo, these convective rainbands had abundant lightning throughout them.

It appears that the existence of cloud-to-ground lightning in tropical cyclones is strongly dependent on the presence of intense outer rainbands. Further analysis needs to be conducted to determine if the two storms studied here provide a glimpse of the norm in hurricane electrification, or the aberration. It is our hope that future studies will have the data available to investigate not only the relationship between reflectivity and cloud-to-ground lightning in tropical cyclones but also the relationship between vertical velocity, cloud microphysics, and lightning.

6. Conclusions

Although this study investigates cloud-to-ground lightning in only two hurricanes, it is the first research to begin to examine the characteristics of lightning flashes in tropical cyclones. We believe our study provides a good building block for future research in a relatively unexplored area. The subject of lightning in hurricanes is important for our understanding of lightning and of hurricane structure and its implications for cloud microphysical processes. There is an obvious void in our understanding of the conditions necessary for hurricane electrification and the resulting cloud-to-ground lightning flashes. Further research must be done along the lines of inquiry of Black and Hallett (1986) to understand the microphysical mechanisms responsible for the differences noted here. It is hoped that in the near future the work of Black and Hallett will be repeated on one or more hurricanes that are within the range of the NLDN. It is our belief that an understanding of the electrical nature of hurricanes will come through studies of the cloud microphysical properties and the dynamics of hurricanes coupled with continuous measurements available from the NLDN.

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