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Lightning Warnings with NLDN Cloud and Cloud-to-ground Lightning Data

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Abstract—**Previous studies [Holle and Demetriades, 2010; Murphy and Holle, 2008] have evaluated the performance of the U.S. National Lightning Detection Network (NLDN) with respect to warnings of cloud-to-ground lightning at specific locations such as airports. The statistics used to evaluate warning performance have included probability of detection (POD), false alarm ratio (FAR), duration of warnings, and number of storms reported. In 2013, the NLDN was upgraded to Vaisala's LS7002 sensors replacing the older generation LS7001 and IMPACT sensors. As a result of this upgrade, in addition to a cloud-to-ground flash detection efficiency of about 95% [Nag et al., 2011], a cloud flash detection efficiency of about 50% is expected for the NLDN. In this study, we examine the warning performance using cloud and cloud-to-ground data from the NLDN after the 2013 upgrade. Data from several regions of the continental U.S. are considered. The warning statistics are evaluated with and without cloud lightning data. The impact of varying outer radii, inner verification areas, and end-of-storm wait times are examined. Upon conclusion of the study, it was found that addition of NLDN cloud lightning added about 10% to the POD, while the FAR was unchanged, and the percent time under valid warning and false alarms increased somewhat. As found previously, a 15-minute warning expiration time was better than 10 minutes, and POD decreased steadily for longer lead times. POD increased steadily for larger outer radii, but FAR also increased. Finally, short exploration of a smaller warning area showed better warning statistics, but there was significant sensitivity to the relative size of the inner versus outer areas.**

Keywords—Lightning safety; airport lightning warnings, cloud-to-ground and cloud lightning warnings.

I. Introduction

A comparison was made of warnings for cloud-to-ground lightning at ten airports across the United States with and without cloud lightning data from the National Lightning Detection Network (NLDN). Over the years, characteristics of the NLDN have been discussed and evaluated [Jerauld et al., 2005; Cummins and Murphy, 2009; Nag et al., 2011]. In 2013, the NLDN underwent a network-wide upgrade as a result of which the capability of the NLDN to detect cloud pulses has increased from a detection efficiency (DE) of between 15 and 25% prior to 2013, to a DE of about 50% by late summer 2013 [Nag et al., 2013].

A series of studies has been conducted examining the capability of NLDN flashes, VHF total lightning mapping, field mills, and GLD360 events to anticipate cloud-to-ground (CG) lightning. A particular interest is to provide CG lightning warnings for airport ground operations [Holle and Demetriades, 2010].

There is one set of warning studies before, and another set after the development of a software package specifically for this purpose in the late 2000s. Prior to the availability of this software package, very limited LF cloud information in the Dallas-Fort Worth area provided a slight increase in probability of detection and reduction in false alarm ratio [Murphy and Holle, 2006a,b, Fig. 4].

Another study [Murphy and Holle, 2008; Murphy et al. 2008] focused on the value of field mills in warnings of CGs with KSC data during two summers. It was found that the addition of two KSC field mills to NLDN flashes made results somewhat worse than with NLDN flashes alone, at least for small Florida summer thunderstorms.

Additional studies used the analysis software package for warning analyses once it was developed. Various unpublished results focused on airport-scale warnings with NLDN CG flashes and VHF total lightning mapping data. Warning statistics for CG flash data and GLD360 strokes were compared at ten airports in the southeast U.S. [Holle and Demetriades, 2010].

None of the past NLDN analyses included LF cloud pulse information, and all of them used CG flashes rather than CG strokes. The analyses used CG flashes in an outer region to anticipate CG flashes in a smaller inner area such as an airport.

In the case of the GLD360 study [Holle and Demetriades, 2010], that network provides only stroke data, and current estimates are that 20% of the reported lightning events are cloud pulses rather than CG [Poelman et al., 2013; Pohjola and Mäkelä, 2013; Said et al., 2013]. However it is not possible at present to distinguish between CG and cloud data with GLD360.

The goal of this study is to anticipate CG strokes detected by the NLDN within an inner warning area consisting of a circle whose radius is 4.8 km (3 miles) around simulated airports at these locations. A short analysis is also included for a smaller inner warning area. Interviews with airport customers indicated that at least two minutes lead time is required for ground crew employees to reach safety during lightning warnings. A two-minute lead time was used in analyses, as well as 10-minute and 20-minute lead times for other possible applications of the warning studies. Results used a 15-minute warning expiration time, the time when activities are to be suspended until an all-clear is sounded; 10-minutes is also explored.

In a related study, MacGorman et al. [2011] determined the difference between the time of first CG flash and cloud lightning from a VHF total lightning mapping network. In the central U.S., half of the CG flashes lagged the first VHF lightning by 5 to 10 minutes, and the delay was longer on the High Plains. The presence of such a lag indicates the potential for cloud lightning to impact warnings. This study uses NLDN cloud lightning rather than VHF mapping, so the impact of NLDN data could be expected to be less.

II. Method

A. Time and Area of Study

Since the NLDN upgrade was ongoing during 2013, the impact of cloud data could not begin until late in the summer when NLDN sensors included most of the upgraded cloud pulse discrimination criteria. Therefore the analysis began on 15 August 2013, and ended when most of the lightning in the U.S. has subsided at the end of September. Analyses during these 47 days were made at ten locations scattered across the country. A range of types of thunderstorms was included, although there was a tendency for lightning to occur in the warmer portions of the country in these months [Holle et al., 2011]. NLDN data were analyzed from 15 August through 30 September 2013. Figure 1 shows the CG, cloud, and total lightning maps across the U.S. during this period.

B. Choice of Analysis Points

Many areas have lightning during this period, which is toward the end of the summer activity [Holle et al., 2011]. Frequent activity is occurring in Florida, Arizona (mainly August), and other locations, while there are some locations in the central states that had almost no lightning during this period. Individual storms can be identified in many cases.

These maps were used to choose ten locations across the country. Factors involved in determining these locations were:

- Some lightning must have occurred during the period,
- Locate the points at medium or large airports,
- Widely dispersed across the U.S.

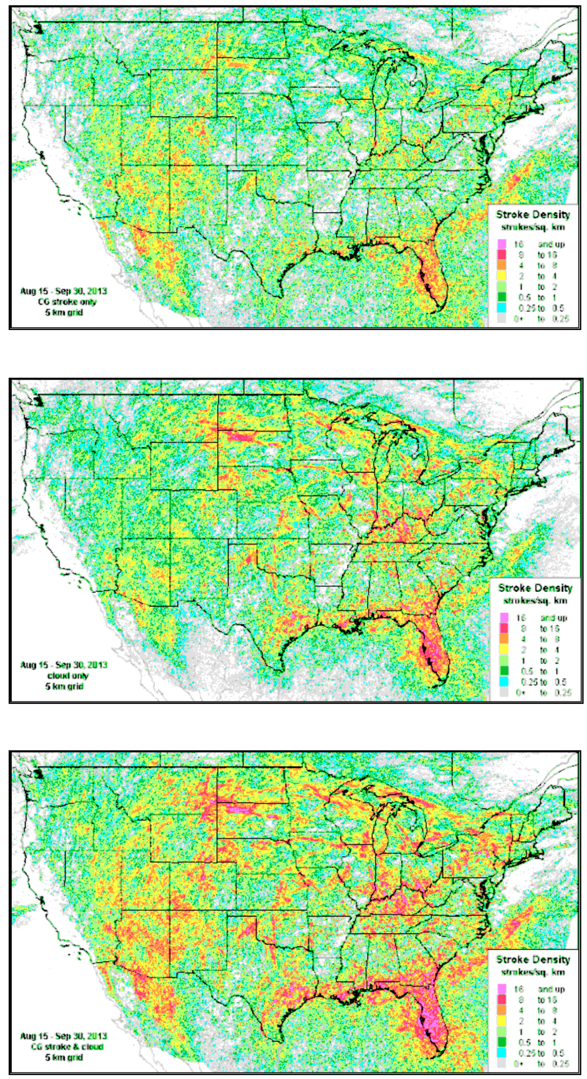


Fig. 1. Maps of NLDN-detected cloud-to-ground strokes (top), cloud pulses (middle), and combined CG strokes and cloud pulses from 15 August through 30 September 2013.

The ten points are shown superimposed on the CG stroke map in Figure 2. All points are over land, and far enough apart so that the same thunderstorms were not sampled. Due to the time of year, there is a tendency for the sample to be biased toward warmer climates such as Florida and Arizona, where storms are somewhat shorter-lived. In general, the other locations at this time of year tend to have more organized, traveling storms and thunderstorm clusters.

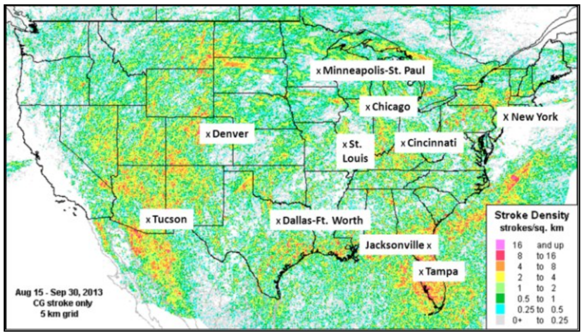


Fig. 2. Ten analysis points superimposed on NLDN cloud-to-ground stroke map for 15 August through 30 September 2013.

C. *Inner Warning Area*

The inner warning area at the airports is a circle with a radius of 4.8 km (3 miles) around the center point of an airport. An inner area of 2.0 km is also explored later in this study. This inner verification circle is a region where lightning is perceived as a danger to airport operations. This verification area is based only on the presence of one or more NLDN cloud-to-ground strokes within the area, since cloud-to-ground lightning is the direct operational danger.

III. RESULTS COMPARED WITH PAST STUDIES

The first step in the analysis is to determine if this 2013 dataset has similar warning characteristics to previous NLDN studies. One feature of these airport warnings was a two-minute lead time for airport ground workers to find safety from lightning. Those studies most commonly found the best results for a 4.8-km (3 miles) inner warning area to be for a 15-km radius and a 15-minute warning expiration time.

Warning statistics are combined from analyses at the ten points in Figure 2. The 2013 analyses for a 15-km outer radius, 4.8-km inner warning radius, 15 minute warning expiration time, and two-minute lead time are shown in the top line of Table 1. Notes on these results are as follows, from left to right:

TABLE I. NLDN CG STROKES (TOP LINE) AND CG STROKES WITH CLOUD PULSES ADDED (LOWER LINE) USED FOR LIGHTNING WARNINGS OF CG STROKES AT 15-KM OUTER WARNING RADIUS, 15-MINUTE WARNING EXPIRATION TIME, AND TWO-MINUTE LEAD TIME FROM 15 AUGUST - 30 SEPTEMBER 2013 AT TEN LOCATIONS. VERIFICATION IS WITH NLDN CG STROKES WITHIN 4.8 KM OF LOCATIONS.

Radius of warning area	**Red conditions**	**Number detected**	**Number of failures to warn**	**Number of false alarms**	**Percent time under valid warnings**	**Percent time under false alarms**
CG strokes only						
15 km	230	55 POD2=0.76	17 FTW=0.24	158 FAR=0.69	0.72%	0.61%
CG strokes + cloud pulses						
15 km	244	59 POD2=0.83	17 FTW=0.17	158 FAR=0.71	0.84%	0.75%

- Probability of detection (POD2) at a two-minute lead time is 0.76. This POD2 is somewhat lower than a POD2 of 0.84 found with NLDN flashes in the southeast U.S. in October 2009 [Holle and Demetriades, 2010], and nearly the same as the 0.78 found at 12 US Airways airports (in many of the same locations as the present study) from May through August 2011 reported at the 2012 ILMC.
- The measure of Failures To Warn (FTW) is 1.00 minus POD2.
- False alarm ratio (FAR) is 0.69. This ratio is somewhat better than the 0.74 found for the Southeast U.S. in October 2009 [Holle and Demetriades, 2010] and similar to the 0.71 for the 12 airports in 2011.
- Average of 23 thunderstorms per airport. For the current study, a total of 230 thunderstorms started and ended over the ten airports, however around half were at Tampa and Jacksonville due to the late summer sample. This is a larger dataset than the 2009 study (129 storms), but much less than used for the 12 airports in 2011 (821 storms).
- Time under valid warnings averages 8.1 hours per airport. This time corresponds to 0.72% of the time during the 47 days of record. The duration is higher than found during October 2009 (0.27%) when lightning frequency is lower than from mid-August through September in the present study. It is about the same as the analysis found for the 12 airports in summer 2011 (0.89%).
- Time under false alarms averages 6.9 hours per airport. This time corresponds to 0.61% of the 47 days. The duration is higher than in October 2009 (0.25%), but about the same as in summer 2011 (0.66%).

These comparisons show that the 2013 dataset is very comparable in performance to warnings based on NLDN flash datasets from past years [Murphy and Holle, 2006a,b]. The late-summer period has an emphasis on Florida storms, as can be expected. Nevertheless, these warnings for strokes are similar to previous warnings for CG flashes such that the 2013 dataset is adequate for testing the impact of cloud pulses on warnings. In fact, it is somewhat remarkable how often the results are similar, despite different in locations, time of year, and flash versus stroke data. The conclusions derived from this comparison of results with CG and cloud pulse data, then, are potentially applicable to other locations and seasons.

IV. Results With and Without Cloud Pulse Data

The next step is to compare the warnings based on CGs strokes only with the combination of CG strokes and cloud pulses. The inner area is the area of concern, that is, advance warning of CG strokes is desired within 4.8 km of the airports' center points. For that reason, only CG strokes are used as verification within the inner warning area.

The outer area used to anticipate CG strokes at the airport can be either CG strokes only, or CG strokes plus cloud pulses with the upgraded 2013 cloud detection efficiency. Because of how the analysis method makes calculations, cloud strokes were not included within 4.8 km of the airports' center points in the warning step. For a 15-km outer warning radius, the CG plus cloud dataset did not include cloud data within 4.8 km, so the inner area is about 10% of the area of the outer circle. The results for CG plus cloud, then, are somewhat conservative since the possible value of cloud pulses for warnings within 4.8 km is omitted.

Comparisons of CG only and CG plus cloud are shown in the lower line of Table 1, from left to right:

- Adding cloud pulses in the outer area between 4.8 and 15 km somewhat increased the number of storms from 230 to 244.
- Most notable is an increase in POD2 from 0.76 to 0.83. That is an increase in POD2 of 9.2% relative to CG only. In addition, taking into account that cloud pulse data in the inner warning area are not included in anticipating CG warnings, which is an area of about 10% of the 15-km circle, then adding cloud pulses has increased POD2 by 10%.
- The FAR increased slightly from 0.69 to 0.71 when cloud pulses are added.
- The duration of both valid warnings and false alarms both increased to some extent with the added cloud pulses.

V. Results At Varying lead Times

Table 1 is only at a lead time for warnings of two minutes (POD2). That is a very short time for evacuation and taking time to reach a safe place. It may be possible to reach safety at an airport where lightning-safe buildings or vehicles can be reached very quickly in two minutes' time. However, there are many other situations where it will take longer. For that reason, the results in Table 2 are expanded to include lead times of 10 and 20 minutes. The results in Table 2 show:

- For CGs only in the outer warning area, the POD reduces drastically from 0.76 for a two-minute lead time to 0.33 for a 20-minute lead time.
- For CGs plus cloud pulses in the outer warning area, the POD is better at all lead times than with CGs only. For example, at a 10-minute lead time, the POD10 is 0.65 compared with a POD10 of 0.60 for CG only. Taking into account the lack of cloud pulse data in the inner area, that POD10 of 0.65 is on the order of 0.70. The cloud pulse data, then, has provided a noticeable increase in the capability to provide meaningful warnings at a 10-minute lead time.
- Note that at a 20-minute lead time, CG only has only a POD20 of 0.33, which is quite poor, while adding the cloud pulse data has increased to a POD20 of 0.42. This is on the order of 0.46 when the lack of cloud data in the inner warning area in these analyses is taken into account. Nevertheless, it is difficult to give adequate, consistent lightning warnings for a lead time of 20 minutes with CGs and cloud pulses from the NLDN.

TABLE II. SAME AS TABLE I, EXCEPT TO ADD LONGER LEAD TIMES OF 10 AND 20 MINUTES.

Radius of warning area	Red conditions	Number detected POD	Number of failures to warn FTW	Number of false alarms FAR	Percent time under valid warnings	Percent time under false alarms
CG strokes only						
15 km	230	55 POD2=0.76	17 FTW=0.24	158 FAR=0.69	0.72%	0.61%
15 km	230	43 POD10=0.60	29 FTW=0.40	158 FAR=0.69	0.72%	0.61%
15 km	230	24 POD20=0.33	48 FTW=0.67	158 FAR=0.69	0.72%	0.61%
CG strokes + cloud pulses						
15 km	244	59 POD2=0.83	12 FTW=0.17	173 FAR=0.71	0.84%	0.75%
15 km	244	46 POD10=0.65	25 FTW=0.35	173 FAR=0.71	0.84%	0.75%
15 km	244	30 POD20=0.42	41 FTW=0.58	173 FAR=0.71	0.84%	0.75%

VI. RESULTS AT VARYING OUTER RADII

Previous tables were for an outer warning radius of 15 km. Previous studies found that 15 km is often the optimal value for CG-only datasets, so the effect of adding cloud pulses is now examined. Table 3 shows statistics at outer warning radii of 10 and 20 km, with and without cloud pulses. The analyses are summarized in Table 3 and show the following:

- POD2: For CGs only in the outer warning area, the number of storms increases steadily. POD2 increases steadily as the area increases from 0.64 at a 10-km radius to 0.81 for 20 km. Adding the cloud pulses increases the POD2 by five to seven percent (unadjusted for omitting cloud pulses in the inner area). That is, cloud pulses make a difference at all radii.
- FAR: For CGs only, FAR increases as the area increases. Cloud pulses have a slightly higher FAR than CGs only at all radii.
- The times under warning increase steadily for larger radii. In general, the cloud pulse data add some time to both valid warnings and false alarms.

The permutations of warning radii show that POD2 is up to 10% better with cloud data than without at all outer radii. The FAR and time under warnings are consistently a little higher with cloud pulse data than with CGs only.

TABLE III. SAME AS TABLE I, EXCEPT TO ADD WARNING RADII OF 10 AND 20 KM FOR POD2.

Radius of warning area	Red conditions	Number detected POD2	Number of failures to warn FTW	Number of false alarms FAR	Percent time under valid warnings	Percent time under false alarms
CG strokes only						
10 km	169	47 POD2=0.64	27 FTW=0.36	95 FAR=0.56	0.53%	0.29%
15 km	230	55 POD2=0.76	17 FTW=0.24	158 FAR=0.69	0.72%	0.61%
20 km	272	58 POD2=0.81	14 FTW=0.19	200 FAR=0.74	0.92%	0.95%
CG strokes + cloud pulses						
10 km	172	50 POD2=0.69	22 FTW=0.31	100 FAR=0.58	0.65%	0.35%
15 km	244	59 POD2=0.83	12 FTW=0.17	173 FAR=0.71	0.84%	0.75%
20 km	284	61 POD2=0.88	8 FTW=0.12	217 FAR=0.76	1.09%	1.08%

In an earlier study, VHF mapping provided a reduction in FAR and false alarm duration of up to 40%. In the present case, FAR and false alarm duration both are slightly worse with the cloud data than without, although the POD2 is distinctly better with the cloud pulses. NLDN cloud pulses are not as complete a representation of cloud lightning extent as that shown by VHF total lightning mapping such as in MacGorman et al. [2011], so the impact of NLDN cloud lighting can be expected to be less, and that is the case in this dataset. NLDN cloud pulses in 2013 are providing an improvement in POD2 statistics that are between the results for NLDN CG-only and those found previously from VHF total lightning mapping.

VII. Results for Varying Warning Expiration Times

Previous results were calculated with a 15-minute warning expiration time. This time relates to how long the warning stays in effect. If new CG or cloud lightning occurs within the outer radius before the warning expires, then the warning is restarted.

To identify the impacts of a 10-minute expiration time rather than 15 minutes, results are compared with and without cloud pulses in Table 4:

- The number of red conditions is the number of storms within the 15-km outer range, in this table. For 10 minutes' warning expiration time, the number of red conditions is 20 to 22% more than at 15 minutes' warning expiration time, both with and without cloud pulses.
- The number of storms detected is similar.
- The POD2 is better at a 15-minute expiration time than at 10 minutes, both with and without cloud pulses.
- Failures to warn increases for the shorter dwell time.
- The number of false alarms at 10 minutes grows by 26% from the 15-minute result for CGs only and 42% for CG plus cloud.
- The duration of valid warnings for 10 minutes expiration time is 22% less than for 15 minutes for CGs only, and 27% less for cloud data.
- The duration of false alarms is increased by 20% at 10 minutes for CGs only, and 9% for CGs plus cloud.

The change to a shorter warning expiration time for both CGs only and CG plus cloud data has had a negative effect in almost every parameter. There are quite a few more storms at a 10-minute expiration time due to thunderstorms being divided into shorter segments. An accompanying issue is that storms then start and stop more often with short intervals between some of them, so safety procedures are more difficult to manage. At 10 minutes, the POD2 is less, and the number of false alarms and time under false alarms are increased. The only benefit is that less time is spent under valid warnings because the storms are ended after 10 rather than 15 minutes. All in all, the net effect is that a 15-minute warning expiration time is the preferred time interval compared with a 10-minute warning expiration time.

TABLE IV. SAME AS TABLE I, EXCEPT TO ADD WARNING EXPIRATION TIME OF 10 MINUTES AT OUTER WARNING RADIUS OF 15 KM.

Radius of warning area	**Red condi-tions**	**Number detected POD2**	**Number of failures to warn FTW**	**Number of false alarms FAR**	**Percent time under valid warnings**	**Percent time under false alarms**
CG strokes only						
10 minutes, 15-km radius	276	52 POD2=0.69	23 FTW=0.31	200 FAR=0.73	0.59%	0.73%
15 minutes, 15-km radius	230	55 POD2=0.76	17 FTW=0.24	158 FAR=0.69	0.72%	0.61%
CG strokes + cloud pulses						
10 minutes, 15-km radius	299	57 POD2=0.77	17 FTW=0.23	225 FAR=0.75	0.66%	0.69%
15 minutes, 15-km radius	244	59 POD2=0.83	12 FTW=0.17	173 FAR=0.71	0.84%	0.75%

VIII. Results for Inner Warning Area of 2.0 km Compared with 4.8 km

All previous results were calculated with an inner warning area of 4.8 km. That distance was chosen because it's the size of a large airport and all operations that may occur on the airport property. For many airports and other facilities, a smaller area is more appropriate. For this situation, some calculations with CGs only were made with the same dataset for an inner warning radius of 2.0 km.

To identify the impact on warnings of a 2.0 km-radius property rather than over a 4.8 km-radius property, results are compared for both sizes in Table 5, as follows:

- The POD2 is generally better for a smaller inner warning area.
- The number of storms detected is about the same.
- The number of false alarms for the smaller airport grows significantly until FAR reaches a very high value of 0.86 at a 20-km outer radius.
- The duration of valid warnings is somewhat shorter for the smaller facility.
- The duration of false alarms is generally longer for the smaller property.

Anticipating lightning over the area of a smaller property can be done somewhat better than a larger airport, but the penalty is a larger FAR and time under false alarms. In particular, note entries for the preferred outer radius of 15 km in Table 5. There are 35 storms detected with a POD2 for the smaller facility, but there are 192 false alarms, a ratio of more than five storms warned falsely for every one that is correctly anticipated; this is not a practical number for operations. In contrast, for the larger facility, there are 173 false alarms for 59 correctly warned storms, a ratio of three false alarms per correct warning.

It should be pointed out that while the Table 5 results appear to be good for an inner area of 2.0 km and outer ring of 5.0 km, that is not extendable to other sizes. For a 2.0-km inner warning area, an outer radius of 10 km has nearly three times as many false alarms, and is worse in most other statistics than a 10-km outer ring for a larger airport. Only when the outer radius is very small and the inner airport area is small did the results exceed other measures of success. In contrast, Table 5 shows a somewhat analogous approach for the larger airport to have an abysmal POD2 of 0.09 when the outer area is 5.0 km and the inner airport area is 4.8 km. This example of two property sizes with close-in outer warning areas shows the complexity of the interactions among the various parameters, regardless of whether cloud pulses are included or not.

Another interesting result in this table relating to the larger property has not been shown before. Note the first line in Table 5 for a 4.8-km inner area, at a 5-km outer radius. That is, the outer radius (5 km) is almost the same as the area being warned (4.8 km). The POD2 in this situation is almost zero (0.09), so this configuration is without value. A future study will examine the value of cloud lightning in the case of the small inner radius; only CGs were used in this 2.0-km study.

Table V. Same as Table I, except for inner warning area of 2.0 km (upper) compared with 4.8 km (lower) for POD2.

Radius of warning area	Red conditions	Number detected POD2	Number of failures to warn FTW	Number of false alarms FAR	Percent time under valid warnings	Percent time under false alarms
CGs at 2.0 km inner warning area						
5 km	89	28 POD2=0.74	10 FTW=0.26	50 FAR=0.57	0.25%	0.29%
10 km	169	32 POD2=0.84	6 FTW=0.16	131 FAR=0.74	0.36%	0.47%
15 km	230	35 POD2=0.92	3 FTW=0.08	192 FAR=0.83	0.49%	0.84%
20 km	272	36 POD2=0.95	2 FTW=0.05	234 FAR=0.86	0.81%	1.26
CGs at 4.8 km inner warning area						
5 km	89	8 POD2=0.09	77 FTW=0.91	4 FAR=0.05	0.38%	<0.01%
10 km	172	50 POD2=0.69	22 FTW=0.31	100 FAR=0.58	0.65%	0.35%
15 km	244	59 POD2=0.83	12 FTW=0.17	173 FAR=0.71	0.84%	0.75%
20 km	284	61 POD2=0.88	8 FTW=0.12	217 FAR=0.76	1.09%	1.08%

IX. Discussion

A large number of variables have been explored in the preceding sections. Fig. 3 compares samples from each of the considered variables. The data in red are the default settings based on past studies, and were the start for this study. It is apparent that POD can vary from as high as 0.95 to as low as 0.09. The choice of parameters indeed makes a difference. The FAR also has important and highly variable values. When any one of the settings is changed, there is an impact on POD and FAR.

X. Conclusions

An analysis was made of the added value of cloud pulses for cloud-to-ground lightning warnings after the 2013 NLDN upgrade. The measured capability of the NLDN for cloud pulses across the U.S. increased from a DE of 15 to 25% prior to 2013 to about 50% by late summer 2013.

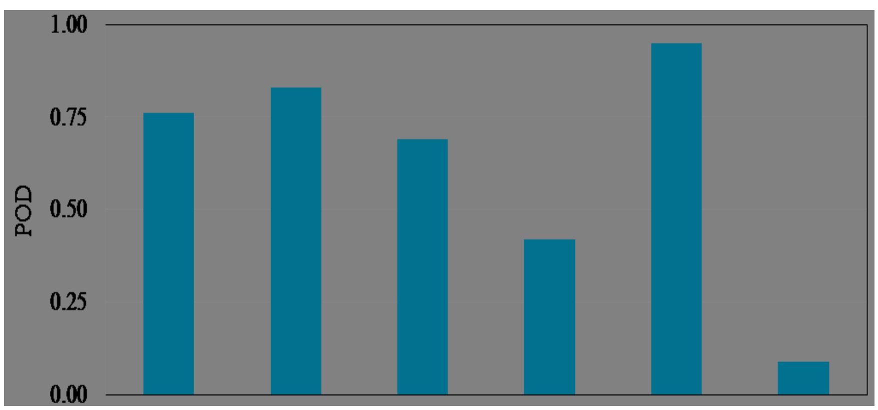
NLDN data from mid-August through September 2013 across much of the U.S. were considered. Ten points were chosen to sample different storms and storm types during the period. Verification was for the presence of CG strokes from the NLDN.

The first step was to verify that thunderstorms from this late-summer 2013 sample had comparable warning statistics to those found in previous studies. The probability of detection for a two-minute warning, POD2, was 0.76 for a 15-minute warning expiration time and a 4.8-km inner warning area. This POD2 is similar to those found in two recent similar studies. In addition, the false alarm ratio of 0.69 and warning durations were similar. Therefore, the 2013 sample is consistent with previous thunderstorm datasets for exploring the value of cloud pulses on warnings.

The next step was to compare warning parameters with cloud pulses added. The verification continued to be the presence of CG strokes within an inner 4.8-km radius. The analysis method does not include cloud pulses within the 4.8-km inner area. The addition of cloud pulses for a 15-km outer warning area increased the POD2 from 0.76 to 0.83, an increase of 9.2% relative to CG only. Taking into account the lack of cloud pulses in the inner area, the increased value of cloud pulses is about 10% compared with CG only. Other warning performance parameters were similar.

These results were for relatively short two-minute warnings. Expanding the warning to longer times, the quality of warnings was somewhat better with the addition of cloud pulses than without cloud pulses. For example, the POD10 for CGs only was 0.60, and 0.65 with cloud pulses.

These analyses were for a 15-minute warning expiration time. When the time is 10 minutes, there is a negative effect on most parameters. There are more storms, a somewhat lower POD2, and somewhat higher FAR and time under warnings. The net effect is that a 15-minute warning time is better than 10 minutes.



POD	0.76	0.83	0.69	0.42	0.95	0.09
FAR	0.69	0.71	0.73	0.71	0.86	0.05
Data	CG	CG+C	CG	CG+C	CG	CG
Outer radius (km)	15	15	15	15	20	5
Lead time (min.)	2	2	2	20	2	2
Inner area (km)	4.8	4.8	4.8	4.8	2.0	4.8
Warning expiration time	15	15	10	15	15	15

Fig. 3. Selected POD and FAR values for various combinations of parameters anticipating the presence of CG strokes within the inner area .

Finally, a small inner warning area with a 2.0-km radius was evaluated rather than a large property with a 4.8-km radius. Only CG data were evaluated at this time. While the POD2 is better for a smaller inner area, there are substantially more false alarms for the smaller property. A future study will evaluate adding cloud pulse data outside an inner radius of 2.0 km, which was not possible with the present dataset.

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