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Lightning Activity within a Tornadic Thunderstorm observed by the Optical Transient Detector (OTD)

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Abstract. The first storm-scale, total lightning observations from space during tornadogenesis are presented. During the overpass of an Oklahoma supercell, just minutes prior to tornado touchdown on 17 April 1995, the NASA (National Aeronautics and Space Administration) OTD (Optical Transient Detector) detected a total of 143 flashes during approximately 3 minutes of observation time. The estimated total flash rate ranges from 45 (raw counts) to 78 (corrected for detection efficiency) flashes min^{-1}. This total flash rate was at least 17 times greater than the cloud-to-ground lightning rate detected by the National Lightning Detection Network (NLDN), indicating most of the lightning was intracloud. Cloud-to-ground lightning at this time was also dominated by positive polarity flashes. In addition, total lightning rates were decreasing rapidly prior to touchdown. These OTD observations are consistent with the limited results from recent ground based measurements of total lightning activity in tornadic storms and corroborate that such storms have unusually high total flash rates, are dominated by intracloud lightning, and that the total flash rates are observed to decrease rapidly in the minutes prior to touchdown.

1. Introduction

On 3 April 1995, the NASA Optical Transient Detector (OTD) was launched by a Pegasus rocket into a low earth orbit aboard the Micro-Lab 1 satellite. This sensor was specifically designed to detect lightning at storm (10 km) scale resolution within its field of view (in excess of 1.5×10^6 km^2) during both day and night. The OTD is in a low earth orbit that limits the viewing time of any particular area on the earth to about 3 mins per overpass. This paper describes an OTD observation of a tornadic thunderstorm that occurred in Oklahoma on 17 April 1995.

Lightning frequency and type (i.e., intracloud or cloud-to-ground) appear to be related to the dynamical and microphysical structure of thunderstorms (e.g., Goodman et al., 1988b; Williams et al., 1989). A strong updraft promotes more frequent interactions between small and large ice phase hydrometeors within the mixed phase region of a thunderstorm, leading to significant storm electrification and lightning. As the number of hydrometeor interactions increase, more charge is separated and lightning activity increases. Stronger updrafts tend to promote more frequent in-cloud lightning activity (Williams et al., 1999). Sferics and L-band radar observations of total lightning in tornadic storms suggest that intracloud processes dominate the total (few cloud-to-ground flashes) as storms become more severe (MacGorman et al., 1989). In addition, recent results from Florida indicate that sudden increases in total lightning activity ("jumps") may be related to updraft intensification and vortex intensification accompanying tornado development (Williams et al, 1999). However, less conclusive relationships have been found between the temporal changes in cloud-to-ground lightning activity and polarity, and tornadic development (Knapp, 1994; MacGorman and Burgess, 1994; Perez et al., 1997).

Some earlier observations from space have examined the lightning activity only in the proximity of tornadic thunderstorms, but not during the tornadogenesis phase of an individual supercell. These prior observations were made from instruments on Defense Meteorological Satellite Program (DMSP) satellites. Nighttime visible imagery from the optical line scanner (OLS) on the DMSP satellite show streaks caused by lightning flashes. Using OLS data, Orville and Vonnegut (1974) found that flash rate densities during the 4 April 1974 tornado outbreak were three times greater than those occurring within a Florida squall line. Turman and Tettlebach (1980) observed three tornadic storms using their own photodiode instrument onboard two DMSP satellites. They called this the Piggyback Experiment (PBE). The device was capable of detecting only about the brightest 2% of the lightning flashes within its 650 km radius field of view. Yet, comparing the three tornadic with the nine non-tornadic storms they found that the lightning flash rate densities during tornadic outbreaks were 5 times greater than for non-tornadic cases.

This paper first briefly describes the OTD instrument and defines how an OTD flash is defined. Then, lightning observations taken by OTD of a tornadic thunderstorm in Oklahoma on 17 April 1995 are presented. The OTD measurements are compared with cloud-to-ground data obtained by the National Lightning Detection Network (NLDN) (Cummins et al., 1998) and radar data from the Twin Lakes, OK (KTLX) WSR-88D radar.

2. OTD Characteristics

The OTD is the first of two low Earth orbiting lightning mappers developed by NASA in the 1990s. OTD is the flight qualified prototype of the Lightning Imaging Sensor (LIS) instrument designed for the NASA Earth Observing System (EOS). The LIS (Christian et al., 1992) was later

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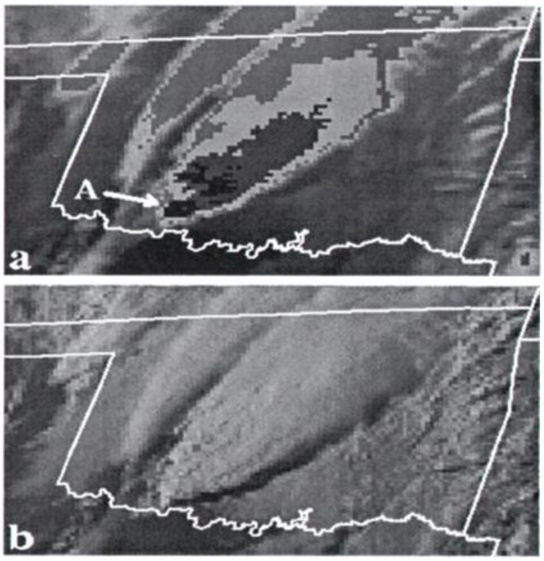

Figure 1. The GOES 8 Infrared (a) and visible (b) satellite imagery of the tornadic cell (labeled A) at 22:45 UTC on 17 April 1995.

launched in November 1997 as a flight of opportunity aboard the Tropical Rainfall Measuring Mission (TRMM). Both the OTD and LIS sensors use an expanded optics wide field of view lens, combined with a narrow-band, 10 Å interference filter that focuses the image on a small, high speed (500 frames s^{-1}), 128 × 128 pixel, charge coupled device (CCD) focal plane. The interference filter is centered about the OI(1) emission multiplet at 777.4 nm. The signal is read from the focal plane into a real-time data processor every 2 ms for event detection and data compression.

The instrument design is driven by the need to detect weak optical emissions from lightning during the day when the background illumination, produced by sunlight reflecting from cloud tops, is much brighter than the illumination produced by the lightning. A combination of filtering methods is used to take advantage of the differences in the temporal, spatial, and spectral characteristics between the lightning optical signal and background noise. After filtering, a modified frame-to-frame background subtraction is used to remove the slowly varying background signal from the raw data coming off the focal plane. If, after background removal, the signal for a given pixel exceeds a specified threshold value, that pixel is flagged as a lightning event. Approximately every 80 s the instantaneous, near-IR background image is also stored, read out, and included in the science data stream. The background image helps identify the cloud top structure and texture, as well as to validate geo-location accuracy.

The event data is sorted into strokes and flashes according to criteria described in the LIS Algorithm Theoretical Basis Document (ATBD) (Christian et al., 1996). An OTD event is defined as the occurrence of a single illuminated pixel exceeding the background threshold during a single frame. Simultaneous events spatially adjacent to one another are assigned to a group (a group is analogous to a stroke). An OTD flash is defined as a set of groups sequentially separated in time by no more than 330 ms and in space by one pixel. It is not possible using OTD data alone to determine if a flash is cloud-to-ground or intracloud. The overall OTD flash detection efficiency is estimated to be between 57–72% (Boccippio et al., 2000) for April 1995.

3. Results

The OTD observed 143 flashes from the tornadic Oklahoma supercell from 22:52:10 to 22:55:20 UTC. An F1 tornado touchdown began at 22:56 UTC. A unique feature of this storm is that it was followed throughout much of its lifecycle by intercept teams (Rasmussen et al, 1994), so that the tornado touchdown times are well known. At least 10 weak, short-lived (F0–F1) tornadoes were documented from this one storm between 21:00 and 01:00 UTC .

The supercell was located at the southern end of a small convective system (Fig. 1). The tornadic cell was identifiable by its cold GOES IR temperatures, persistent strong vertical reflectivity, and a cluster of cloud-to-ground lightning. The portion of the complex north of the supercell was generally multicellular in character.

The OTD lightning associated with the tornadic storm is determined from the pattern of illuminated pixels within the CCD focal plane array. Two separate "streaks" of pixels are formed as OTD passes overhead. The events are then mapped onto the OTD background image. The texture patterns of the OTD background and geolocated GOES imagery were cross-correlated to associate the lightning to the tornadic storm.

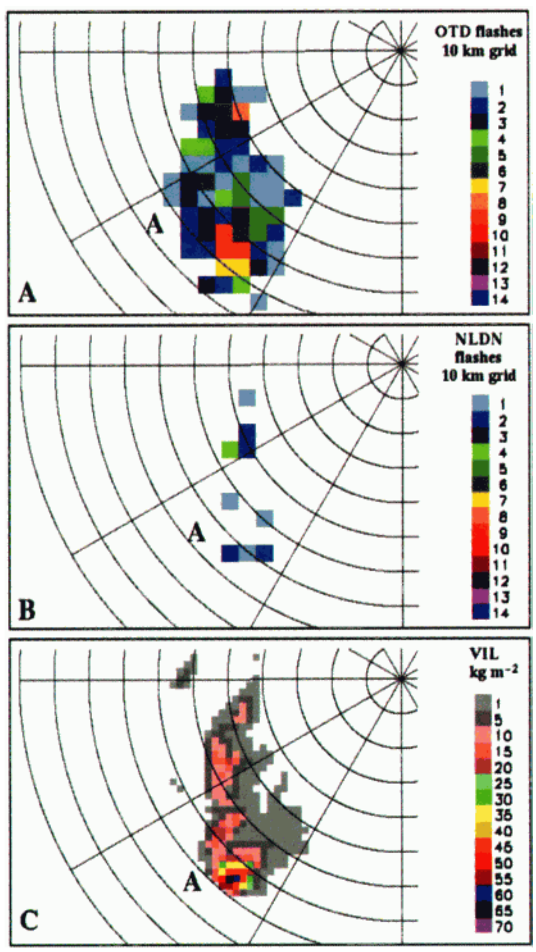

Figure 2. OTD (a) and NLDN (b) lightning flash density plots, and VIL (c) for the tornadic supercell (labeled A). The VIL was computed from the KTLX WSR-88D weather radar in Twin Lakes, OK for the radar volume scan starting at 22:51 UTC and ending at 22:56 UTC. The 20 km range rings are relative to the KTLX radar.

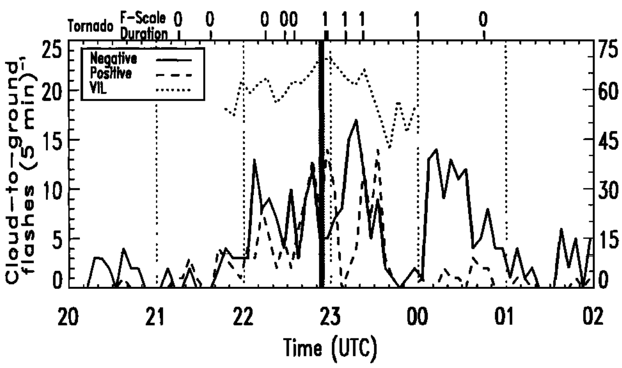

Figure 3. Time history of 5 min cloud-to-ground lightning rates, VIL, and tornado times and Fujita intensity scale for the 17–18 April 1995 tornadic supercell. The gray vertical stripe indicates the OTD overpass interval.

Spatial plots of cloud-to-ground flash density derived from NLDN, total flash density derived from OTD, and VIL (Vertically Integrated Liquid Water) (Greene and Clark, 1972) computed from the Twin Lakes, Oklahoma (WTLX) WSR-88D radar data are shown in Figure 2. VIL is a measure of storm mass used by forecasters to determine storm strength and has been shown to be correlated with total flash rates (Goodman et al, 1988b). The radar volume scan that started at 22:51 UTC and ended at 22:56 UTC reveals a VIL pattern similar to the OTD lightning density pattern. The tornadic storm has a VIL value of 69 kg m^{-2} at this time. Devore (1983) found that severe weather was likely at VIL values greater than 50 kg m^{-2} for springtime Oklahoma storms.

A primary maximum in the OTD lightning density plot delineates the tornadic supercell (Fig. 2b, storm A). The cloud-to-ground lightning data (Fig. 2c) also show a cluster at the location of the maximum VIL (storm A), with another primary cluster about 50 km to the north. The low cloud-to-ground lightning density values do not distinguish the supercell storm from the non-severe storm to the north.

The time history of 5 min cloud-to-ground flash counts, VIL and tornadic activity for the supercell are shown in Figure 3 to provide a context for the OTD observations. The maximum VIL was computed from 2153–0000 UTC, starting when the storm was within 200 km of the KTLX radar. The cloud-to-ground lightning associated with the tornadic cell was obtained by plotting the flashes onto 15 min U.S. composite radar images and manually clustering and assigning the lightning to the storm. The maximum VIL values for this storm exceeded 56 kg m^{-2} from 2200–2346 UTC. The VIL values increased from 56 kg m^{-2} at 2216 UTC to near 70 kg m^{-2} about 5 minutes after the OTD overpass.

The cloud-to-ground lightning activity was predominately negative during the first hour or so. Beginning shortly after the first F0 tornadoes and increasingly after 2130 UTC, a significant fraction (up to 70%) of the cloud-to-ground lightning was of positive polarity. More positive than negative polarity cloud-to-ground flashes were observed during the 10 min period encompassing the overpass until just after 2300 UTC when the first F1 tornado has ended. Negative polarity discharges dominate during the next F1 tornado at 2310 UTC until the polarity switches again to positive during and subsequent to another brief F1 some 10 minutes later around 2322 UTC.

MacGorman and Burgess (1994) found many supercell storms that produced tornadoes and large hail were also dominated by positive polarity ground flashes. Other studies have shown unusually high intracloud flash rates accompanied by low cloud to ground flash rates (without respect to polarity) when supercell updrafts and mesocyclone shear were very strong (MacGorman et al., 1989).

The current study is the first time that the total lightning activity and cloud-to-ground flash polarity accompanying tornadogenesis have been reported. Of particular interest during the overpass is the significant intracloud lightning activity during a period also dominated by positive polarity cloud-to-ground lightning. There is a question about whether some intracloud discharges are mis-classified as weak positive polarity cloud-to-ground lightning when the peak current is less than 10 kA (Cummins et al., 1998). During the period of positive polarity dominance from 2245–2305 UTC only 3 of the 44 positive cloud-to-ground flashes had peak currents below 10 kA.

An expanded time history of OTD total and NLDN cloud-to-ground flash rates for the tornadic storm is shown during the overpass period in Figure 4. The OTD series is divided into 30 s intervals beginning at the time the storm was first observed by OTD. The NLDN series is in 30 s intervals starting at 22:52 UTC. Note that the OTD raw flash rate is about 1 flash s^{-1} during the first minute of observation. The maximum cloud-to-ground flash rate is 5 flashes min^{-1}. Also, we note the rapidly decreasing OTD flash rate trend leading up to the visual report of tornado touchdown. This is characteristic of the previously documented lightning "jump," where the tornado touchdown follows the decreasing flash rates by ten minutes or less (Williams et al., 1999). No discernible temporal pattern or trend is evident in the infrequent cloud-to-ground flash rate.

The OTD detected 143 flashes from the tornadic storm during the entire period (~3.2 min) that the storm was within the OTD field of view, which equates to an average flash rate of 45 flashes min^{-1}. Only 8 cloud-to-ground flashes were recorded (3 negative and 5 positive) from the cell during this period resulting in an average cloud-to-ground flash rate of 2.5 min^{-1}. Only one of the 5 positive ground discharges observed during this brief interval is questionable because its peak current is 9.4 kA, while the others range

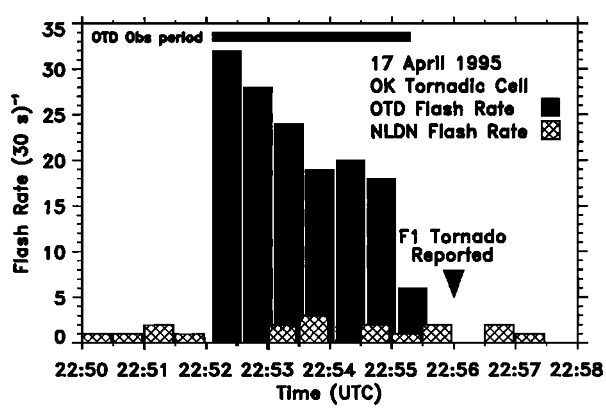

Figure 4. Time history of OTD and NLDN 30 s lightning flashing rates for the tornadic thunderstorm of 17 April 1995. The time of tornado occurrence is indicated. The OTD observation period is also shown.

from 53–93 kA. All of the cloud-to-ground flashes were single stroke flashes, except for one two stroke positive flash. Based on the OTD raw flash counts and assuming the NLDN accurately identified all of the cloud-to-ground flashes, we estimate 16.9 intracloud flashes for each cloud-to-ground flash (94.4% of the total flashes were intracloud). We can account for the detection efficiency of OTD (57–72%) (Boccippio et al., 2000) and NLDN (80–90%) (Cummins et al., 1998) to provide an estimate of the maximum flash rates. The intracloud to cloud-to-ground flash ratio could range from 18.9 (95.0% intracloud) to as high as 27.2 (96.5% intracloud). Further, the average total flash rate ranges from 62 to 78 flashes min^{-1}. This flash rate is indeed significant as Williams et al. (1999) have suggested that severe storms (tornadoes, large hail, strong winds) are very likely when total flash rates exceed 60 min^{-1}.

4. Summary and Conclusions

Lightning observations of a tornadic thunderstorm observed from space just prior to tornado touchdown are presented. The methodology of obtaining flashes from NASA's OTD instrument is described and the flash rates are calculated. The high percentage of intracloud flashes produced by the storm is significant. During the ~3.2 min the storm was observed by OTD, it produced a significant fraction of intracloud lightning (94.4%). The intracloud percentage within the tornadic storm may be as high as 96.5% when accounting for the detection efficiency of both NLDN and OTD. The tornadic storm produced a minimum total flash rate of 45 min^{-1} that might be as great as 78 min^{-1} (considering the OTD flash detection efficiency). Significant intracloud lightning rates and storm mass (VIL) are documented during a period of positive ground strike dominance. This has been suspected by earlier authors, but not previously reported and confirmed.

The time series of lightning counts for the tornadic storm showed a decrease in flash rates just prior to touchdown. A large increase in total flash rates followed by a rapid decrease has been observed prior to tornadogenesis in tornadic storms in Florida (Williams et al., 1999). They attribute the decrease in flash rates with the descent of angular momentum and the nascent tornado circulation downward with the storm downdraft. The OTD and NLDN measurements also reinforce the idea of the high ratio of intracloud to cloud-to-ground lightning in these types of storms.

Changes in total lightning rates (as opposed to only cloud-to-ground) appear to be a sensitive indicator of changes in thunderstorm structure. Used in conjunction with other current observations (such as Doppler radar), severe storm warning capabilities may be improved (Goodman et al., 1988a; Williams et al., 1999). Unfortunately, lightning life cycle studies of individual cells from low earth orbit are limited to a few minutes at most. This could be remedied with a geo-synchronous version of OTD, which could provide continuous coverage over a large continental region at storm scale resolution (Christian et al., 1992).

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