UPGRADED NLDN CLOUD PULSE DETECTION FOR SMALL AIRPORT WARNING AREAS

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1. INTRODUCTION

1.1 Background

Lightning-caused impacts to both people and infrastructure are substantial in the U.S. and globally (Holle 2015). In terms of lightning avoidance for individuals as well as industrial applications, a balance needs to be addressed between safety and efficiency. The case of ground operations at airports is an example of exposure to the lightning threat in terms of refueling, baggage handling, aircraft and cabin maintenance, aircraft movement, food catering, and other activities. An informal survey of media reports shows several cases per year globally where ground workers are injured, often several at a time, and occasionally a fatality results. Due to the size of the workforce at larger airports, the potential for major delays can result in large minute-by-minute costs and affect operational efficiency. In addition, the cascade effects of lightning-caused delays at one airport are substantial in terms of schedule impacts (Steiner et al. 2014).

Over the last decade, a series of studies has been conducted examining the capability of National Lightning Detection Network (NLDN) flashes, VHF total lightning mapping, field mills, and GLD360 strokes to anticipate cloud-to-ground (CG) lightning. A particular interest has been to provide CG lightning warnings for airport ground operations, such as Holle and Demetriades (2010).

During the period of these studies, characteristics of the NLDN have been evaluated (Jerauld et al. 2005; Cummins and Murphy 2009; Nag et al. 2011). These are the latest in a series of NLDN network performance ground-truth examinations. In 2013, the NLDN underwent a network-wide upgrade that increased the capability to detect cloud pulses 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).

Airport customers have indicated that at least two minutes' lead time is required for airport ground employees to reach safety during lightning warnings. As a result, a two-minute lead time is mainly emphasized in these analyses; 10-minute and 20-minute lead times for warnings are also explored. Results are mostly for 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 briefly.

1.2 Earlier warning studies

Initial analyses used CG flashes in an outer region to anticipate CG flashes in a smaller inner area such as an airport. These NLDN analyses used CG flashes, not CG strokes or cloud pulses.

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 were shown to provide a slight increase in probability of detection and reduction in false alarm ratio for warnings (Murphy and Holle 2006a,b, Fig. 4).

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

Additional CG-only studies used the analysis software package for warning analyses in unpublished results that continued to focus 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). In the case of the GLD360 study (Holle and Demetriades 2010), that network provides stroke data. Current estimates are that 20% of reported lightning events are cloud pulses rather than CGs (Poelman et al., 2013; Pohjola and Mäkelä, 2013; Said et al., 2013).

1.3 Warning studies with cloud pulses added

MacGorman et al. (2011) identified the potential value of cloud pulses in warnings. The difference between the time of first CG flash and cloud lightning from a VHF total lightning mapping network was determined. 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 information to impact warnings.

The first NLDN study that focused on adding CG strokes and high-DE cloud pulses used data from late 2013 after the major NLDN upgrade in cloud pulse detection was completed. Results were for ten airports across the U.S. from 15 August through 30 September (Holle et al. a,b,c). Because this was a late summer period after the NLDN upgrade was substantially completed, the sample was somewhat limited and was comprised substantially of Florida thunderstorms at Jacksonville and Tampa.

The analyses to be presented in this paper will have two new features:

- It will have a much larger sample size of thunderstorms for examining the impact of cloud pulses from all of the 2014 summer compared with the limited sample from late 2013.
- The potential of NLDN CG strokes to anticipate CG lightning within a much smaller inner warning area at an airport will be featured. All previous studies were for large airport properties consisting of an outer circle with a radius of 4.8 km (3 miles) around ten simulated airports. Now, the emphasis will be on warning for small regions within an airport consisting of a circle with a radius of 500 m (0.3 miles).

2. METHOD

2.1 Time and area of study

The analysis begins on 01 June and ends on 30 September 2014. Analyses during these 122 days were made at ten locations scattered across the country. A range of types of thunderstorms was included at the same airports used in Holle et al. 2014 a,b,c). Figure 1 shows the CG, cloud, and total lightning maps across the U.S. during this period.

2.2 Choice of analysis points

Many areas of the country have lightning during this period, which is the most active period of the year (Holle et al. 2011). Frequent activity is occurring in Florida, the Gulf Coast, Midwest, Central Plains, Arizona, and many other locations. These maps were used to choose ten locations across the country. Factors involved in determining these locations were:

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

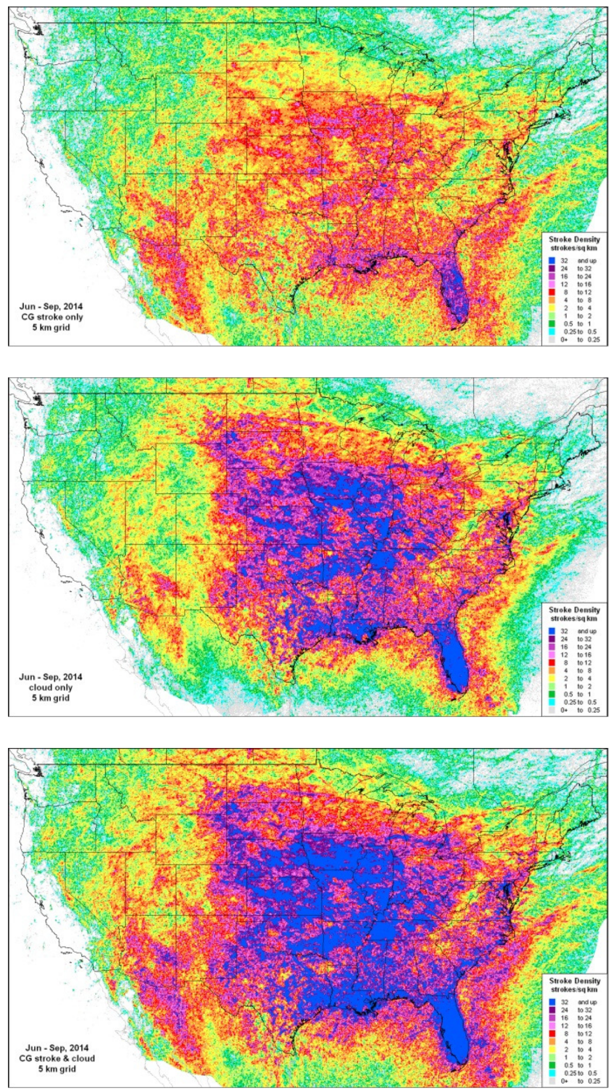

FIG. 1. Maps of NLDN-detected CG strokes (top), cloud pulses (middle), and combined CG strokes and cloud pulses from 01 June through 30 September 2014.

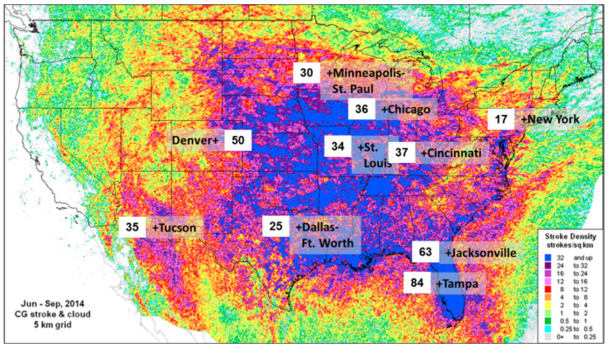

FIG. 2. Ten analysis points superimposed on NLDN cloud-to-ground stroke map from 01 June through 30 September 2014. The number of days with lightning within 15 km are indicated in white boxes.

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.

2.3 Outer and inner warning areas

Past studies were for inner warning areas with a circle of a radius of 4.8 km (3 miles) around a center point. An inner area of 0.5 km is primarily explored in this study. This circle is a region where lightning is perceived as a danger to airport operations (Fig. 3). The verification is for one or more CG strokes within the inner area, since CGs are the direct operational danger. Cloud lightning pulses within the outer radius are also extensively explored for their value in warnings for the inner area to be monitored.

An example of these areas is shown in Fig. 4 for the Dallas/Fort Worth International Airport (DFW). The outer radius of 4.8 km is an airport-wide warning, while the 0.5-km radius refers to operational airport areas where personnel are outside and exposed to the lightning threat.

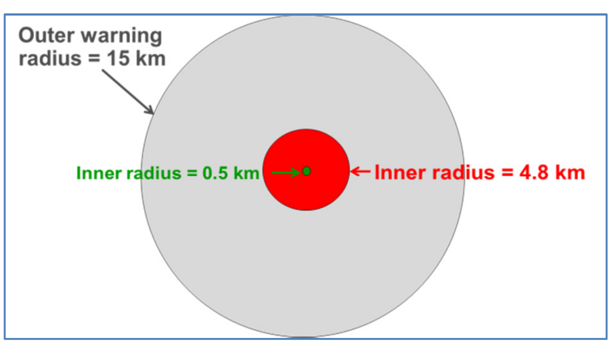

FIG. 3. Example of an outer warning radius of 15 km, and inner radii of 0.5 and 4.8 km.

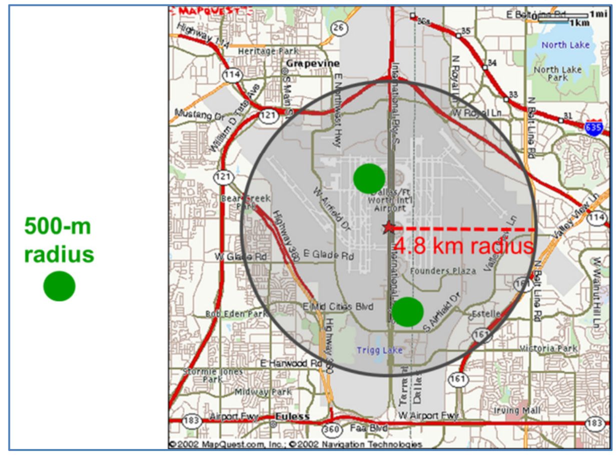

FIG. 4. Example of warning radii superimposed on Dallas/Fort Worth International Airport.

3. RESULTS AT 4.8-KM INNER RADIUS

3.1 Comparison with past studies

The first step in the analysis is to determine if the much larger 2014 dataset has similar characteristics to datasets used in previous NLDN studies. Most prior results were for a two-minute lead time for airport ground workers to find safety from lightning. The studies most commonly found the best results for a 4.8-km (3 miles) inner warning area to be at a 15-km radius and a 15-minute warning expiration time.

Warning statistics are combined in Table 1 from analyses at the ten points in Figure 2. The 2014 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, then comparison is made with results found using two other datasets. Notes on these results are as follows, from left to right:

- Probability of detection (POD2) at a two-minute lead time is 0.77. This POD2 is nearly the same as the 0.78 found at 12 airports (in many of the same locations as the present study) from May through August 2011 reported at the 2012 International Lightning Meteorology Conference. It is also similar to the 0.76 indicated with the late 2013 dataset (Holle et al. 2014 a,b,c).
- The measure of Failure To Warn (FTW) is 1.00 minus POD2.
- False alarm ratio (FAR) is 0.69. This ratio is somewhat better than 0.71 found for the 12 airports in 2011, and the same as found in 2013.

TABLE 1. Measures of the value of NLDN CG strokes for warnings of CG strokes at 15-km outer warning radius, 15-minute warning expiration time, and two-minute lead time from 01 June - 30 September 2014 at ten locations, compared with two previous studies. Verification is with NLDN CG strokes within 4.8 km of locations.

Data source Outer radius	Storms	POD2	FTW	FAR	Time in valid warnings	Time in false alarms
CG strokes, this study 15 km	846	0.77	0.23	0.69	1.14%	0.91%
CG strokes, summer 2011, 12 airports 16 km	821	0.78	0.22	0.71	0.98%	0.73%
CG strokes, late 2013, 10 airports 15 km	230	0.76	0.24	0.69	0.72%	0.61%

- Time under valid warnings averages 1.14% of the time during the 122 days in summer 2014. The duration is about the same as for the 12 airports in summer 2011, but more than for the shorter late-summer 2013 study.
- Time under false alarms averages 0.91% of the 122 days. The duration is higher than in summer 2011 and late summer 2013.

These comparisons show the 2014 dataset to have a very similar warning performance based on NLDN flash datasets from past years. In fact, it is remarkable how often the results are similar, despite differences in locations, time of year, and flash versus stroke data. There appear to be underlying time and space scales of lightning that are being indicated by the similarity of these parameters from independent datasets. Further studies are indicated on this topic. Nevertheless, the conclusions derived from this comparison of results with CG data are potentially applicable to other locations and seasons.

3.2 Addition of cloud pulses

The inner area is where advance warning of CG strokes is desired, so only CG strokes are used as verification within the inner warning area. The outer area used to anticipate CG strokes at the airport can have CG strokes only, or CG strokes plus cloud pulses. Because of how the analysis method makes calculations, cloud strokes were not included within 4.8 km of the center points, about 10% of an area with a 15-km circle.

Comparisons of CG only and CG plus cloud pulses are shown in Table 2, from left to right:

- Adding cloud pulses in the outer area between 4.8 and 15 km somewhat increased the number of storms from 846 to 877.
- Most notable is an increase in POD2 from 0.77 to 0.90. That is an increase in POD2 of 13% relative to CG only.
- The FAR increased slightly from 0.69 to 0.72 when cloud pulses are added.
- The duration of both valid warnings and false alarms both increased to some extent with cloud pulses added.

TABLE 2. Same as Table 1, except for adding cloud pulses data for the summer of 2014.

Data source Outer radius	Storms	POD2	FTW	FAR	Time in valid warnings	Time in false alarms
CG strokes only 15 km	846	0.77	0.23	0.69	1.14%	0.91%
CG strokes plus cloud pulses 15 km	877	0.90	0.10	0.72	1.26%	1.14%

4. RESULTS AT 0.5-KM INNER RADIUS

Tables 1 and 2 were for inner areas of 4.8-km radius, that is, a large airport. Now a much smaller area on the size of a single facility within an airport is considered, such as a refueling area.

4.1 Comparison at 0.5 with 4.8 km inner radius

Table 3 shows improvements in several measures of performance for the smaller inner warning area with a 0.5-km radius. POD2 has increased from 0.90 for a large inner area to 0.97 for the smaller inner area. However, FAR has also increases from 0.72 to 0.96. While the percentage time in valid warnings is only 20% as long as before, the false alarm duration is nearly twice as long for the smaller inner area.

4.2 Results at varying outer radii

Previous tables were for an outer warning radius of 15 km. Table 4 shows statistics at the additional outer warning radii of 5 and 10 km, with and without cloud pulses. The analyses are summarized in Table 4 and show the following:

- POD2: Table 3 showed a 15-km outer radius to have a POD2 of 0.97 with cloud pulses. A smaller outer radius of 10 km (6 miles) also has the same POD2 and a somewhat better FAR of 0.94 compared with 0.96 at 15 km. Note however that reducing the outer radius to 5.0 km results in a lowering of POD2 to 0.88. Both warning percentages gradually decrease with a smaller outer radius.
- When cloud pulses are not included, the lower section of Table 4 shows that larger radii have a similar performance, but the 5-km outer radius is too small since POD2 drops to 0.76.

As discussed earlier in this paper, airports and airlines must consider both safety and operational efficiency when setting lightning warning radius distances. A comparison of Tables 3 and 4 provides some interesting insights into ways to maintain a high level of safety, while also minimizing the duration of ground operation stops. For example, if a large airport does not apply one warning area radius for all ground operations at that airport (e.g. “Inner radius=4.8 km” from Table 3), but instead applies separate warning area radii around smaller ground operation areas at the airport (e.g. “Inner radius of 0.5 km from Table 4), significant warning duration reductions occur without compromising safety.

Table 3 shows a POD2 of 90% and a total warning duration of 2.4% of the time during this study using an outer warning area radius of 15 km to warn for all ground operations within an inner radius of 4.8 km. By comparison, the with and without cloud pulse results in Table 4 show actual improvements in POD2 (97% vs 90%) with large reductions in warning durations (2.4% vs 1.52% and 1.23%, respectively) using an outer warning radius of 10 km to warn for all ground operations within an inner radius of 0.5 km. This 0.5 km inner radius approach could be used by small airports and used at different terminals/maintenance areas at larger airports.

This permutation of warning radii shows that the combination of POD2 and FAR are slightly better at 10 km than either 15 km or especially 5 km.

4.3 Results at varying lead times

All previous tables are for warnings of two minutes (POD2). That is a very short time to reach a safe place. It may be possible to reach safety at an airport where lightning-safe buildings or vehicles are nearby in two minutes. However there are many other situations where it will take longer. For that reason, the previous results are expanded to include lead times of 10 and 20 minutes.

The results in Table 5 show that for CGs plus cloud pulses in the outer warning area, the POD reduces significantly from 0.97 for a two-minute lead time to 0.67 for a 20-minute lead time. The conclusion is that it is difficult to give adequate, consistent lightning warnings for a lead time of 20 minutes with CGs and cloud pulses from the NLDN.

In an earlier exploratory Vaisala study, VHF mapping provided a reduction in FAR and false alarm duration of up to 40%. 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 lightning can be expected to be useful but not exceptionally good, and that is the case in this dataset. NLDN cloud pulses in 2014 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.

TABLE 3. Same as Table 1, except to add an inner area with 0.5-km radius during the summer of 2014 for CG strokes plus cloud pulses.

Data source Outer radius	Storms	POD2	FTW	FAR	Time in valid warnings	Time in false alarms
Inner radius=0.5 km						
15 km	880	0.97	0.03	0.96	0.26%	2.13%
Inner radius=4.8 km						
15 km	877	0.90	0.10	0.72	1.26%	1.14%

TABLE 4. Same as Table 1, except to add outer warning radii of 5 and 10 km for POD2 for an inner radius of 0.5 km.

Inner radius NLDN data	Storms	POD2	FTW	FAR	Time in valid warnings	Time in false alarms
0.5 km CG strokes + cloud pulses						
Outer radius						
5 km	404	0.88	0.12	0.89	0.14%	0.60%
10 km	660	0.97	0.03	0.94	0.20%	1.32%
15 km	880	0.97	0.03	0.96	0.26%	2.13%
0.5 km CG strokes only						
Outer radius						
5 km	344	0.76	0.24	0.88	0.15%	0.56%
10 km	665	0.97	0.03	0.96	0.20%	1.03%
15 km	858	1.00	0.03	0.96	0.23%	1.80%

TABLE 5. Same as Table 1, except to add longer lead times of 10 and 20 minutes.

Data source Lead time	Storms	POD2	FTW	FAR	Time in valid warnings	Time in false alarms
CG strokes + cloud pulses						
2 minutes	660	0.97	0.03	0.94	0.20%	1.32%
10 minutes	660	0.85	0.15	0.94	0.20%	1.32%
20 minutes	660	0.67	0.33	0.94	0.20%	1.32%

4.4 Results at varying warning expiration times

Previous results were calculated with a 15-minute warning expiration time, which 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 in Table 6:

- There are 19% more storms for 10 minutes' warning expiration time than at 15 minutes' warning expiration time, within the 15-km outer range
- The POD2 is slightly better at a 15-minute expiration time than at 10 minutes.
- Failures to warn increase somewhat for the shorter warning expiration time.
- The FAR at 10 minutes is slightly worse than at 10 minutes.

- The duration of valid warnings for 10 minutes expiration time is 15% less than for 15 minutes.
- The duration of false alarms is 12% less at 10 minutes than 15 minutes.

The change to a shorter warning expiration time for CG plus cloud data has had a slight negative effect. 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 slightly less, and the number of false alarms slightly more. The only benefit is that less time is spent under valid warnings because the storms are ended after 10 rather than 15 minutes. 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 6. Same as Table 1, except to add warning expiration time of 10 minutes at outer warning radius of 10 km for CG strokes plus cloud pulses.

Warning expiration time in minutes	Storms	POD2	FTW	FAR	Time in valid warnings	Time in false alarms
10 minutes	787	0.95	0.05	0.95	0.17%	1.18%
15 minutes	660	0.97	0.03	0.94	0.20%	1.32%

5. PERFORMANCE COMPARISONS AT 4.8 VERSUS 0.5 KM INNER RADII

Lightning warning statistics have been developed at two sizes of vulnerable facilities. A 4.8-km radius includes 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 radius of 0.5 km.

Figures 5 and 6 compare results that cut across those shown in the previous tables. All of these results are for a 10-km outer radius, and are per airport. The number of storms in Figure 5 is shown to be quite similar for all four settings. However, the number of false alarms is substantially more for the smaller inner area. Figure 6 shows that the number of hours with valid warnings drastically reduces when the smaller inner area of 0.5 km is considered. However, the number of false alarms steadily increases. Anticipating lightning over the area of a smaller property can be accomplished somewhat better than a larger airport, but the penalty is a larger FAR and time under false alarms.

6. CONCLUSIONS

Two topics related to issuing lightning warnings at airports were addressed. The first was to verify prior results of adding cloud pulses to CG strokes with a much larger dataset. The second was to greatly reduce the warned area to a small section of an airport rather than the entire property.

The first topic was to verify the added value of cloud pulses for CG 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 for the summer of 2014 across much of the U.S. were considered. Ten points were chosen to sample different storms and storm types. Verification was for presence of CG strokes from the NLDN. It was found that thunderstorms from the large 2014 sample had comparable warning statistics to those found previously. The probability of detection for a two-minute warning, POD2, was 0.77 for a 15-minute warning expiration time and a 4.8-km inner warning area. In addition, the false alarm ratio of 0.69 and warning durations were similar to previous conclusions. The much larger 2014 sample confirms the 2013 study that showed cloud pulses increasing POD2 by 13%.

The second topic was to significantly reduce the airport property to be warned from a radius of 4.8 km in all previous studies to 0.5 km. POD2 increased from 0.90 for the larger inner area to 0.97 for the smaller inner area to be warned. The FAR also significantly increased from 0.72 to 0.96 for CGs plus cloud pulses. A reduction in the outer radius from 15 km to 10 km showed it to be somewhat preferable; a 5-km outer radius has worse performance than 10 or 15 km. For a warning longer than two minutes, the quality of warnings was somewhat better with the addition of cloud pulses; for example, POD10 was 0.85 and 0.67 at 20 minutes. These analyses were for a 15-minute warning expiration time. When the warning expiration time is 10 minutes, there is a small but negative effect on most parameters. Finally, the net effect of reducing the inner radius from 4.8 km to 0.5 km resulted in the same number of storms but a large increase in false alarms. Most dramatic was a decrease in hours with valid warnings for the smaller area while the hours with false alarms increased for the smaller area.

In conclusion, the value of NLDN cloud pulse data relative to CG strokes only is confirmed. And, the smaller inner area of 0.5-km radius has better warning statistics than the 4.8-km radius, but there are also more false alarms.

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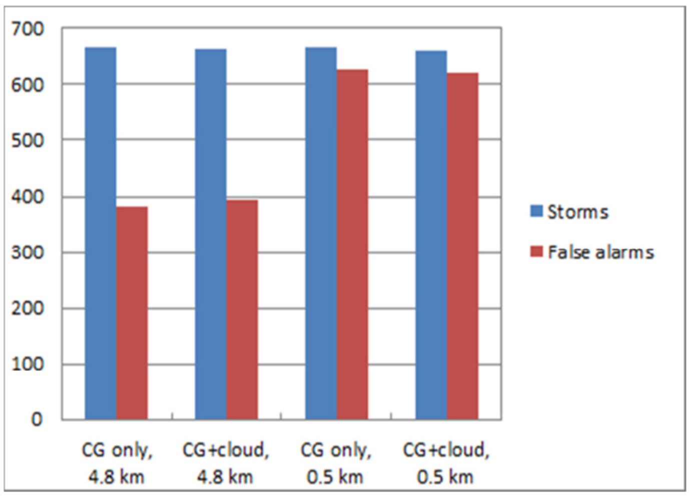

FIG. 5. Number of storms and false alarms per airport at inner radii for 0.5 and 4.8 km for CG strokes only, and with cloud pulses. Outer radius is 10 km.

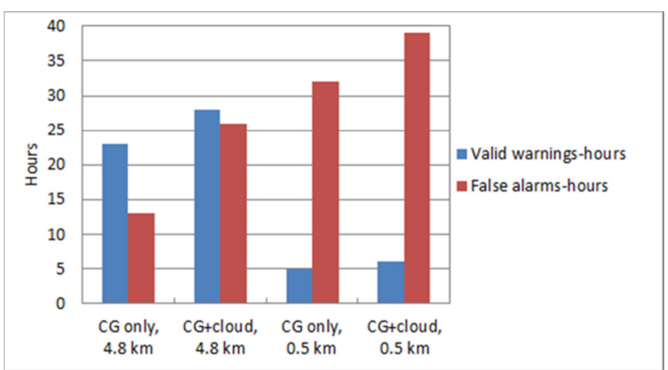

FIG. 6. Number of hours of valid warnings and false alarms per airport for inner radii of 0.5 and 4.8 km for CG strokes only, and with cloud pulses. Outer radius is 10 km.

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