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Early History of Using Total Lightning Data at NWS Melbourne, Florida

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ABSTRACT

This forecaster's note documents the early history (1989–1998) of the use of total lightning data within an operational forecast and warning environment. As early as 1989, the Melbourne field office of the National Weather Service had access to real-time cloud-to-ground lightning data. In 1993, the Lightning Detection and Ranging system (capable of detecting all types of lightning flashes) became available. In 1996, these two lightning data sets, along with radar data, were incorporated into the Lightning Imaging Sensor Data Applications Display (LISDAD) system. During a 3-y period (1996–1998 inclusive), the LISDAD permitted forecasters to observe relationships of total lightning with a variety of convective events, including pulse-severe thunderstorms in the warm season, cool-season tornadic supercells, tornadic mini-supercells in tropical cyclones, and non-severe storms. Major findings included: 1) "lightning jumps" with warm-season pulse-severe storms several minutes prior to reported severe weather; 2) cool-season tornadic supercell storms with very large total flash rates; and 3) tornadic mini-supercells in tropical cyclones produced only small amounts of lightning, however this sporadic activity benefited forecasters by implying stronger updraft development in a favorably sheared environment, in turn implying possible storm rotation and potential tornadogenesis. Finally, given the availability of total lightning datasets to operational forecasters, local forecast products could more effectively provide the public information about the overall lightning threat.

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1. Introduction

The Melbourne (MLB) office of the National Weather Service (NWS) is located in the central Florida peninsula, a region well-documented for receiving frequent lightning. Both climatologically (Hodanish et al., 1997; Orville and Huffines 2001; Orville et al. 2011) and statistically (Ashley and Gibson 2009; NOAA 2013a,b), lightning is a primary hazard to people and property alike (Curran et al. 2000).

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The first type of lightning information to become routinely available to NWS MLB forecasters was cloud-to-ground (CG) flash data in 1989, courtesy of Atmospheric Research Systems Incorporated (ARSI) of nearby Palm Bay, FL (R. Holle 2013, personal communication). A second and more robust lightning system became available in 1993 through a memorandum of agreement between NASA and NWS MLB. Called Lightning Detection and Ranging (LDAR), this system measured the three-dimensional aspects of all lightning flashes across the region. With both systems in place, NWS MLB forecasters had the unprecedented capability to observe and to track

total lightning activity [in-cloud (IC) and CG] across the forecast area of responsibility.

In 1996, in a truly landmark event, the streams of both CG data [commonly known by this date as the National Lightning Detection Network (NLDN)], and LDAR were aligned with KMLB Doppler radar data. This system, developed in collaboration between the NWS, NASA and the Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL), allowed forecasters and researchers alike to observe total lightning trends with individual thunderstorms over the central Florida region.

This paper documents how total lightning information was used in operations at NWS MLB during the years 1989–1998. In section 2, we elaborate on the ARSI CG, NASA LDAR and MIT/LL LISDAD systems. In section 3, we discuss operational applications of all three systems. This includes showing lightning characteristics of severe storms, such as pulse-severe warm-season thunderstorms, cool-season tornadic supercells and tornadic supercells associated with tropical cyclones (TCs). We also discuss how lightning data were used to improve short-term forecast and warning products. In section 4, we discuss the expansion in use of total lightning information at some other NWS offices, and how this data has assisted in warning operations. Section 5 summarizes our work.

2. Lightning systems

a. CG PC-based system

As early as 1989, forecasters at NWS MLB had access to CG lightning data to assist with short-term forecasts and warnings. NWS MLB was one of the first local NWS field offices to have access to this type of data, as CG lightning data did not become available to other NWS field offices until the advent of the Advanced Weather Interactive Processing Systems (AWIPS) in the late 1990s.

Operated by ARSI, CG data were acquired through the Lightning Positioning and Tracking System (LPATS) using a time-of-arrival technique to locate the flashes (Lyons et al. 1989). The LPATS eventually would be combined with the Lightning Location and Protection system, operated by Global Atmospherics Incorporated. This merged network would evolve into the NLDN (Cummins and Murphy 2009; Orville 2008), and eventually

the North American Lightning Detection Network. Access to the ARSI CG data was established through an automated dial-up connection between ARSI and NWS MLB, and data were displayed using NWS MLB modified software (Sharp 2011, personal communication). This PC-based CG system allowed forecasters to observe the polarity, current magnitudes, and location of flashes across the Florida peninsula and surrounding coastal waters (Fig. 1.)

Figure 1: Photo of the PC based cloud-to-ground lightning display at NWS MLB, c. 1992.

b. NASA LDAR system

NASA developed the LDAR system to give increased lead time to the overall lightning activity for lightning-sensitive operations near Kennedy Space Center (KSC). The system was unique in that it detected individual discharges or point sources of lightning in three-dimensional space (x,y,z), and displayed the data in real time. All types of lightning were detected by this system: cloud-to-cloud, cloud-to-air, IC, and CG. Location errors of LDAR point sources over the KSC were on the order of 100 m, but errors increased systematically with range due to radial smearing (Williams et al. 2000; Roeder 2010). Lennon and Maier (1991) give a thorough description of the LDAR system. Mazur et al. (1997) compare LDAR and interferometric systems for lightning detection.

In 1991, the Applied Meteorological Unit (AMU) was created under a memorandum of agreement with NASA, the U.S. Air Force, and the NWS. The primary reason for AMU was to transition weather-related technologies into operational applications (Madura et al. 2011). Accordingly, an LDAR system was placed in the operations area of NWS MLB in 1993. A dedicated T1 communications line brought data from KSC to NWS MLB 24 h a day.

The LDAR software mapped the data in three dimensions by displaying the point data in an X-Y (plan view) format. The data then were projected on an east-west vs. altitude panel and a north-south vs. altitude panel. Five min of point data were displayed at any given time. A fourth panel displayed a histogram of all the point data in 1-min increments. Figure 2 shows an example of the operational LDAR display.
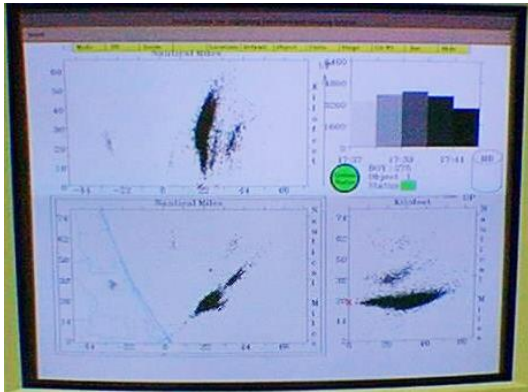

Figure 2: Photo of the Lightning Detection and Ranging system display at NWS MLB, c. 1994.

c. The LISDAD system

In 1996, MIT/LL, NWS MLB and NASA began a collaborative lightning-research project. In August of that year, NWS MLB received a workstation which incorporated radar data from MLB WSR-88D and lightning data from both the NLDN and LDAR. The two primary objectives of this lightning workstation, called Lightning Imaging Sensor Data Applications Display (LISDAD), were:

- Observe how total lightning relates to severe convective storm morphology over central Florida, and

- Compare ground-based total lightning data (LDAR) to a satellite-based lightning detection system.

The LISDAD system continuously monitored and displayed lightning and radar data over the central Florida peninsula and adjacent coastal waters. Radar data (composite reflectivity, echo top, maximum dBZ, and height of maximum dBZ) for thunderstorms were ingested into LISDAD from the radar product generator. Total lightning data were gathered from the KSC LDAR system, while CG NLDN data came from

the Integrated Terminal Weather System at the Orlando International Airport.

To create lightning flash information from LDAR data, the raw point sources (x,y,z) were grouped via the LL/MIT "fixed D" flash analysis algorithm, which used a single fixed-space scale ("fixed D") of 5000 m and single fixed-time scale of 300 ms (Boldi et al. 1998). This algorithm was used to calculate flash rates throughout the time LISDAD was at NWS MLB, and also was used by the NASA Marshall Space Flight Center for the Lightning Imaging Sensor (LIS, Christian et al. 1999).

A "singleton" flash is defined as being composed of one LDAR point source that is not subsequently associated to any other flash by the time-space association algorithm. We assume singletons have passed all data quality thresholds, and were included in the LISDAD flash-rate analyses. Singletons represent about 12% of all flashes observed by the LISDAD system (Boldi et al. 1998; Williams et al. 1999).

Flash rates calculated using LISDAD were substantially higher than more recent flash algorithms. Williams et al. (2000) used a modified LL/MIT flash algorithm in which the distance parameter was no longer fixed, leading to a 50% reduction in flash rates. The root cause of the higher flash rates was the increasing error with distance of the KSC LDAR point-source data. High flash rates, compared to other systems that used more robust flash algorithms, occurred because of LISDAD's using 1) singletons in the flash analysis and 2) a fixed distance parameter in the flash algorithm. We discuss additional flash algorithms in section 4.

The LISDAD graphical display was designed to be a user-friendly system for the operational meteorologist. The initial concept for the display was simply to overlay composite radar reflectivity data with total lightning and NLDN flash data. Storm cells were identified using the NSSL Storm Cell Identification and Tracking (SCIT) algorithm (Johnson et al. 1998). Lightning flash data then were linked to each cell using a flash-association algorithm (Boldi et al. 1998). Total lightning information for each cell was updated every 60 s while radar data were updated every 5 min. Storm cells were numbered and marked by a color-coded circle. Black circles signified no lightning while cyan circles were associated with lightning. To view lightning and radar characteristics of a specific

cell, forecasters would click on the circle to display a pop-up box with trends in lightning and radar data (Fig. 3). Forecasters could zoom and re-center on individual cells or pan to observe convection over most of the Florida peninsula. If the display became cluttered, forecasters had the option to remove cell information. LISDAD also had archiving and simplistic playback capability, allowing easy review of archived data for case studies. The other stand-alone systems (LDAR and the PC based CG system) did not have this capability in a user-friendly format.

Forecasters interacting with LISDAD soon recognized that cells showing rapid increases in total lightning were conducive to severe weather. In order to identify potentially severe cells, LISDAD was redesigned to produce a pop-up box automatically displaying the lightning and radar trends. A red circle also would mark the cell of interest.

Figure 3: Photo of the LISDAD display showing storms off the east coast of Florida, c. 1997. A pop-up box showing lightning trends within one cell is shown in the upper right corner.

3. Operational applications

a. Pulse-severe and supercellular storms

During the 3 y (1996–1998) in which LISDAD was at NWS MLB, a variety of thunderstorm types were analyzed, including pulse-severe storms, supercells, and tropical convection. One of the primary findings was that total lightning flash rates for pulse-severe storms exceeded 60 min^{-1}, sometimes reaching 500 min^{-1}. A distinguishing feature of these severe pulse storms was the presence of "lightning jumps"—an abrupt increase in flash rate prior to the maximum rate for the storm. These "lightning jumps" were found to precede reported severe weather by 5–20 min (Williams et al. 1998; 1999).

The first documentation of the phrase "lightning jumps" in relation to severe convection is found in preprints of the American Meteorological Society's 19th Conference on Severe Local Storms, containing several papers written by researchers and meteorologists who worked with LISDAD. One of them, Hodanish et al. (1998a), examined 18 pulse-severe storms, defining "lightning jump" as, "an increase in total lightning over a time period of at least 2 min, in which the total flash rate increases at least 50 flashes during the entire lightning jump time period. The end of the jump occurs when 2 consecutive 1-min flash rates are less than, or equal to, the prior 1-min flash rate". Of the 18 pulse severe storms, 14 showed the lightning jump characteristic.

Goodman et al. (1998) compared total lightning to the vertical development of horizontal mesocyclonic shear associated with three tornadic storms. They found total lightning rapidly increased (lightning jumps) in association with vertical updraft growth. Lightning was extraordinarily active (lightning jump rates of 47 min^{-2} and peak flash rates of 140 min^{-1}) and was overwhelmingly dominated by IC flashes (~30:1 IC to CG ratio).

Williams et al. (1998) analyzed numerous severe and non-severe storms, with an emphasis on two supercell storms in a strongly baroclinic environment. They found no severe thunderstorms having maximum total lightning flash rates of ≤60 min^{-1}. As total flash rates rose, the probability of storm severity increased (Fig. 4). The most systematic characteristic of the severe storms was the rapid increase in IC flash rates (lightning jumps) to 20–100 min^{-2} prior to the development of severe weather. Their two supercell storms produced maximum IC flash rates of 554 and 567 min^{-1}, and lightning jumps of 60–160 min^{-2}. Hodanish et al. (1998c) analyzed mesocyclone intensity using the total lightning activity of a long-lived tornadic supercell. Flash rates exceeded 200–400 min^{-1} while the storm was tornadic.
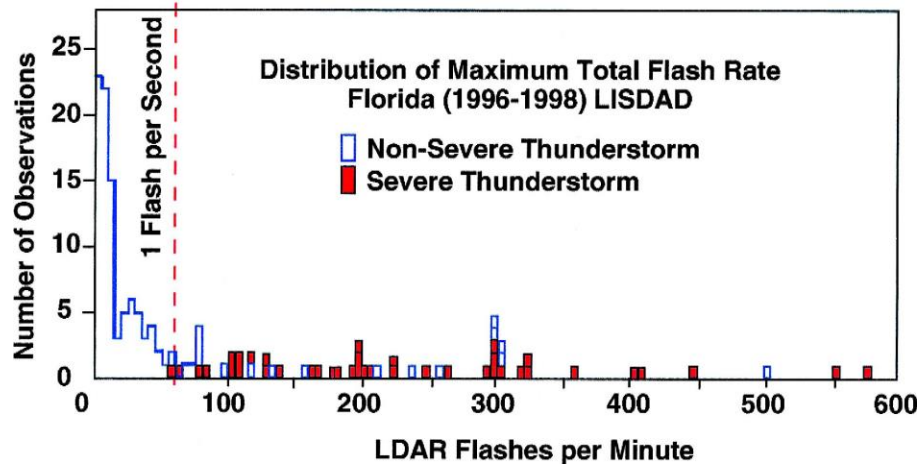
Figure 4: Peak flash rates for Florida thunderstorms based on LDAR observations. From Fig. 3 in Williams et al. (1999).
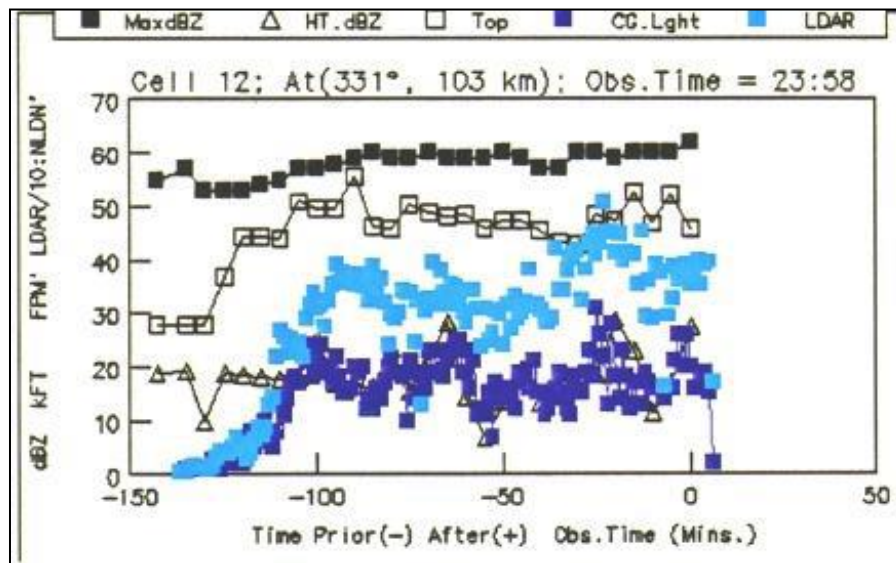

Figure 5: Plot of a rapid rise (lightning jump) in total lightning for a severe storm. Total flash rates averaged 300–500 min^{-1} for >100 min. Black solid squares indicate the maximum dBZ value. Open black squares represent storm top. Open black triangles represent the height of maximum dBZ. Light blue squares represent total lightning. Purple solid squares indicate CG lightning. Total lightning data are scaled up by a factor of 10.

For total lightning information to be an asset to warning operations, the forecasters needed a signal, such as lightning jumps, to indicate that a cell was becoming severe. The LISDAD cell-based trend information could alert the forecaster that the cell was intensifying rapidly (Fig. 5). An additional advantage of LISDAD to warning operations was that lightning data updated every 60 s, compared to 5 min for the WSR-88D. Observing 1-min lightning trends could increase the confidence in the warning decision process.

A rapid increase in lightning activity occurring between radar volume scans could prompt a previously undecided forecaster to issue a warning immediately versus waiting several more minutes for the next radar volume scan.

b. Tornadoes associated with TCs

Total lightning activity, associated with tornadic mini-supercells embedded within rainbands of TCs, also was analyzed. Spratt et

al. (1998) examined five individual tornadic mini-supercells associated with TC's Gordon (1994) and Josephine (1996). Unlike the pulse-severe and nontropical supercell storms that had flash rates generally >100 min^{-1}, total lightning activity for tornadic cells within TC rainbands was substantially less.

We now examine lightning with a long-lived supercell in TC Josephine. This tornadic storm was tracked by the MLB WSR-88D for >3.5 h as it moved northeast across the central Florida peninsula (Fig. 6) and produced seven tornadoes (NCDC 1996). LISDAD tracked a majority of the tornadic supercell's lifetime and documented the lightning characteristics associated with the first six tornadoes.

Figure 6: Track of the long-lived tornadic supercell over the central Florida peninsula, associated with TC Josephine on 7 October 1996. Numbered red lines mark tornado tracks. Dots with circles are the parent mesocyclone locations. Selected mesocyclone times (UTC) are highlighted.

A timeline of tornado occurrences and associated total lightning activity is shown in Fig. 7. Lightning information appears in three staggered pop-up boxes. This format was used due to the SCIT algorithm's difficulty with tracking the rotating storm. At times the SCIT algorithm either would lose the storm, or would identify two cells within the same storm. As discussed in Boldi et al. (1998) and elaborated in

Hodanish et al. (1998c), the *same* lightning flash activity cannot be shared between the SCIT-identified cells. For example, if lightning within an isolated storm is "X" flashes, and the SCIT algorithm identifies two cells within that storm, then the combined lightning flash activity between the two cell IDs must add up to "X".

The first pop-up box in Fig. 7 (cell #10) was identified at 1832 UTC, was tracked for 35 min, and was lost at 1907 UTC. In the meantime, the SCIT algorithm re-identified the storm (cell #9) from 1902–2044 UTC. A third pop up box (cell #5) was identified briefly as a separate cell within this same storm for a 10 min time period (1927–1937 UTC). As shown by the red arrows, six tornadoes occurred during this ≈2.25 h period (1832–2044 UTC). The first occurred between 1845–1900 UTC, the second between 1904–1906 UTC, and the third from 1906–1920 UTC. The fourth, fifth and sixth tornadoes likely occurred at 2000, 2033 and 2042 UTC, respectively [we say *likely*, as we believe the times given in Storm Data (NCDC 1996) are incorrect by 4–13 min; see below].

Total lightning occurred during each of the first three tornadoes, but the flash rates were temporally sporadic. When total lightning did occur, flash rates ranged from 1–8 min^{-1}. Two CG flashes also were noted shortly after 1900 UTC. Sporadic lightning also occurred from 1935–1945 UTC without tornadoes.

Storm Data (NCDC 1996) denotes that tornadoes four, five and six occurred at 2004, 2045 and 2052 UTC respectively. We believe that the tornadoes actually occurred 4–13 min earlier. Figure 6 shows the tornado tracks, and time and location of the parent mesocyclone as it moved northeastward across the peninsula. For the first three tornadoes, the reported start times match up very well with the parent mesocyclone locations. However, for tornadoes four, five and six, the times given in *Storm Data* would place the tornadoes several kilometers to the northeast of the parent mesocyclone locations. Based on this, we believe these three tornadoes likely occurred earlier and closer to the parent mesocyclone than what was reported in Storm Data. *Storm Data* can be inaccurate, as numerous formal studies have shown documented bias and reporting artifacts (Cintineo et al. 2012; Trapp et al. 2006; Doswell et al. 2005; Witt et al. 1998; Hales 1993; Kelly et al. 1985; Morgan and Summers 1982).

Conversely, tornadoes can occur several kilometers away from the parent low level mesocyclone (Speheger et al. 2002).

Total lightning activity was noted at and around the time of the fourth tornado, as flash rates ranged between 6–14 min^{-1}. No lightning was observed at the times of tornadoes five and six, but instead occurred several minutes earlier and later, in each case. Flash rates ranged between 1–12 min^{-1}. Occasional CG lightning flashes also were observed.

Two additional tornadic mini-supercells moved across the central Florida peninsula on the same day. The second produced three F0 tornadoes. However, only minimal lightning activity (all IC) was detected near the times of the

first two tornadoes, and no lightning was observed with the third. The third tornadic supercell produced a waterspout, followed nearly 20 min later by an F2 tornado. No lightning was observed during either tornadic phase of this cell, and only a very brief period of IC lightning occurred midway between the demise of the waterspout and onset of the F2 tornado. No LISDAD plots were available for either mini-supercell.

The last two tornadic mini-supercells examined by Spratt et al. (1998) were associated with TC Gordon (1994) and prior to LISDAD. As such, only raw LDAR point source data along with a corresponding radar image will be discussed.
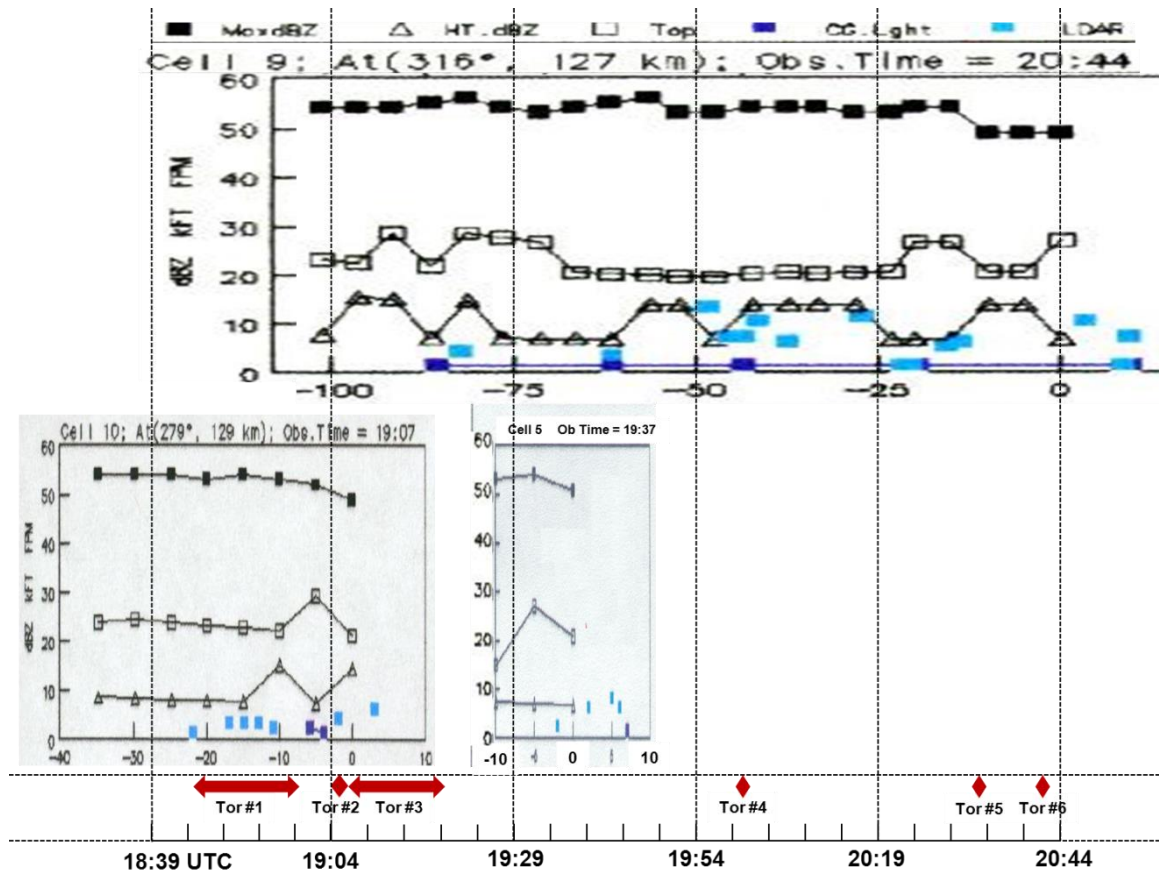
Figure 7: Composite of LISDAD pop-up boxes showing lightning characteristics of a tornadic mini-supercell which moved northeast across the east-central Florida peninsula on 7 October 1996. Red arrows denote tornado times (UTC) as follows: #1, 1845–1900; #2, 1904–1906; #3, 1906–1920; #4, 2000; #5, 2033; and #6, 2042 UTC (see text for discussion regarding the last 3 tornado times). Symbols as in Fig. 5.
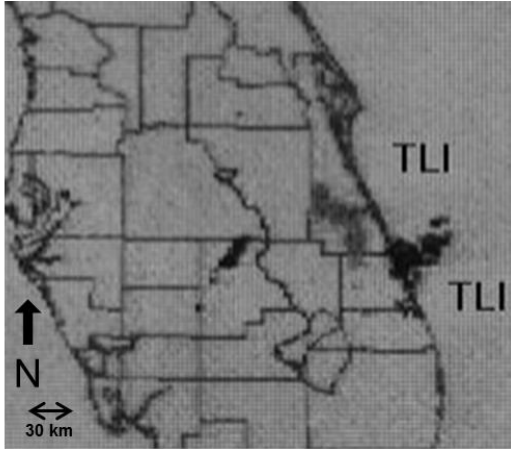
Figure 8: Observed LDAR point-source data (gray and black dots) over the central Florida Peninsula between 2330–2359 UTC 15 November 1994. From Spratt et al. (1998).

Figure 8 shows all of the LDAR point-source data that occurred during a 30-min time period (2330–2359 UTC 15 November 1994) over the east-central Florida peninsula. These data were the result of six IC flashes between 2332–2345 UTC. Figure 9 shows a composite radar image taken at 2340 UTC, when a waterspout moved onshore across southern Brevard County, eventually producing F2 damage. As shown in Fig. 8, all of the LDAR point-source data occurred with convection just to the west through south of the mini-supercell.
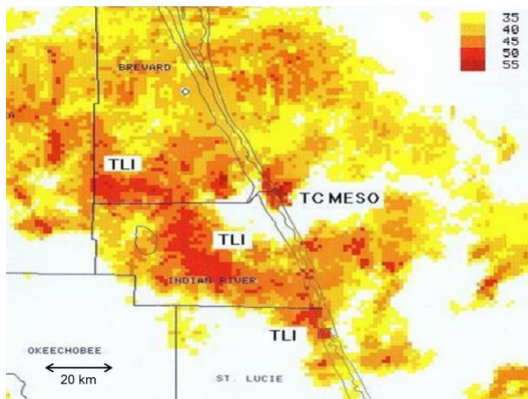
Figure 9: Composite radar reflectivity at 2340 UTC 15 November 1994 for the east coast of Florida. TLI symbols represent LDAR point-source data in Fig. 8. TC MESO represents the cell that produced the F2 tornado along the coast in extreme southern Brevard County. County names are labeled. From Spratt et al. (1998).

Seven hours after the southern Brevard County F2 tornado, a second mini-supercell associated with TC Gordon developed across interior northern Brevard County. This storm eventually produced a short-lived tornado 20 km south-southwest of Daytona Beach. No LDAR point-source data accompanied this cell throughout its lifetime.

Although strong TC tornadoes can occur in the absence of total lightning, the latter's presence can be important to TC forecast and warning operations. Total lightning activity (versus the absence of lightning activity) implies the presence of stronger updrafts (Sharp 2005; Spratt et al. 1998). Therefore, in the presence of a favorably sheared environment, total lightning activity can be used as a proxy for locations of enhanced updrafts that imply increased potential for tornadogenesis.

c. *"Bolts from the blue"*

The LDAR system permitted forecasters to observe detailed three-dimensional aspects of lightning flashes, especially for those near the LDAR system. One type of discharge, observed on a couple of occasions, was a "bolt from the blue", defined as: lightning that comes out of the side of the midlevel precipitation region and travels a substantial horizontal distance away from the parent updraft, then turns towards and strikes the ground away from the cloud boundary. An example of a "bolt from the blue" lightning flash is shown in Fig. 10.

Figure 10: A photo of a "bolt from the blue" lightning flash. Note that the flash travels horizontally away from the parent updraft, and then strikes the ground. Photo courtesy Robert Prentice.

Two known "bolt from the blue" cases were captured by the KSC LDAR network, the first documented by Forbes et al. (1995*)*. As seen in Fig. 11, a flash exits the main storm towers about 8–9 km AGL, travelling horizontally in clear air for ≈6 km, and then striking the ground.
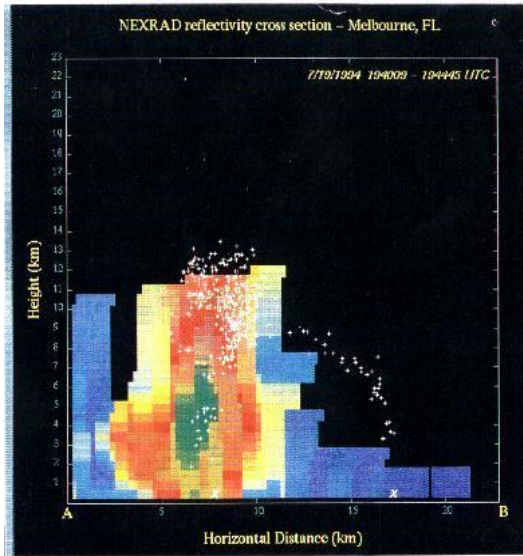
Figure 11: KMLB Radar reflectivity cross section and KSC LDAR point source data (small + symbols) showing a "bolt from the blue" lightning flash. Distance units are km. From Forbes et al. (1995).

The second "bolt from the blue" was documented by the lead author and is illustrated on a modified LDAR display in Fig. 12a. This flash struck very near the NWS MLB office. The resulting thunderclap startled the staff. including the lead author who was on duty at the time. Immediately afterward, the lead author ran outside and noticed the skies were generally clear overhead, with thunderstorms to the distant west. The LDAR display showed that the flash travelled horizontally for ≈35 km. A radar image (Fig. 12b) around flash time indicated that a broken line of thunderstorms (>40 dBZ echoes) was located ~30–60 km west of the office, moving inland along the sea-breeze front.

Holle et al. (1993) found that people in Florida were more likely to be struck by lightning at the end of a storm than at the beginning or middle. He surmised that this was likely due to people resuming outdoor activities too soon after the storm had ended. Limited photos and documentation of "bolts from the blue" (e.g. Rison et al. 2003) indicate that they

exit the rear of the storm, then travel horizontally in roughly the opposite direction of storm motion. "Bolts from the blue" can be very dangerous in this regard since they appear, to the unfamiliar, to strike well after the storm. More information about these types of lightning flashes. along with additional photographs, can be found in NOAA (1999).

d. Forecast products

To satisfy the NWS mission of protection of life and property, NWS MLB forecasters in the early-to-mid 1990s began to use detailed lightning information in a variety of aviation and public products. With access to both NLDN and LDAR data, forecasters identified five distinct lightning-diagnosis benefits: initiation, location, amount, trends (increasing, decreasing, movement), and cessation.

With this information, forecasters could improve both aviation and public products. Aviation applications included configuring alert areas on each of the lightning systems for the Terminal Aerodrome Forecast (TAF) airports located at Orlando, Daytona Beach, Vero Beach, and Melbourne. The intent was to optimize the use of "TSRA" (thunderstorm) and "VCTS" (vicinity thunderstorm) alerts during the first 2 h of the TAF, and to expedite Local Airport Advisories as needed. (Sharp 1998; 2005).

The Hazardous Weather Outlook (HWO) product was designed to discuss upcoming weather hazards during the next seven days, for public and interagency planning purposes. With respect to lightning, the HWO described the geographical distribution and timing of the onset and ending of CG activity across the NWS MLB forecast area. Particular attention was given to sensitive situations where large numbers of people were expected to be outdoors, away from safe shelter. This would include central Florida tourist attractions, area beaches, major golf courses, and the marine community.

As convective events unfolded across the MLB forecast area, lightning information was routinely included in the short-term forecast ("NOW") product. LDAR data were used to detect the early signs of electrical activity aloft over generalized areas before CG strikes occurred. The term "lightning storm" actually was used in the NOW product when the predominant weather threat was CG lightning. Preliminary quantitative descriptors of CG discharge frequency were

a)
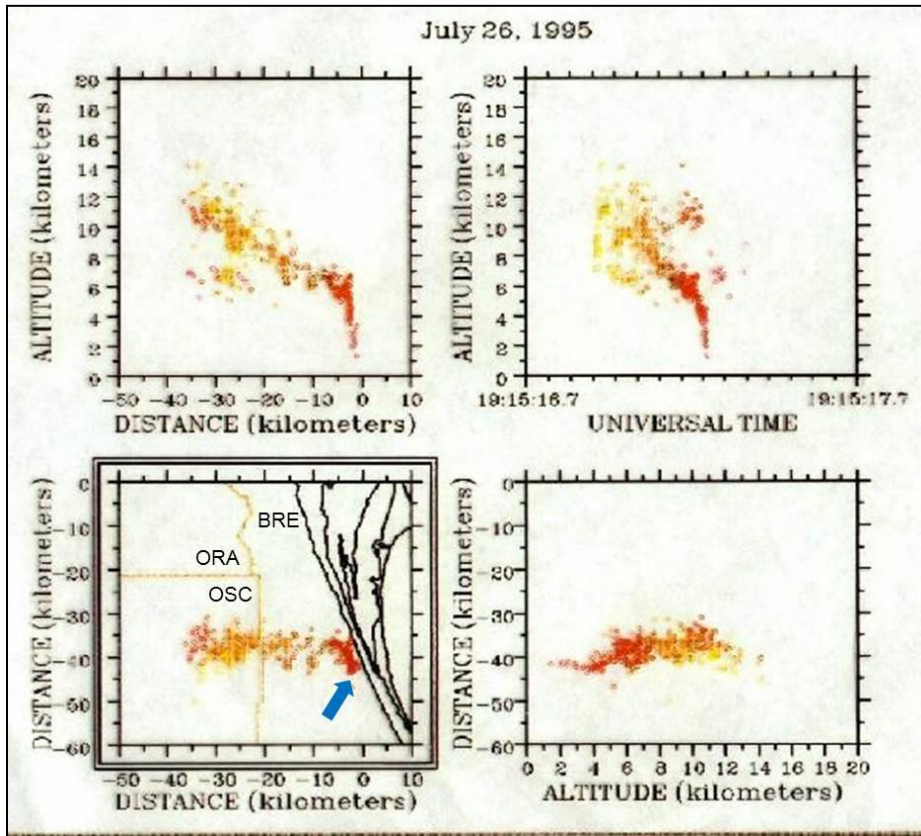
b)
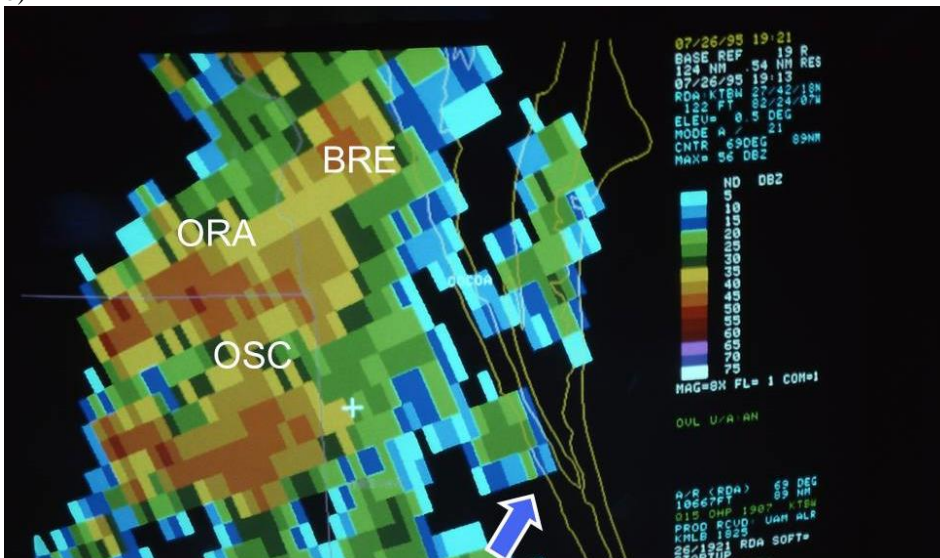
Figure 12: a) Four-panel LDAR plot of the "bolt from the blue" near the NWS MLB office (blue arrow, lower-left), 1915:17.24 UTC 26 July 1995. The upper-right panel shows 1 s of LDAR point data. Yellow points represent the beginning of the flash; red represents the end. b) photo of a computer monitor displaying 0.5° base reflectivity over the same region at 1913 UTC (≈2 min before the flash). Radar data were from Tampa Bay, FL, as the MLB radar was inoperative. Distance units are km. OSC, ORA and BRE represent Osceola, Orange and Brevard counties, respectively. Blue arrow points to the approximate location of NWS MLB.

defined as occasional (<2 min^{-1}), frequent (3–11 min^{-1}) and excessive (≥ 12 min^{-1}) (Hodanish 1996; Sharp 2005). Once a storm was categorized as excessive, an Excessive Lightning Alert (ELA) was issued for the storm.

The scenario most often prompting an ELA was the collision of the east- and west-coast sea breezes during the warm season (Hodanish et al. 1997). At times, isolated storms also reached and maintained excessive rates. If a storm, which was producing excessive CG lightning flash rates began to appear severe, it no longer was referenced as a lightning storm, but a severe thunderstorm, and the appropriate severe weather warning (severe or tornado) was issued. Even then, the frequency of the CG lightning was mentioned explicitly with any warning or severe weather statement, as lightning was likely the first hazard to arrive and the last to depart (Fig.13). It was surmised that if lightning were described as the first hazard to impact an area, the public would be more likely to move quickly to a safe location. Examples of ELA statements can be found in Sharp (1998; 2005).

SEVERE WEATHER STATEMENT
NATIONAL WEATHER SERVICE
MELBOURNE FL
532 PM EDT TUE JUL 29 1997

...SEVERE THUNDERSTORM WARNING FOR ORANGE COUNTY UNTIL 615 PM...
...SEVERE THUNDERSTORM WARNING FOR OSCEOLA COUNTY UNTIL 625 PM...

    AT 529 PM DOPPLER RADAR INDICATED A SEVERE THUNDERSTORM 5 MILES EAST OF THE DISNEY COMPLEX. THIS STORM WILL BE CAPABLE OF PRODUCING DAMAGING WINDS...LARGE HAIL AND RAINFALL ACCUMULATIONS IN EXCESS OF 2 INCHES PER HOUR. IN ADDITION... LIGHTNING DETECTION EQUIPMENT WAS INDICATING EXCESSIVE FLASH RATES OF 20 FLASHES PER MINUTE. OTHER STRONG TO SEVERE STORMS WERE LOCATED IN EASTERN OSCEOLA COUNTY 10 MILES WEST OF THE ST JOHNS RIVER. THE STORMS WERE SHOWING VERY LITTLE MOVEMENT.

Figure 13: An example of lightning information added into a severe weather statement. From Hodanish et al. 1998a.

By the end of the 1997 warm season, NWS Southern Region Headquarters endorsed the use of total lightning information in public and aviation products by supporting Project ELISE (Enhanced Lightning Information and Services Experiment). ELISE had lightning-related objectives, such as the inclusion of lightning information within public products, as well as experimental public lightning advisories for individual counties (Hodanish et al. 1998b).

In the late 1990s, AWIPS made major changes in the way data were viewed by NWS meteorologists. All data, including CG information, were available on a single workstation. Forecasters could overlay CG data on a variety of products, including radar, satellite, observational, and analysis fields. Lightning climatology research between NWS personnel and Florida State University (Lericos et al. 2002) and Texas A&M University (Hodanish et al. 1997) led to AWIPS-based lightning threat products, including the HWO, the ELA, and graphical lightning threat maps. Those now are issued both in text and graphical format, and are generated as needed using AWIPS via the Graphical Forecast Editor or Warning Generator. Numerous examples of such products are found in Sharp (2005). Real-time graphical hazard products can also be viewed at: http://www.srh.noaa.gov/mlb/ghwo/ghwomain.php.

4. Operationally oriented studies of total lightning: 1999–2012

The primary goal of this paper is to document the use of total lightning information in operations at NWS MLB between 1989–1998. Since then, its use has expanded to other NWS offices and associated applied-research organizations (e.g., NASA Short-term Prediction Research and Transition Center, NSSL Hazardous Weather Testbed). Given a strong link between the research at NWS MLB in the 1990s and research that has been ongoing since, we believe it is appropriate to discuss how total lightning information has been used for forecast and warning operations at other NWS offices and associated research centers. We also discuss how this research has led to a satellite-based total lightning detection system to be launched in late 2015.

Since the development of the original LDAR system at the KSC, additional total lightning mapping networks have been deployed across the U.S. As of early 2013, networks were located in Georgia, Alabama, Texas, Oklahoma, New Mexico, Colorado, and the Washington, DC area. Fortunately, several NWS offices have access to several of these networks, and use the data in severe weather operations. Below we summarize the findings of several severe-storm case studies that occurred in the Huntsville, AL and Dallas/Ft Worth, TX NWS offices.

The Northern Alabama Lightning Mapping Array (NALMA) is one of the most scientifically documented arrays accessible to NWS forecasters. Goodman et al. (2005), in examining pulse-severe storms in the warm season and cool-season tornadic storms, found total lightning flash rates of 300 min^{-1}, with a strong increase 9 min prior to severe-weather reports from pulse storms. The cool-season tornadic storms showed peak flash rates reaching 70–100 min^{-1} and showed increases during storm intensification of as much as 20–25 min^{-2} before some of the tornadoes. One of the larger, more complex supercells in his study generated peak total flash rate >800 min^{-1}, but this was an atypical case. Darden et al. (2010), in an examination of a tornadic supercell in Alabama, found lightning jumps (in this case rapid increases in source density) 10–20 min prior to tornadogenesis. Several forecasters working this event recognized significant jumps in the total lightning rates, providing additional warning confidence. White et al. (2012) showed how the NALMA assisted forecasters during a severe weather episode, in that source density rapidly increased prior to severe storm development. In particular, a lightning jump occurred 14 min before the first report of severe weather (large hail). This storm produced a tornado 26 min after the lightning jump.

McKinney et al. (2009) analyzed total lightning activity associated with several supercells that occurred in the north Texas region. Total lightning data in this analysis was acquired by an LDAR II network, operated by Vaisala. The LDAR II data were ingested into AWIPS, displayed as Flash Extent Density (FED). Four important findings of their study are summarized below.

First, FED jumps occurred up to 14 min before tornadogenesis with several of the supercells. FED jumps also were observed with numerous reports of severe hail. Second, FED data highlighted changes in both cell intensity and movement, which made it an important addition to the WSR-88D data. This finding was very beneficial in situations where the radar may not sample a storm adequately (e.g., "cone of silence"), or if the radar became inoperative. Third, qualitative displays of total lightning data could be used by forecasters as indicators of the presence of a strong updraft within a storm. Regions of little total lightning activity within a strong updraft or downdraft region, including features such as lightning holes and updraft notches, were observed with three cases. Fourth, FED appendages were observed with multiple supercells before and during shifts in reflectivity-derived storm track. These appendages may indicate updraft development on a preferred flank of the storm, suggesting the potential for deviant storm motion.

In addition to the operationally related studies discussed in the previous 3 paragraphs, several other studies (Goodman et al. 1988; MacGorman et al. 1989; Williams et al. 1989, 1999; Buechler et al. 2000; Goodman et al. 2005; Bridenstine et al. 2005; Wiens et al. 2005; Steiger et al. 2005, 2007; Gatlin 2006; Krehbiel 2008) have demonstrated the potential use of total lightning data in decision support during severe weather situations. These studies have found positive correlations between severe weather and rapid increases in total lightning.

Not all severe weather is preceded by a lightning jump, nor do all storms that have lightning jumps produce severe weather. Despite these occasional discrepancies, numerous examples of rapid increases in lightning tens of minutes prior to severe weather have been documented in locations where ground-based lightning mapping arrays are operational.

A primary goal in recent years has been to develop lightning jump algorithms to improve lead times for severe weather operations. Schultz et al. (2009) found promising results for six algorithms on 85 thunderstorms (47 nonsevere, 38 severe) that developed within the NALMA and Washington, DC LMA networks. The "2σ" lightning jump algorithm had a high probability of detection (POD; 87%), a modest false alarm rate (FAR; 33%), and a Heidke skill score of 0.75. A second lightning jump algorithm, "Threshold 8", showed a POD of 81%

and a FAR of 41%. Average lead time to severe-weather occurrence for these two algorithms was 23 min.

Gatlin and Goodman (2010) developed and tested an algorithm on 19 severe thunderstorms which produced 110 documented severe-weather events across northern Alabama and southern Tennessee. Lightning jumps preceded 90% of these events, with as much as a 27-min lead time. However, 37% of lightning jumps were not followed by severe-weather reports. Various configurations of the algorithm were tested, and the best performance statistics were POD of 0.74, FAR of 0.40, and Critical Success Index (CSI) of 0.49.

Schultz et al. (2011) expanded on their 2009 research, examining 711 thunderstorms that developed across north Alabama, Washington, DC, the eastern Colorado–western Kansas region, and Oklahoma. Their 2009 study showed best statistical results with the 2σ algorithm, the only algorithm used in their 2011 work. Performance metrics for the 711 thunderstorms were: POD 0.79, FAR 0.36, CSI 0.55 and HSS 0.71. The average lead time of jump occurrence to severe weather was 20.65 min.

The overall goal of these three studies (Schultz et al. 2009, 2011; Gatlin and Goodman 2010), is to advance the development of an operationally applicable jump algorithm to improve warning operations. These algorithms can be tailored for use with terrestrial-based lightning mapping arrays or from space using the Geostationary Operational Environmental Satellite Series R (GOES-R) Geostationary Lightning Mapper, scheduled to be launched in October 2015. One of the primary benefits of a space-based detection system is the capability of covering the entire CONUS and coastal waters, allowing all NWS offices to use total lightning information to improve warning and forecasting operations.

5. Summary

This paper has described the early history of using total lightning information in an operational NWS environment. CG lightning data became available to NWS MLB forecasters in 1989, about a decade before being routinely available to other NWS forecast offices. The much richer total lightning data from the KSC

(LDAR) arrived in 1993, and allowed MLB forecasters to observe total lightning activity over the entire county warning area. In 1996, the LISDAD system combined the two lightning data sets with WSR-88D data. For the first time, this permitted forecasters to observe total lightning activity associated with a variety of convection, including supercell thunderstorms, pulse severe storms, TCs, and non-severe thunderstorms.

In the 3 y when LISDAD was operational at NWS MLB, a strong working relationship developed between the forecasters and the NASA and MIT scientists. The result was several scientific papers related to the findings of the LISDAD system (Goodman et al. 1998; Hodanish et al. 1998a,b,c; Williams et. al. 1998, 1999; Sharp 1998; 2005, Spratt et al. 1998). One of the main findings was that total lightning increased rapidly before the onset of severe weather. These lightning jumps were documented with a majority of warm-season pulse storms, with severe weather occurring 5–20 min after the lightning jumps ended. Also, cool-season tornadic supercells tended to have large total flash rates, exceeding 200–500 min^{-1} in several cases. Tornadic mini-supercells associated with TCs showed very little lightning. However, even the presence of infrequent total lightning can be an important indicator, by serving as a proxy for enhanced storm updrafts and the potential for tornadogenesis.

With access to total lightning information, NWS MLB forecasters during the 1990s had the ability to forecast more precisely the beginning and end times of convection. Lightning information was broadcast to the general public via a variety of text and graphical products.

In the 2000s, additional land-based lightning mapping networks came online across several regions of the United States. Data from these networks confirmed what was found with LISDAD—that lightning jumps occurred with many (but not all) thunderstorms before severe weather reports. LISDAD and other land-based lightning mapping networks laid the groundwork for a satellite-based lightning detection system (Weber et al. 1998). This satellite-based lightning detection system, known officially as the Geostationary Lightning Mapper, will be launched into space on an upcoming NOAA GOES-R satellite scheduled to be launched in October 2015.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (E. Brian Curran):

Initial Review:

Recommendation: Decline.

General comments (author): *I wish to let everyone know of the following 4 significant changes to the paper:*

A) *We changed the title of the paper slightly from, "Early history of using total lightning data in NWS operations" to, "Early history of using total lightning data at NWS Melbourne FL". This was done at the request based off one of the reviewers (yourself) and the Editor of EJSSM.*
B) *We added an introduction section to the paper. This was based off one of the reviewers (yourself) and the Editor of EJJSM.*
C) *We added a new section, section 4, to the paper titled operationally oriented studies of total lightning: 1999 – 2012. Although the primary goal of this paper was to discuss the early history of total lighting usage at NWS MLB, as suggested by one of the reviewers, there is a strong link between the work that was done at NWS MLB in the 1990s and what is ongoing today with respect to total lightning activity.*
D) *We expanded the Abstract per request of one of the reviewers [who] suggested that we mention key findings [that] were not originally in the abstract.*

Below are my responses to your review (my responses are in italics):

Substantive comments: I believe the intended purpose of this paper (hereafter referred to as Hodanish et al.) is to document early observations of VHF radio mapping (an overview of which may be found in MacGorman and Rust 1998, p. 151–158) of the complete lightning flash (intracloud and ground flashes and air discharges, commonly referred to in the literature and commercially as "total lightning", or TL) and the use of these observations in a National Weather Service (NWS) operational environment. I say that I believe this as I cannot find in Hodanish et al. (but, perhaps, in the paper's abstract) a stated purpose for documentation of these early observations. I also believe the title of Hodanish et al. to be misleading, as this paper documents early use of TL data only at the NWS office in Melbourne, FL (NWS MLB) and does not consider early uses of these data in other operational settings (e.g., Goodman et al. 2005; Patrick and Demetriades 2005; McKinney et al. 2008; Darden et al. 2010; Seroka et al. 2012).

Based on your suggestion, we have changed the title of the paper slightly to "Early history of using total lightning data at NWS Melbourne Florida". Our primary goal of this paper is to let the readers know of the early history of total lightning usage in an operational NWS environment.

We have also discussed the use of total lightning in operations at other WFOs across the nation, specifically at Dallas/Ft Worth and Huntsville. Please see section 4 of the updated paper.

The primary reason why I recommend rejection of Hodanish et al. is that this paper, in my opinion, is fundamentally no different from Hodanish (1996). It appears to me that sections of Hodanish (1996) were copied verbatim (for instance, compare Sec. 3.1 of Hodanish (1996) to Sec. 2a of Hodanish et al.). While the observations made at NWS MLB in the 1990s may be unique in that they represent the first use of TL data in an operational setting, I do not find anything new here that extends into the present the value of TL data in operational warning and decision support activities. Simply put, I cannot justify a reason why EJSSM should accept for publication minor revisions of a paper written more than 15 years ago.

We have removed most of the Hodanish 1996 text from the updated paper. Parts of Hodanish 1996 that we kept are now in section 3d. I do not agree with you in that the original paper (version 1 which you reviewed) is fundamentally no different than Hodanish 1996. It is true that the part of the original paper

which discussed the CG lightning systems and LDAR systems is not fundamentally different than Hodanish 1996, however a large part of the original paper discusses the LISDAD system, and LISDAD was not discussed at all in Hodanish 1996. Most of the relevant information in the original (and current) paper discusses what was learned from LISDAD.

I also argue that including Hodanish 1996 into sections of the original paper is improper. As you know, Hodanish 1996 was a non-peer reviewed article. According to Eloquent Science, copying text from a non-refereed article to a refereed article does not imply improper behavior. As Dr. Schultz states (pg 189, 1st full paragraph): "Submitting the same abstract to different conferences, however does not necessarily constitute duplicate publication, nor does submitting a non-peer-reviewed conference abstract or article to a peer reviewed journal". If possible, I would like to see the editor of EJSSM clarify this issue.

[Editor's note: While agreeing with Dr. Schultz on the issue, we encourage authors to 1) minimize the amount of duplicate (verbatim) text to the least amount necessary to reinforce the pertinent argument(s), and 2) cite the source of that material specifically. When encountering reused material from non-refereed publications, reviewers should evaluate it on those bases.]

Another reason why I recommend rejection of Hodanish et al. is because this paper contains no introduction. The importance of an introduction in a scientific paper cannot be overstated. Schultz (2009, p.33) claims that the introduction is one of the most frequently read parts of a paper after the title and abstract. Lacking an introduction assumes that the reader is already familiar with the subject material—a dangerous assumption! For instance, Hodanish et al. does not contain a substantive literature review or synthesis to assist readers unfamiliar with VHF mapping of the lightning flash (e.g., Mazur and Ruhnke 1993), observed relationships between spatial and temporal TL activity and severe convective weather (e.g., Goodman et al. 1988; Williams et al. 1999; Lang and Rutledge 2002; MacGorman et al. 2011), or research linking observed TL trends to severe convective weather (e.g., Williams et al. 1999; Gatlin and Goodman 2009; Schultz et al. 2009; Metzger and Nuss 2012). Lastly, there does not appear to be a statement or paragraph summarizing how the paper is organized.

You (and the Editor of EJSSM) are correct that it was improper to not include an introduction in our paper. As I stated at the beginning, an introduction has been included.

In the introduction, we decided to not include a thorough review of VHF mapping systems. The goal of our paper was to discuss the history of what was found using the early lightning systems at NWS Melbourne, and not a scientific review of VHF mapping systems. Back in the 1990s, the VHF system in which we were using was the KSC LDAR system, and we make reference to the workings of this system by referencing Lennon and Maier (1991).

In the introduction, we did add a paragraph on how the paper is organized.

I did not spend a lot of time [with technical comments] because I felt there was enough justification early in the review process to reject Hodanish et al. Logically, the paper could be organized better. I don't understand why the authors chose to separate the LISDAD applications prior to and after 1996, or why LISDAD work apparently ended in 1998 after the NWS Southern Region "legitimized" the NWS MLB TL initiative (Project ELISE) at the end of the warm season in 1997. It is not obvious to me how the second "bolt from the blue" case is somehow unique from that of a very long horizontal intracloud flash propagating within a charged trailing stratiform region of a forward propagating MCS and terminating in a ground flash some tens of kilometers rearward relative to the convective line (Mazur et al. 1998; Stolzenburg et al. 1998; Carey et al. 2005 make similar observations). Also, the authors could do a better job of explaining why they used WSR-88D mesocyclone data instead of ground truth to shift the tornado touchdown times (sixth paragraph in Section 3b).

We made major organizational changes overall to the paper. We now have an introduction. Section 2 discusses the 3 lightning systems (CG...LDAR...LISDAD). Section 3 discusses "Operational Applications" and we have subsections for a) Pulse severe and supercells, b)TC mini-supercell[s], c) bolts from the blue,

and d) forecast products. Section 4 discusses other NWS studies related to total lightning (as per request of another reviewer). Section 5 summarizes the work.

LISDAD actually continued on a MLB for an additional year (1999), however, to the best of my knowledge, NWS MLB staff were not active in analyzing any of the data on a day to day basis as they did during the 1996–1998 time frame. The LISDAD system during this year just collected data that the MIT folks analyzed. To the best of my knowledge, none of the 1999 data which was collected has ever been published formally.

Regarding the bolt from the blue, it will never be known if this was a true "bolt from the blue" as we defined it in our paper or a flash in which you describe. However, from a public perspective, it was a "bolt from the blue" flash. From my recollection, I immediately went outside after this flash occurred and it was pretty clear overhead. Additionally, the flash occurred relatively early in the day (315 pm local Florida time), the boundary was moving westward and there was not a dense cirrus canopy overhead. If it were late in the day in which cirrus covered a large part of the Florida peninsula, I could buy your argument, but given the time of the day and movement of the cells, I would believe there is enough evidence that this was a true "bolt from the blue" case. I only wish that KMLB was not out of service on this date, as this would have helped in defining the radar reflectivity better.

Regarding the mesocyclone locations, we have discussed this in much more detail in 3b. In matter of fact, this section has been extensively re-written and the figures have been made larger (as per the request of another reviewer).

[Minor comments omitted...no second review]

REVIEWER B (Ronald L. Holle):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

General comments: I have reviewed the paper, "Early history of using total lightning data in NWS operations" by Hodanish et al. for publication in the Electronic Journal of Severe Storms Meteorology. This paper summarizes the first years of the use of total lightning data in an operational NWS setting. Since total lightning data have grown to become a more common tool in the meteorological community, it is useful to identify where, when, and how the early efforts developed. This paper synthesizes the various early approaches that are mostly available only in conference preprints, as indicated in the reference list. In general, the paper flows well through time, with benchmark figures and references along the way. Some more general, as well as technical comments are provided below with regard to clarification of text and figures.

Substantive comments: During the period of this review, GAI was the company that operated the National Lightning Detection Network (not Data Network) in Tucson, AZ, not Melbourne.

As per our private email around 20 January 2013, ARSI was the company that ran the LPATs lightning detection system which NWS MLB first used in 1999. This information is briefly discussed in the Introduction and more extensively in section 2a.

The idea of Storm Data being incorrect may or may not be appropriate, but the logic is not very complete. Is the opinion based only on the radar data? If so, is this a typical assumption of how tornado tracks should relate to radar in tropical cyclones? A little more explanation would be helpful here.

I have added an explanation, and have extensively re-written the section discussing total lightning associated with tropical cyclone (TC) tornadic mini-supercell. It is now section 3b.

The idea that cells with total lightning indicate stronger updrafts in a tropical cyclone situation is an important positive result of this paper. It could be added to the abstract and the conclusions.

It has been added to the abstract and the conclusion. Note that since I added this additional info about TCs in the abstract, I had to mention brief significant findings of supercellular convection (large flash rates) and pulse-severe convection (lightning jumps) to the abstract.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General comments: This is a second review of the paper, "Early history of using total lightning data at NWS Melbourne Florida" by Hodanish et al. for publication in the Electronic Journal of Severe Storms Meteorology. The paper has been significantly improved by the authors' responses to the first set of reviews. The additions of a substantive introduction and a review of recent research have given a more complete context of total lightning's early operational use. A few mainly minor comments, as follows, should be addressed. Once those are resolved, I don't need to see the paper again.

The full effort of the authors is appreciated for responding to the reviews. The following are particularly good new or revised sections [*page numbers omitted due to subsequent changes from editing*]:
- A concise overview of the paper in one place.
- One of the major points in operational use was how a forecaster used the data when other information was inconclusive.
- The definition of bolt from the blue is good to have.
- A useful description of the transition from a lightning storm to a severe storm.

[Minor comments omitted...]

REVIEWER C (Geoffrey T. Stano):

Initial Review:

Reviewer recommendation: Accept with major revisions.

Substantive comments: Although this is an historical account of the early LDAR usage, the authors are recommended to include brief comments on where total lightning usage is today in the appropriate sections. There is a strong link between the early and current work. Including these comments will demonstrate that the examples and efforts described in the manuscript were not one-off activities. Suggested locations are listed in the comments below.

This has been done. However, we decided it best if we simply include a new section towards the end of the paper. By doing this, we keep the paper in chronological order. This new information is now in section 4, titled, "Operationally oriented studies of total lightning: 1999–2012". In this new section, we stressed how total lightning activity has improved NWS operations since ~2000 to present. [W]e also discuss the relevancy of "lightning jumps", lightning jump algorithm developments and how this all relates to the GOES R launch in October 2015 (Goodman–personal communication).

2) Section 1b: This provides good background material on the origin of the LDAR network. The second paragraph discusses the AMU collaborating with NWS Melbourne to provide an LDAR display system in operations. Did the initial collaboration with the NWS Melbourne office also include activities with the 45th Weather Squadron as they also benefited from the installation of an LDAR display system? It appears that the timeline for the Weather Squadron receiving LDAR data was later than NWS Melbourne. If this

was a more coincident activity, adding additional detail of the NWS Melbourne / 45th Weather Squadron interactions would provide an interesting historical perspective.

I emailed Dave Sharp who was the SOO (and still is) at NWS MLB during the time of the study. He wrote back and stated, "As I recall, formal interactions with the 45WS regarding LDAR use was not overly widespread. There were common interests, to be sure. They were very interested in supporting their lightning watches/warnings and we were very interested in the severe storm detection capacity. Through the AMU, there were tasks to deal with the data volume (early days of confined bandwidth) and also to provide cursory training to operators." I also do not remember working closely with the 45th with respect to the LDAR system. Although we both had forecast responsibilities, their responsibilities were more space-mission related while ours was public related. In a nutshell, we shared the data feed from the LDAR from the KSC, but we used the data differently and independently from each other.

3) Section 1c: Item two in the primary objectives of LISDAD references satellite-based lightning detection. This is a major point that is not referenced again until the final sentence of the summary section and warrants a brief link to current activities.

This point regarding the satellite based system has been mentioned in the last paragraph in the new section 4. It is also mentioned again at the end of the summary (section 5).

General comment: Several events in the manuscript highlight maximum IC flash rates >500 flashes min^{-1}. These are massive values compared to most other studies, although Williams et al. (1999) does describe storms >300 flashes min^{-1} and such flash rates have been observed with other ground and satellite observations. For additional context for the reader, a short discussion of how singletons, the flash algorithm, and the LDAR's own detection efficiency may affect the flash rate is recommended. The underlying results (lightning jumps) are not disputed but the specific flash rate values stand out.

First…singletons affecting flash rate: we increased the discussion regarding singletons in the document. It is under section 2c, specifically the 3rd, 4th and 5th paragraphs. The singletons accounted for about 12% of all flashes as measured by the LISDAD (Bob Boldi, personal communication). We should note that singleton detection was dependent on the distance away from the LDAR unit (see images below). However, we did not believe this was critical to mention in the paper, and likewise it was not mentioned. If you believe we need to mention this in the paper, we will be more than happy to oblige.
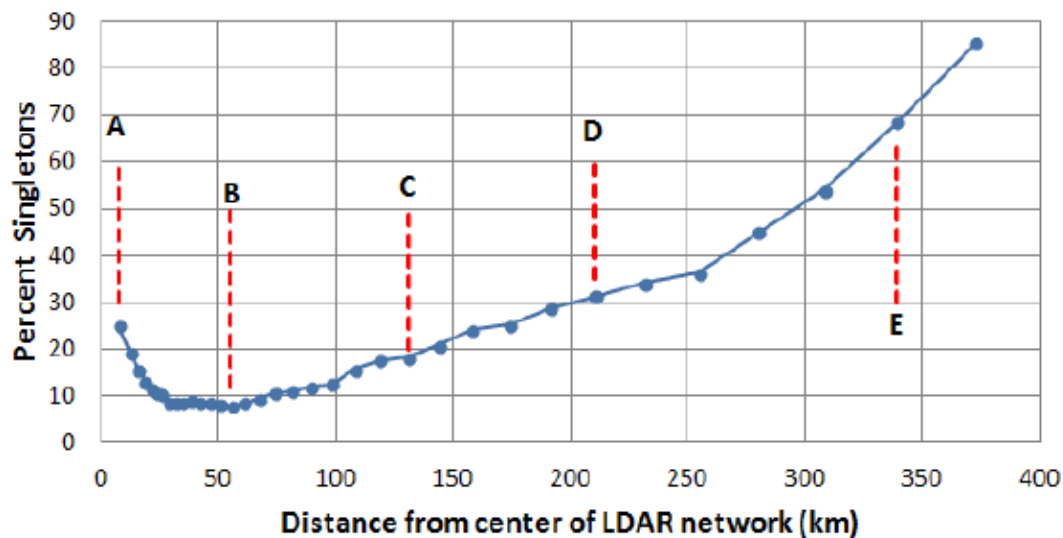
The image above shows percentage of singletons vs. distance from LDAR network. Note that the KSC LDAR unit back in the 1990s could detect flashes >350 km distant! From a LISDAD perspective, data within 150 km was more realistically used. Note that in Fig. 5 in our updated paper, the storm that was producing the very high flash rates was 103 km from the LDAR network. At this time the storm was producing about 400 flashes min^{-1}. Given the image above, about 12% of the flashes were "singletons". Also note that the "A", "B", "C", "D" and "E" in the image above are related to the individual storms shown immediately below.
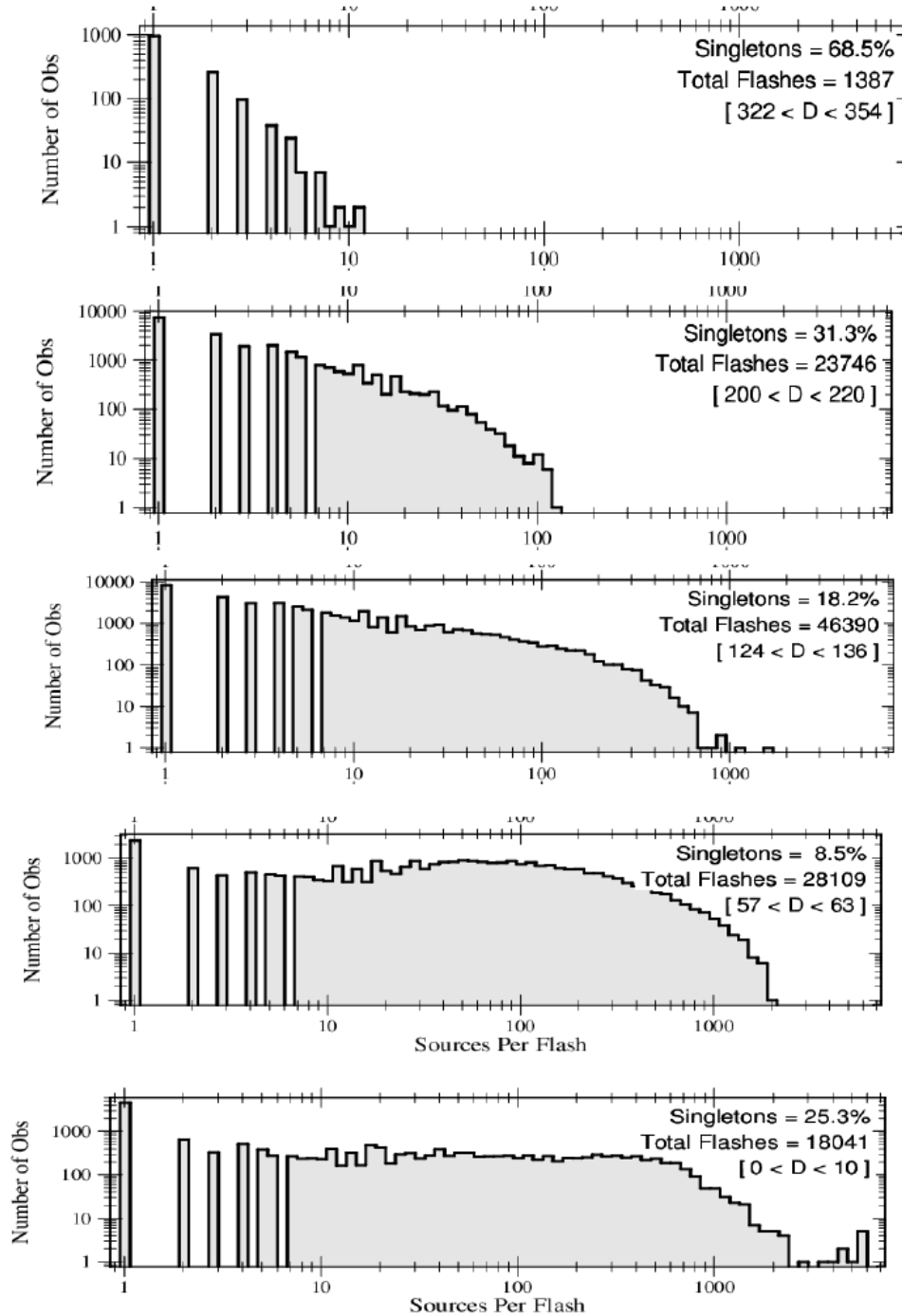
Second…algorithms affecting flash rate: we also discuss this issue in section 2c. In the LISDAD at NWS MLB, the LL/MIT "fixed D" time-space association algorithm was used during the 3 years in which LISDAD was at NWS MLB. This algorithm was relatively simple, but compared to other algorithms used in the Williams 2000 paper, it had a tendency to show relatively high flash rates. A modified LL/MIT algorith which has a variable distance (variable 'D') showed about 50% fewer flashes. The reason for the high flash rates was primarily due to the increasing error with distance of the LDAR source points ("radially smearing"). This smearing is less noticeable on todays LDAR II units due to increased distance between the sensors.

Third…LDAR detection efficiency affecting flash rates: this one was a bit tougher. I could not find anything in the literature that discussed in detail on how the effeciency decreases with range. Several papers mention it decreases systematically with range (e.g., Williams 2000), but none give specific details. Lennon and Maier (1991) discusses accuracy near the LDAR system ("X and Y 30 meters, Z 90 meters"), but for accuracy "outside the network", they gave a simple equation $D^{2/6}$. I really did not understand how this equation related to accuracy with distance. What I did do is I added the following text to section 2b, paragraph 1: "Location error of the LDAR point sources over the KSC is in the order of 100 ms, but this error increases systematically ('radial smearing') with range."

The initial discussion of "lightning jumps" is significant. This concept has evolved to become a cornerstone of total lightning applications and is under review by NOAA to be tested as an operational algorithm. Recommend briefly including current relevance of "lightning jumps."

We have added significantly more on lightning jumps in section 4. Numerous other studies related to lightning jumps since 1999 have been discussed in section 4.

Orville climatologies are good supporting references to Hodanish et al. (1997).

I believe the climatologies you are talking about are the climatologies Dr. Orville did for each NWS Offices in the OCONUS. Unfortunately, this material was never written up in an informal or formal document. To the best of my knowledge, there is no way I can reference this material. If you are aware of other Orville work that could complement Hodanish et al. (1997), please let me know.

LDAR's sub-radar temporal update is very significant. Recommend additional sentence or two explaining how this is useful to an operational forecaster.

This has been done, and is the last paragraph in section 3a.

Similar to several of the above comments, a couple sentences describing how the ELISE project has evolved to the current day would be good.

This has been done and is discussed in the last paragraph in section 3d.

This is related to comment 3 above in that the satellite component of these activities is the next major change for operational total lightning activities. The expanded discussion should remain in section 1.c., but also include GOES-R and the Geostationary Lightning Mapper. This will prevent adding new information in the summary.

As was discussed above in the very beginning, we decided to create a new section (section 4) to include all total lightning activities from 1999 to current. In this new section we discussed the GOES R activities (See the last paragraph in section 4. We also mention this in the conclusion.).

[Minor comments omitted...]

Dr. Stano, thank you for taking the time to review the paper, it is appreciated.

Second review:

Recommendation: Accept with minor revisions.

General comments: The authors have taken the time and effort to include the four major revisions (listed as A, B, C, and D in the authors' response) to the content and organization of the paper. The major push for the introduction and the new section 4 have done two things: improve the organization and provide context for why the early work at NWS Melbourne still has relevance to total lightning applications today. This provides additional purpose for discussing the use of these data at NWS Melbourne in the mid-1990s.

After having the opportunity to see the other reviews, I went back to fully review Hodanish (1996). Conceptually Hodanish (1996) and the manuscript under review do focus on the same issue of how lightning data were used operationally. The reviewer raised a legitimate point and I wanted to look at the comparison in more detail. I do feel that the authors have taken steps to address these concerns. Also, this effort is working to release the content into the peer reviewed realm. The current manuscript does differentiate itself with the discussions on the use of LISDAD (as per the authors' comments) and does include more detailed discussions of operational utility versus Hodanish (1996), which had more generalized results. I believe the historical significance of these activities, when compared to current activities, further helps this revised version of the manuscript.

What has impressed me the most with reading about LISDAD is that some of the capabilities available with LISDAD are only now being re-introduced with AWIPS II efforts.

Substantive comments: *[Review-embedded reposting of round-1 replies above is omitted for space considerations…]*

Thank you for the details [on LDAR] and the discussion in section 2b. With the change of the title to focus specifically on NWS Melbourne, the level of detail presented in section 2b is good. The original title left the discussion open to include more than NWS Melbourne, which drove my original questions about other partners with NWS Melbourne.

The inclusion in section 4 is good as it presents the new topic outside of the summary in section 5. The discussions serve as a good opportunity to bridge the initial work at NWS Melbourne to how these will be applied with the future NWS capabilities once the Geostationary Lightning Mapper is launched.

Discussion of singletons, flash algorithms, and detection efficiency:
I appreciate the approach you took with the edits, and the effort to address the concerns as my initial comments were wandering into the weeds. I think it was important to address some of the systematic reasons for understanding the various flash rate magnitudes. Overall, I think the revised manuscript gets the right balance by discussing the details without turning the paper into an evaluation of flash algorithms. My early concern was that singletons were dominating the results, but Bob Boldi's response discounts this. The LISDAD fixed distance parameter, as you indicate, is a strong explanation given the original LDAR had more radial smearing than the current LDAR II or lightning mapping arrays. I did like the comparison to Williams et al. (2000) as it demonstrates some differences in the flash algorithms, but the main take-away of the high flash rate magnitude remains.

I like your own reference (Hodanish et al. 1997) as it relates specifically to the Florida peninsula and covers monthly climatologies. The main references that came to mind were Orville and Huffines (2001) and Orville et al. (2011), so I feel I was less specific with my comment than I should have been. While not as specific to the NWS Melbourne region as Hodanish et al. (1997), the two references by Dr. Orville reinforce the magnitude of cloud-to-ground lightning over the peninsula both during the time period of your manuscript as well as more recently.

Orville, R. E., and G. R. Huffines, 2001: Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98. *Mon. Wea. Rev.*, **129**, 1179–1193.

Orville, R. E., G. R. Huffines, W. R. Burrows, and K. L. Cummins, 2011: The North American Lightning Detection Network (NALDN)—Analysis of flash data: 2001–09. *Mon. Wea. Rev.*, **139**, 1305–1322. doi: http://dx.doi.org/10.1175/2010MWR3422.1.

I have added these references to the paper. They are cited at the beginning of the Introduction.

I have no further substantive reviews as my previous concerns were addressed and the response to the other reviewers has resulted in an improved layout and organization.

[Minor comments omitted...]

Thank you for the opportunity to review the manuscript and for raising several interesting discussion points during the review process.

You are welcome.