Melick, C.J, A.R. Dean, J.L. Guyer, and I.L. Jirak: Cloud Flash Lightning Characteristics for Tornadoes without Cloud-to-Ground Lightning. Preprints, *41st Natl. Wea. Assoc. Annual Meeting*, Norfolk, VA, Natl. Wea. Assoc.

Cloud Flash Lightning Characteristics for Tornadoes without Cloud-to-Ground Lightning

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ABSTRACT

The Storm Prediction Center (SPC) has traditionally utilized cloud-to-ground (CG) lightning to identify thunderstorm development and the potential for severe weather occurrence. Still, recent evidence has shown that tornadoes do sometimes occur in situations where CG flashes are absent. In the last few years, cloud flash (CF) data as part of total (CG + CF) lightning has been available at SPC from the Earth Networks Total Lightning Network (ENTLN). The current study examined United States tornado events that were not associated with CG lightning for the time period during which CF lightning data were available. The purpose of this examination was to provide some basic characteristics and environmental conditions of no-CG tornado reports with an emphasis on the relationship to CF activity using lightning data from the ENTLN.

CG lightning was absent in about 2% (66) of all tornadoes during a three year period (2013-2015) with a significant portion of these rated as EF0. Unexpectedly, though, only 17% (11) of no-CG tornado reports occurred with CF, thus implying that total lightning was often lacking in these tornadic storms as well. Most events were confined east of the Rocky Mountains with a tendency of EF1+ tornadoes and/or those reports with one or more CF ("Just CF") to occur in the southeastern part of the United States. Furthermore, "Just CF" tornado reports usually developed in the late afternoon hours and tend to be favored in the winter and summer whereas those no-CG events without CF lightning exhibit a more even distribution from spring to fall. As for longevity, results presented here suggested that tornadoes without CG, and even more so without any total lightning, tend to be shorter-lived with shorter paths compared to all 2,806 tornado reports from 2013-2015. Based on the evaluation of four instability parameters, environments of no-CG tornado reports were often less conducive for convection and severe weather compared to all tornadoes.

1. Introduction and Background

Observations are utilized heavily by the NWS Storm Prediction Center (SPC) for many of their short-term forecast products. For instance, near real-time analysis of lightning flashes in conjunction with severe storm reports can aid in the issuance of tornado watches by documenting the occurrence of convective initiation and trends in thunderstorm activity. This relationship in storm intensity is generally common as deep, robust convective updrafts are necessary for lightning production and often the development of severe thunderstorms capable of producing tornadoes. Still, recent work by Guyer and Dean (2015) has shown that tornadoes can occur infrequently without any cloud-to-ground (CG) lightning present. For instance, they found a lack of CG flashes from Vaisala's National Lightning Detection Network (NLDN) in about 2% of all tornado reports based on a ten-year period [2005-14] from *Storm Data*. Other studies (e.g., Schultz et al. 2011, Melick et al. 2015) have also documented severe weather occurrence (which is defined by the NWS to also include hail ≥ 1" in

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diameter and straight line winds gusts ≥ 50 kt) in the absence of CG flashes.

The climatology and environmental conditions of nearly 300 no-CG tornadoes across the contiguous United States were examined in Guyer and Dean (2015). They found that while buoyancy tended to be weak (MLCAPE < 500 J/kg) compared to all tornadoes, other near storm environment parameters were similar. Consistent with the somewhat limited instability, no-CG tornadoes were relatively favored over the full tornado climatology to occur more frequently in the cool season and during the morning and early afternoon part of the day. While most of these events were weak and short-lived, Guyer and Dean (2015) highlighted an EF2 tornado without CG flashes that struck parts of Valdosta, Georgia, on 29 December 2014. However, their study did not examine total lightning activity, through the inclusion of cloud flashes (CF).

A more complete viewpoint of examining all electrical activity within severe storms through incorporating total lightning [CG + CF] datasets can be justified for a couple of reasons. In terms of actual counts, the CG portion is predominantly small when compared with CF. Furthermore, and more importantly, CF flashes often precede CG flashes in identifying convective initiation (MacGorman and Rust 1998). Thus, the current study builds upon the work of Guyer and Dean (2015) by examining United States tornado events that were not associated with CG lightning but for which CF lightning data was available from 2013-2015. The purpose of this examination is to provide some basic characteristics and environmental conditions of no-CG tornado reports but with an emphasis on the relationship to CF activity.

2. Data

a.) Lightning and Tornado Reports

SPC has used CG flashes from lightning detection networks over the last 30 years to monitor ongoing convective systems (Bothwell 2014). During that period, real-time data access has been primarily limited to the NLDN data from Vaisala. The recent availability of total lightning offers a unique perspective on electrical activity in thunderstorms. For SPC, the acquisition of total lightning data occurred by late 2012 from the Earth Networks Total Lightning Network (ENTLN). As with any new dataset, though, the usefulness of CF characteristics is still needed in forecaster training, particularly with how the data aids in the diagnosis of severe convective storms related to severe weather.

For the current work, the ENTLN was utilized as the focus for documenting the occurrence of no-CG tornadoes for consistency with using CF from the same network. Tornado reports that matched CF lightning availability from a three-year period (2013-2015) were collected from the SPC "ONETOR" database, which is based upon the official record from *Storm Data* produced by the National Centers for Environmental Information (NCEI). In addition to location and start time for each tornado, additional useful information including EF-ratings, path lengths, duration, and number of deaths were available for examination. Only tornadoes after 4 June 2013 were retained owing to a major upgrade in the ENTLN, thereby effectively reducing the sample size to 2,806 tornado reports.

b.) SPC Environmental Database

The process of matching lightning characteristics with tornado occurrence was accomplished using the SPC environmental database (Schneider and Dean 2008), which contains severe storm events and environmental parameters derived from hourly, 40-km mesoanalysis grids (Bothwell et al. 2002). For the mesoanalysis grids generated routinely at SPC, surface METAR observations are merged with a short-term surface/upper-air analysis from the Rapid Refresh model (Benjamin et al. 2016). In recent years, this framework has served to facilitate several climatological studies (e.g., Edwards et al. 2012; Guyer and Dean 2015; Smith et al. 2012; Thompson et al. 2012) on the relation of severe-weather environmental fields to other observational data types (e.g., radar analyses for diagnosing convective mode; lightning). Given that prior investigations were restricted to NLDN CG flashes, the SPC environmental database was updated here with total lightning information acquired from the ENTLN.

3. Methodology

Tornado reports were matched to ENTLN lightning data from hourly CG and CF counts for the 40-km grid box containing the tornado report.

Then, gridded values of parameters related to assessing convective potential were extracted from the SPC environmental database for each of the 2,806 observational records. In order to highlight the importance of CF, subset datasets from all of the tornado reports were subsequently constructed by separating instances where hourly CG flash tallies were zero and one or more CF occurred from those cases where total lightning was absent (i.e. CG+CF was set to zero). As a result, this allowed an examination of environments of No-CG tornado reports with CF (hereafter referred to "Just CF") to those without CF (hereafter referred to "No Lightning").

In this "grid point" approach, though, lightning activity is required to be nearly coincident with severe weather occurrence and would therefore discount nearby-related CG flashes. Thus, a separate analysis was conducted to ensure that no CG lightning occurred in spatiotemporal proximity to the tornado-producing storm. Following the methodology pursued in Guyer and Dean (2015), this more realistic perspective was obtained by applying a four-hour temporal window (1 hour prior to the analysis hour to 2 hours after the analysis hour) surrounding the tornado report in addition to a 3x3 neighborhood grid (120 km x 120 km). Because of the relatively broad spatiotemporal matching criteria, the above methodology likely underestimates the actual number of tornadoes that occurred with an absence of CG lightning.

4. Results

a.) No-CG Tornadoes: Grid Point vs Neighborhood

From the 2,806 tornado reports retained in this study, Table 1 shows there were 240 (~9% of sample size) events which had no-CG lightning within the grid box. That count dropped to only 66 (~2% of sample size) when applying the spatiotemporal neighborhood approach. This difference in the event definition was further explored by examining those 174 cases which indicated an absence of CG at the grid point but with CG present nearby. In this perspective, Fig. 1 reveals a wide distribution in lightning occurring in close proximity to the tornado report as the interquartile range was nearly 100 CG flashes with a median count of 29. Given that the nearby activity was not isolated enough to ignore, the authors feel that the neighborhood concept provides a more accurate portrayal of tornadoes that have no CG lightning present. While a more rigorous classification perhaps using radar analyses might change the results somewhat, the sample size would still remain relatively low considering the limited time period of available ENTLN data for investigation.

Table 1. Counts of ENTLN no-CG tornado reports based on *Storm Data* and corresponding relative percentage of sample sizes from 2013-2015 using grid point and spatiotemporal neighborhood methods. The last row represents the difference between the grid point and neighborhood totals.

Report Count Type: Grid Point vs. Neighborhood for ENTLN	Counts (Percentage)
No-CG Grid Point	240 (~9%)
No-CG Neighborhood	66 (~2%)
No-CG Grid Point but CG Neighborhood	174(~6%)

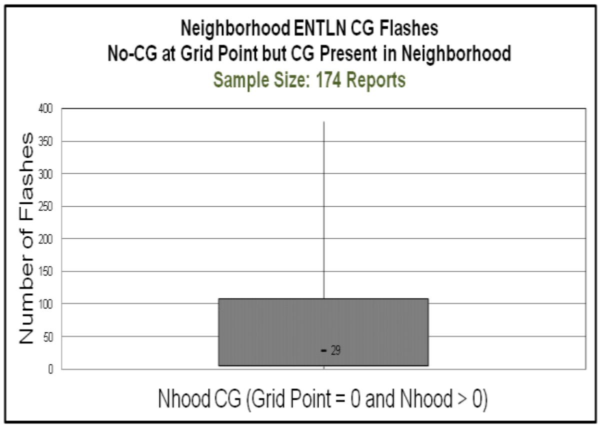

Figure 1: Box-and-whisker plot for counts of ENTLN CG flashes using the spatiotemporal neighborhood approach for *Storm Data* tornado reports from 2013-2015 when there were CG flashes nearby but none present at the grid point. The whiskers represent the 10th and 90th percentiles of the distribution and the sample size represents 174 tornado reports.

b.) Basic Characteristics Relative to CF Presence

Only 17% (i.e., 11 events) of the neighborhood no-CG (ENTLN) tornadoes occurred with CF implying that if CG flashes are absent, then total lightning is often absent as well. Specifically, ranked CF counts shown in Fig. 2 also highlights isolated CF activity (1-2 flashes) nearby in a majority of those rare reports with counts of more than 10 CF only occurring in three separate episodes. The most active event (38 CFs) occurred with an isolated, EF0 tornado on 23 February 2015. Actually, a breakdown of all neighborhood no-CG tornadoes by EF rating (Fig. 3) reveals a high proportion (i.e. 76%) are of the weakest variety (EF0), similar to what was observed by Guyer and Dean (2015). Beyond that, though, the distribution tails off substantially with the EF1 and EF2 categories representing 21% and 3% (2 reports) of the remaining sample size, respectively. Over the course of the short time period examined from 2013-2015, no EF3-EF5 tornadoes occurred when CG lightning was not present nearby.

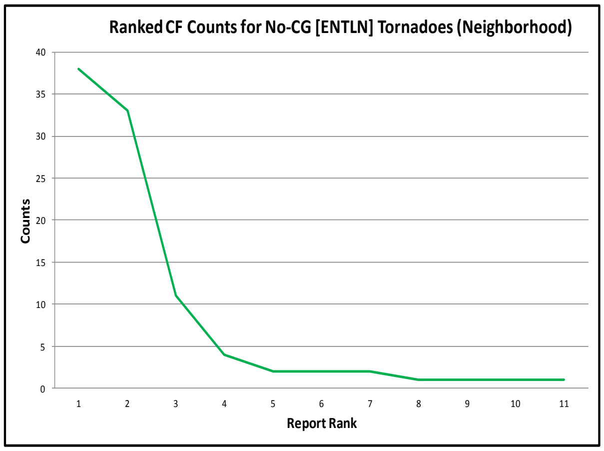

Figure 2: Ranked ENTLN CF counts for no-CG tornadoes using the spatiotemporal neighborhood approach. Only reports with one or more CF (i.e., 11 events) were included in the plot.

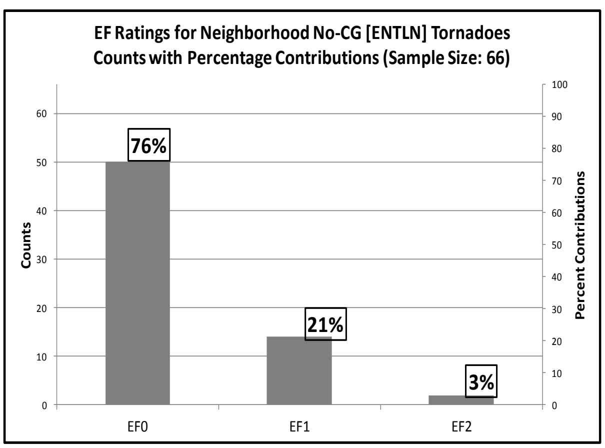

Figure 3: Counts for EF tornado ratings for neighborhood no-CG (ENTLN) tornado reports. Percentage contributions relative to a sample size of 66 are also provided on the plot.

For the current work, it was also of interest to understand differences in tornado ratings when CFs were present. For this purpose, Fig. 4 displays relative percentages for subsets of no-CG tornadoes based on whether the reports were classified into the EF0 or EF1 or greater (EF1+) categories. EF ratings appeared to have minimal impact as the "Just CF" grouping occurred about as rarely (~15-20%) in either case. In terms of a spatial pattern, neighborhood no-CG tornadoes (Fig. 5) were spread across the contiguous United States with most occurring east of the Rocky Mountains. In addition, partitioning of the dataset further revealed that EF1+ tornadoes and/or those reports with "Just CF" tend to be found in the southeastern part of the country (Fig. 5).

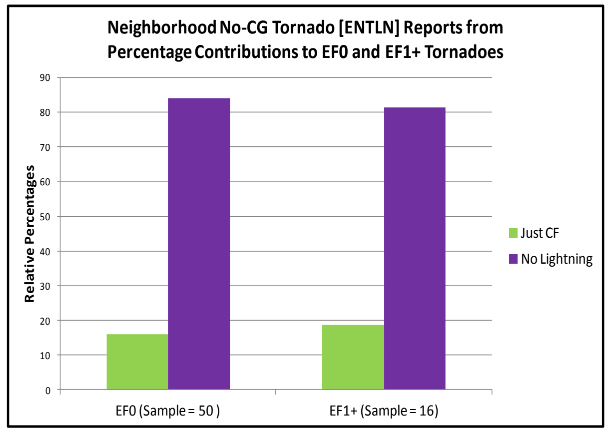

Figure 4: Relative percentages for subsets of neighborhood no-CG (ENTLN) tornadoes ("Just CF" and "No Lightning") based on whether the reports were classified into the EF0 or EF1 or greater (EF1+) categories. The sample sizes for EF0 and EF1+ groupings included 50 reports and 16 reports, respectively.

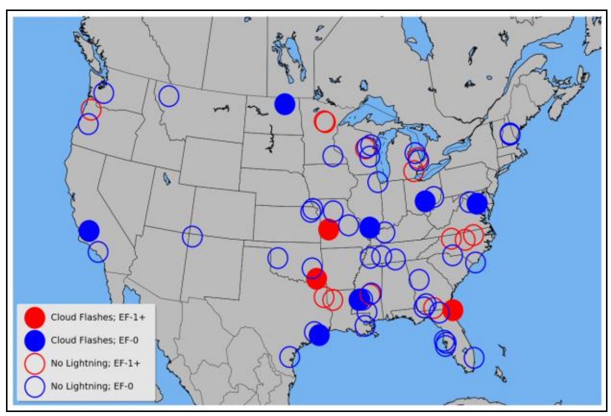

Figure 5: Spatial plot for the 66 neighborhood no-CG (ENTLN) tornadoes with the legend in bottom-left corner representing breakdowns for EF ratings (EF0 or EF1+) and whether or not CF ("Just CF" or "No Lightning") occurred.

For the purpose of providing diurnal trend characteristics, the data were binned every three hours and then relative percentages to the total tornado report counts were computed for each time period (Fig. 6). The "Just CF" subset mainly occurred in the late afternoon with no activity during the late evening to early morning hours (i.e. 03-15 UTC). Of course, it should be acknowledged that this finding is only preliminary (and inconclusive) as a percentage value of slightly over 50% between 21-00 UTC (Fig. 6) translates to only 6 events. In contrast, there was much greater spread over the course of the day in the 55 "No Lightning" events with a peak in the late afternoon. As for intra-annual influences, separate results similar to the diurnal analysis were also obtained for each of the three-month combinations representing the four meteorological seasons (Fig. 7). In comparing the relative percentages from the two subsets of neighborhood no-CG tornadoes, the "Just CF" reports tend to be favored in the winter and summer whereas the "No Lightning" events exhibit a more even distribution from spring to fall.

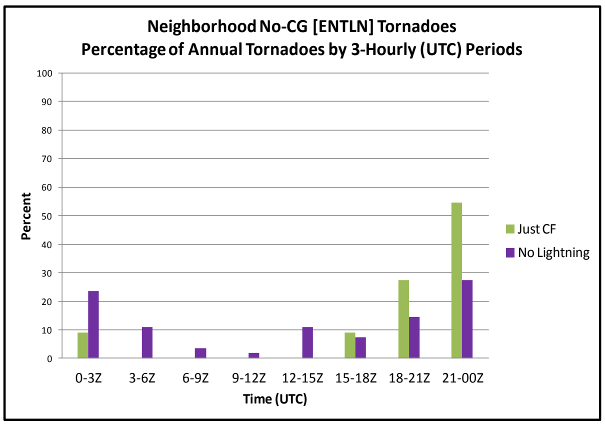

Figure 6: Percentage for subsets of neighborhood no-CG (ENTLN) tornadoes ("Just CF" and "No Lightning") by 3-hourly (UTC) time periods.

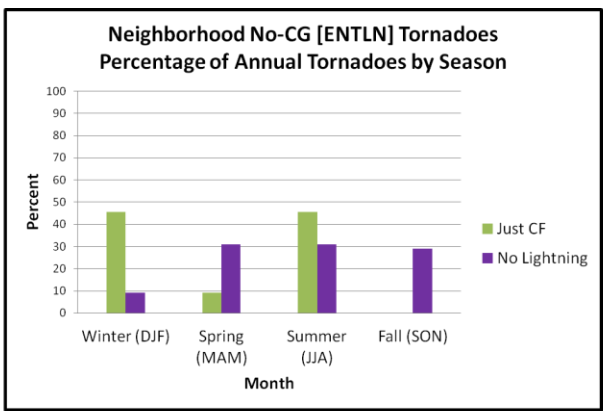

Figure 7: Same as in Fig. 6 except for breakdown by all four seasons.

Consideration was also given to investigating the longevity for those tornadoes where lightning was absent when evaluated against the entire 2013-2015 dataset. To this end, Fig. 8 provides the distribution for the number of minutes the event lasted for all tornadoes as well as for the "Just CF" and "No Lightning" report groupings. This diagnosis suggests that all three datasets are more similar than different given the sufficient overlap in the corresponding percentile values. Still, a more limited interquartile range was noted for the "No Lightning" results with fewer longer-duration tornadoes. For instance, the tornado would usually only persist for a couple of minutes (e.g., median durations in Fig. 8) regardless of lightning occurrence but would be less likely to continue longer than 5 minutes with no lightning.

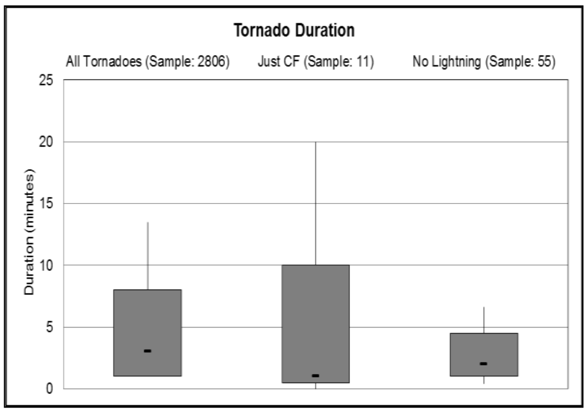

Figure 8: Box-and-whisker plot of tornado duration (in minutes) for all tornadoes compared to subsets of neighborhood no-CG (ENTLN) tornado reports ("Just CF" and "No Lightning"). The sample sizes for the separate groupings are given in parentheses. The tails represent the 10^{th} and 90^{th} percentile rankings.

Correspondingly, tornado path lengths were also explored here by producing box and whiskers plots (Fig. 9). Once again, this assessment resembled that for tornado longevity except that the distribution was even more limited on the lower end of distances traversed for the "No Lightning" events. In particular, results greater than one mile were less common compared to the "Just CF" and "All Tornadoes" datasets (e.g., 75^{th} percentiles in Fig. 9). Thus, there is evidence that tornadoes without any total lightning tend to be brief and have shorter path lengths.

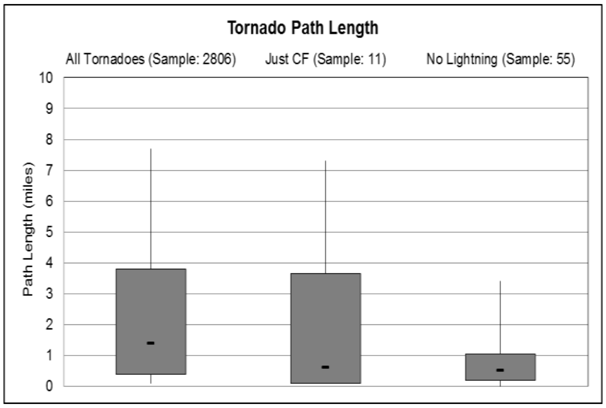

Figure 9: Same as in Fig. 8 except for tornado path length (in miles).

c.) Environment Characteristics Relative to CF Presence

A series of box and whisker plots were created to represent a few of the environmental parameter fields of interest to convection and severe weather. First, a comparison of Significant Tornado Parameter (STP – Thompson et al. 2004; 2012) suggested an environment much less conducive for severe weather for no-CG events compared to all tornadoes (Fig. 10), analogous to the findings in Guyer and Dean (2015). Furthermore, Fig. 10 also revealed similar distributions between "Just CF" and "No Lightning" subsets with STP values substantially less than 1. This assessment agrees with the fact that EF2 ratings only made up 3% of no-CG tornadoes (Fig. 3) whereas the much larger collection (2806) of all reports included a greater portion (~11%) of significant tornadoes (EF2+). Likewise, the diagnosis from Fig. 11 showed that about 75% of the events had MLCAPE values less (greater) than 500 J/kg for no-CG (all) tornado reports. Again, results for both "Just CF" and "No Lightning" datasets were similar.

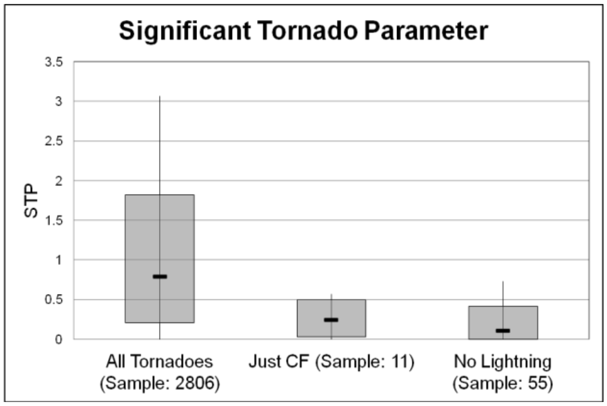

Figure 10: Same as in Fig. 8 except for matched values of Significant Tornado Parameter obtained from the SPC Environmental Database.

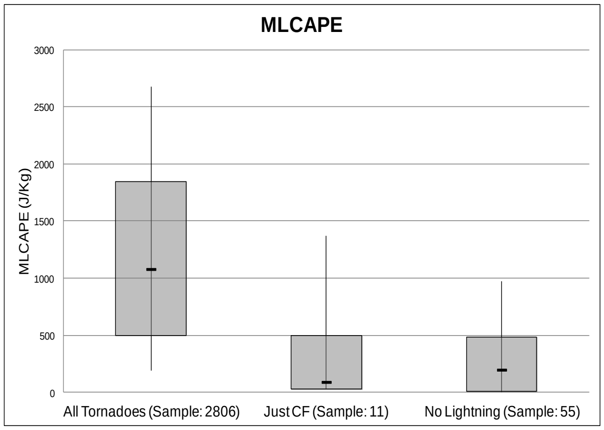

Figure 11: Same as in Fig. 8 except for matched values of MLCAPE (in J/Kg) obtained from the SPC Environmental Database.

Storm-relative helicity (SRH) was also analyzed for the tornadic events (Fig. 12). Although better overlap in SRH values was evident between the datasets, the environment was less favorable for rotating updrafts in no-CG tornado reports compared to all tornadoes. Also, the comparison of the no-CG tornado subsets in Fig. 12 suggested comparable results between the two. To round off the evaluation, the potential for mixed-phase hydrometeors and charge separation was explored by utilizing equilibrium level (EL) temperature. As can be seen in Fig. 13, EL temperatures overall were much warmer in no-CG events than all tornado events, indicating shallower convective storms. While the presence of CF favored slightly lower EL temperatures with higher percentiles than no-lightning events, the differences were overall minor especially taking into account the small sample sizes.

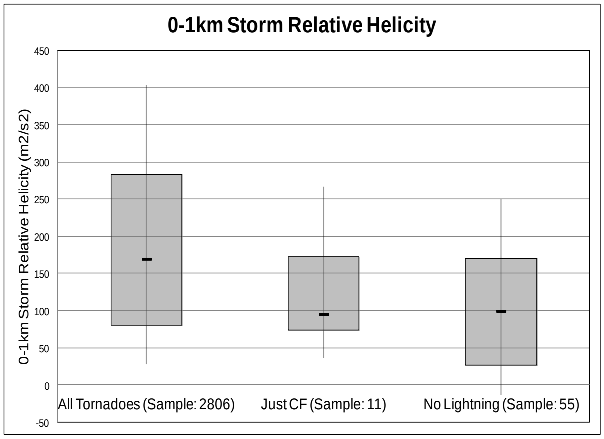

Figure 12: Same as in Fig. 8 except for matched values of 0-1km Storm Relative Helicity (in m^2/s^2) obtained from the SPC Environmental Database.

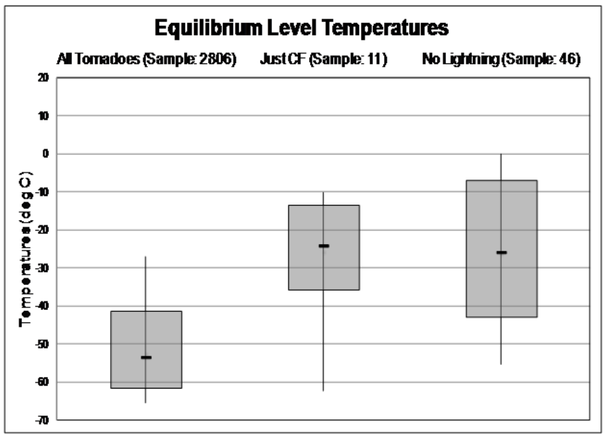

Figure 13: Same as in Fig. 8 except for matched values of Equilibrium Level Temperature (in degrees C) obtained from the SPC Environmental Database. The reduced sample size from 55 to 46 for the "No Lightning" dataset was the result of CAPE being set to zero for 9 reports.

5. Summary and Conclusions

SPC has long utilized CG lightning to track the presence of thunderstorms and for documenting changes in intensity that might indicate an environment favorable for producing severe weather although tornadoes occasionally occur without CG flashes. Specifically, Guyer and Dean (2015) discovered no CG flashes in NLDN data for about 2% of all tornado reports based on a ten year period [2005-14] from *Storm Data*. While most of these events were weak and short-lived, Guyer and Dean (2015) provided evidence of an EF2 tornado that was not associated with any CG lightning in the vicinity leading up to or right after the event. Total lightning data, through the inclusion of CF, were not available for examination in that study. Thus, the current study examined CF lightning data available from the ENTLN for United States tornado events that were not associated with CG lightning. The purpose of this examination was to provide some basic characteristics and environmental conditions of no-CG tornado reports, similar to Guyer and Dean (2015), but with an emphasis on the relationship to CF activity.

CG lightning was absent in about 2% (66) of all tornadoes during a three year period (2013-2015) with a significant portion of these rated as EF0. Unexpectedly, though, only 17% (11) of no-CG tornado reports occurred with CF, revealing that total lightning was often lacking in these storms as well. Furthermore, even in those 11 rare tornadic events, CF counts showed only isolated activity (1-2 flashes) occurring nearby. Spatially, most no-CG tornadoes were confined east of the Rocky Mountains with a tendency of EF1+ tornadoes and/or those reports with "Just CF" to occur in the southeastern part of the United States. Other characteristics showed that "Just CF" tornado reports developed in the late afternoon hours and tend to be favored in the winter and summer whereas the "No Lightning" events exhibit a more even distribution from spring to fall. As for longevity, tornadoes without CG, and even more so without any total lightning, tend to be shorter-lived and cover shorter paths compared to all tornado reports from 2013-2015.

Based on the evaluation of four instability parameters, environments of no-CG tornado reports were often less conducive for convection and severe weather compared to all tornadoes, with STP and MLCAPE separation the greatest. For instance, about 75% of the MLCAPE distribution was less (greater) than 500 J/kg for no-CG (all) tornado reports. Consequently, STP values were often substantially less than 1 for both the "Just CF" and "No Lightning" subsets. Although better overlap in SRH values was evident between the datasets, the environment was less favorable to rotating updrafts in no-CG tornado reports compared to all tornadoes. Regularly, EL temperatures were less than -40 degrees C for all tornado reports with much warmer (shallower) cloud tops (depths) in no-CG events. While some caution should be taken with some of the conclusions offered considering the limited time period available for diagnosis of total lightning data, the authors feel this study provides a promising, initial insight into the importance of incorporating CF within research at SPC. In order to provide a more robust assessment, the current analysis will be updated to incorporate future years as total lightning data become available.

Acknowledgements. This extended abstract was prepared by Chris Melick with funding provided by NOAA/Office of Oceanic and Atmospheric Research under NOAA-University of Oklahoma Cooperative Agreement #NA11OAR4320072, U.S. Department of Commerce. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of NOAA or the U.S. Department of Commerce.

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