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Preliminary Analysis of Lightning Warnings in and near the Rocky Mountains using U.S. National Lightning Detection Network and Electric Field Mill Data

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Abstract— **Measurements of electrostatic field are known to provide some marginal value in lightning warning applications, above and beyond that provided by lightning locating systems (LLSs). However, when a simple electric field threshold is used, numerous false alarms also typically occur. To date, most analysis of the utility of electrostatic field measurements in lightning warning have taken place either very close to sea level (e.g. Kennedy Space Center / USAF Eastern Range, Puget Sound, Nanjing, China) or at fairly low altitude (northeastern Spain). These studies have all utilized measurements taken by one or more Electric field mills (EFMs). EFM networks have been installed at high altitudes in Colombia (at Medellín, 1600 m MSL, Manizales, 2000 m, and Bogotá, 2700 m), but to date, only one analysis of the contribution to lightning warning from an EFM at 1600 m in Medellín has been published. One case of EFMs deployed in a moderately high-desert environment (White Sands Missile Range, NM, U.S., 1200 m MSL) showed false alarms due to blowing dust. High-altitude environments are important in applications such as mining and recreation. High-altitude sites differ significantly from near-sea-level sites in the proximity of the thunderstorm charge centers to the ground, and they may also differ significantly in the dominant mechanisms of thunderstorm development and propagation. For example, whereas sea breezes are a major factor in the development of thunderstorms in coastal sites such as Kennedy Space Center, they are completely absent in high-altitude, interior continental locations. In order to augment the diversity of information available about the contribution of electrostatic field measurements to lightning warning applications, we have taken EFM measurements during the summer of 2015 on the roof of the Vaisala facility in Louisville, CO, U.S., at an altitude of 1640 m MSL and adjacent to the eastern slope of the Rocky Mountains. Although this site is not directly in the highest terrain, it is in a transitional area where thunderstorms can occur due to a variety of synoptic and mesoscale forcing mechanisms but upstream of where storms often organize into well-defined propagating lines or mesoscale convective systems. This site at mid-latitudes is expected to be quite distinct from the near-equatorial Medellín. In this paper, we present our initial findings based on the EFM data, along with some preliminary comparisons of thunderstorm behavior between the adjacent mountains and the Vaisala facility based on U.S. National Lightning Detection Network (NLDN) data, in order to make some inference about the utility of EFM measurements in the higher terrain.**

Keywords—lightning warning; EFM; electrostatic field; high altitude

I. INTRODUCTION

Lightning warning is a critical component of the effort to protect people from lightning risk. Numerous studies in various parts of the world have shown that the populations most vulnerable to lightning injury and death are those in rural areas where dwellings often do not provide adequate protection and/or a lot of work takes place outdoors, particularly in agriculture (e.g. Raga et al. 2014, Gadge and Shrigiriwar, 2013, Dlamini 2009, Navarrete et al. 2014, Zhang et al. 2012). Recreational activities are also a frequent source of lightning casualty, as documented by, e.g., Mills et al. (2008), Gadge and Shrigiriwar (2013), and Jensenius (2014).

Mountainous areas are often the site of both outdoor labor activities, particularly mining, and numerous types of recreational activity. Indeed, Ashley and Gilson (2009) found that the U.S. state of Colorado, which has the highest average terrain altitude among states in the continental U.S., ranked 4th among all U.S. states in terms of lightning fatality rate, despite its much lower ranking in population (22nd as of 2014), and Roeder et al. (2014) noted that Colorado has a higher lightning casualty rate than surrounding mountainous western U.S. states because of the high incidence of recreational activity. To complicate matters further, high-altitude sites can be particularly challenging in terms of advance warning of lightning threat: The diurnal cycle of thunderstorm activity in the vicinity of high terrain shows that the mountains are frequently the first place where thunderstorms develop each day (e.g. Holle 2014, and Holle and Murphy 2015, regarding the diurnal cycle of the North American monsoon). Indeed, Hodanish et al. (2004) documented a case of a small cloud that developed directly over a 4300-m peak and produced a single cloud-to-ground flash that resulted in a fatality.

A number of studies have shown that lightning locating systems (LLSs) are effective in lightning warning because most thunderstorms approach from elsewhere rather than forming directly overhead (e.g. Murphy and Holle, 2005, 2006, 2008). In a few studies, it has been inferred that on the order of 10% of storms develop overhead (e.g. Murphy et al. 2008, Holle et al. 2014). That inference has been made both on the basis of direct analysis of cloud-to-ground (CG) lightning detection data (Murphy et al. 2008) and by inference from the gain in probability of detection from the addition of cloud lightning data to CG data (Holle et al. 2014). It is important to note, however, that these analyses were done in locations that are mostly or entirely away from high terrain. Given what is noted above about the first thunderstorm development of the day in high terrain, it is quite possible that a larger percentage of storms develop directly overhead at high-altitude sites than elsewhere.

To date, the literature has described three main ways of detecting the development of thunderstorms, and at least two of them are specific to the first lightning flash (the 3rd being geostationary satellite-based detection of convective initiation – see Mecikalski et al. 2015). Radar can detect the development of precipitation in the mixed-phase region of the cloud, where electrification takes place, and dual-polarization radars offer the additional advantage of the specific identification of ice. In the context of the lightning warning problem, Woodard et al. (2011) and references therein have discussed the use of single- and dual-polarization radar data. To be effective at detecting the conditions conducive to electrification, however, the radar beam does have to sample the relevant range of altitudes. Furthermore, the detection of precipitation in the right temperature band to produce electrification is not a guarantee of sufficient charge separation to produce lightning. Aside from radar, electric field mills (EFMs) can be used to detect the slow change in the quasi-static electric field that is associated with charge separation. Unlike radar, this is a direct detection of charge separation. However, EFMs are short-range instruments, detecting significant departures from the fair-weather electric field only over distances from a few km to perhaps as much as 20 km, and they are subject to false detections due to non-lightning related charge separation from dust storms, blowing snow, and charged raindrops. EFMs have been applied to the lightning warning problem primarily at sites either at or near sea level (e.g. Hoeft and Wakefield, 1992, Murphy et al. 2008, Zeng et al. 2013) or in modest terrain at or below about 1000 m MSL (Rison and Chapman, 1988, Montanyá et al. 2004, Aranguren et al., 2009, Ferro et al. 2011).

We are aware of only one study, López et al. (2012), in which electric field measurements made at a mountainous site were systematically applied to the lightning warning problem. That site is Medellín, Colombia, at 1600 m MSL and about 6.25 °N latitude in the deep tropics. The López et al. study is quite relevant insofar as Colombia has also been the focus of a detailed study of lightning casualties (Navarrete et al. 2014). Obviously, one study provides no geographic or climatological diversity in the use of electric field measurements at high altitudes in the lightning warning problem. Our objective in this paper is to add a mid-latitude site to increase slightly that diversity of information. Specifically, we present electric field and lightning observations between July 3 and December 18, 2015, (most of the 2015 thunderstorm season plus some of the post-season) at the Vaisala facility in Louisville, CO, U.S., at an altitude of 1640 m MSL and latitude of 39.97 °N.

II. METHODS

A. General

In our prior studies of lightning warning methods, such as Murphy et al. (2008), we considered an *Area of Concern* (AOC) surrounding the central point of interest of the warnings. The AOC is typically designed to represent the area in which CG lightning is sufficiently close to be threatening. The AOC may double as a buffer zone to take into consideration the size of a large facility such as an airport. The AOC is typically surrounded by a second region called the *Warning Area* (WA). The primary purpose of monitoring lightning activity within the WA is to provide advance notice of the possibility of CG lightning in the AOC. Once a warning is initialized, a count-down timer referred to as the *dwell time* is initiated. Each time that a new lightning discharge or other warning-triggering event occurs while the dwell time has not yet expired, the timer is restarted. The purpose of the dwell time is to serve as the time period over which one would normally wait at the end of each thunderstorm episode before considering it safe to resume outdoor activity. A standard value is 30 minutes, following the convention of the “30-30 rule” and subsequent lightning safety guidelines (Roeder, 2008).

B. Prior literature

In their study over Medellín, Colombia, López et al. (2012) used a dwell time of 30 minutes. The AOC and WA were both circles with radii of 10 and 20 km, respectively. The electric field threshold was 2 kV/m, although they used not just a field threshold, but rather, a combination of that plus field rate-of-change plus field changes due to lightning. They did not specifically indicate that any smoothing was applied to the electric field data, but given the reliance on both the rate of change of the field and the sudden changes in field due to lightning, we suspect that no smoothing was applied. Note that, according to López et al. (2012), a more detailed description of the Medellín EFM and associated data collection was given in a 2006 thesis by Aranguren, but repeated on-line searches for that document failed to provide an electronic copy of it, and thus, we have inferred the above information based on the López et al. paper alone.

Aranguren et al. (2009) deployed an EFM in Terrassa, Spain, at an altitude of approximately 300 m MSL, over two summer seasons. The AOC in their study was also a circle with a radius of 10 km, and the dwell time was set to 30 minutes. The WA was not used, because the warning decisions were based solely on the EFM data. In the first instance, a simple electric field threshold was applied, and the characteristics of the warnings were examined as that threshold was varied between 0.1 and 3.0 kV/m. Following that, these authors also examined the use of polarity reversals as the means of triggering warnings. In all cases, the raw electric field observations were smoothed with a 60-second running average in order to focus on the slowly-varying field changes associated primarily to the electrification process and avoid rapid changes in field due to lightning discharges.

Murphy et al. (2008) used data from two EFMs at the NASA Kennedy Space Center. In their study, the dwell time was set to 15 minutes. The AOC and WA were both boxes, rather than circles, that extended out ±10 and ±20 km from the center point. Electric field thresholds of 1 kV/m and 2 kV/m were used. Unlike López et al. (2012), no additional electric field criteria other than the basic threshold were applied in the warning analysis. The EFM data were originally sampled at a rate of 50 Hz, but similarly to Aranguren et al. (2009), the goal was to look at the slowly-varying field changes, and therefore, Murphy et al. (2008) smoothed the EFM data with 10- and 60-second running averages, ultimately finding that 10-second smoothing produced better warning performance.

The warning rules used by Murphy et al. (2008) were that a warning was only triggered if (a) lightning was observed in the WA and 1 EFM was above threshold, (b) both EFMs were above threshold, or (c) lightning occurred in the AOC. Relative to the case where lightning in the WA by itself was allowed to trigger, the EFM-inclusive set of rules actually performed somewhat worse because at least one high field was required in addition. Thus, the rules used by Murphy et al. (2008) and those used by López et al. (2012) and Aranguren et al. (2009) are not directly comparable. When one or two smoothed electric field values were required to be above threshold as part of the warning rules, the best performance (both highest POD and lowest FAR) was found with 10-second smoothing and 1-kV/m threshold.

More recent studies have employed more complex methodology, and not always with detailed explanation. Zeng et al. (2013) used electric field data sampled at one-second intervals at four separate sites near Nanjing, China, at or below about 100 m MSL altitude. The warning rules were all based on a combination of radar and electric field information, not just electric field alone. The rules involved in the warning involved the absolute electric field exceeding a threshold over a certain fraction of the time covering three radar scans, or at least two jumps in electric field exceeding a different threshold within a time covered by two radar scans. The optimal field threshold was found to be 1 kV/m, and the optimal threshold of the one-second jumps in field was found to be 0.15 kV/m/s. Srivastava et al. (2015) modeled the evolution of electric field as a Markov chain. The EFM was located in northeastern India at an altitude of 609 m MSL. Srivastava et al. noted that the electric field "variation" was stored every minute of the day, but it was not clearly stated whether that was a one-minute average of data sampled at a higher rate, or an instantaneous value. Based on five ranges of absolute electric field, five states were defined, with the final state being the one associated with lightning warning. On the basis of the one-minute data, lightning warnings were triggered when the probability of transition to that final state was greater than 0.15.

C. *Specific methods used in this study*

A Vaisala EFM550 was installed in the central roof area of the north building of the Vaisala facility in Louisville, Colorado. Standard roof-mounting practice was used, and the EFM was located in the middle of a flat roof approximately 10 m from the roof edge and approximately 10 m from the roof access area, a small room with a height of approximately 3 m above the roof line. The enhancement factor was set to 1.0, consistent with a standard roof mount, and this resulted in typical fair-weather electric field readings of 0.04 to 0.08 kV/m. ASCII data with a resolution of 0.04 kV/m were logged to a file beginning on 2015-07-02. During the initial three weeks of operation, the data were recorded once every 10 seconds, but starting at 20:00 UT on 2015-07-24, the sampling rate was increased to once per second. Both sampling rates automatically introduced some smoothing of lightning-caused electric field changes, and thus, we did not apply any further smoothing prior to using the data in this study.

Due to an intermittently bad contact in the sensor head prior to 2015-11-09 21:40 UT, there were occasional jumps of approximately ±1 kV/m during times when the field was at or below about 1 kV/m. The problem was fixed at 21:40 UT on 2015-11-09, too late to catch any thunderstorms, but prior to the first major snowfall of the season. Several attempts were made to correct the jumps, but all were only partly successful. Because nearly all of the jumps occurred during low-field conditions, rather than attempting to correct the data, we opted simply to extract all periods of time that had fields in excess of ±1.5 kV/m with a 30-minute buffer on either side of the first and last crossing of that field value. Please note that the value of ±1.5 kV/m was selected only as a means of avoiding the majority of the false jumps, not as a warning criterion.

Lightning data from the U.S. National Lightning Detection Network (NLDN) were used both as part of the warning triggering criteria and as the validation data set. The "two-region" approach (Murphy and Holle, 2006) was adopted, using concentric circles as the area-of-concern (AOC) and warning area (WA). The center of the AOC was initially collocated with the EFM site at latitude, longitude of 39.97, -105.12. In addition, in order to assess the differences in the lightning-only warning performance between the EFM site and a higher-altitude location nearby, we also set an AOC and WA centered on a popular mountain recreational area located 40 km from the Vaisala facility at an altitude of 3200 m MSL. No EFM is currently available at that location, but we are able to compare the performance of lightning-only warnings using NLDN data at the two locations.

The specific warning parameters and triggering rules in this study were set as follows: The dwell time was set to 30 minutes, as in both López et al. (2012) and Aranguren et al. (2009). The AOC and WA were circles with radii of 10 and 20 km, respectively. All warnings in which at least one CG stroke was ultimately observed in the AOC were "effective alarms" in the terminology used by both López et al. (2012) and Aranguren et al. (2009), and warnings in which no CG occurred in the AOC were false alarms. When lightning data alone were used to trigger warnings, any discharge, whether cloud or CG, within either the AOC or WA was permitted to trigger a warning; this is referred to as the "lightning only" rule in the remainder of the paper. When the EFM at the Vaisala facility was included, warnings were triggered under one of two conditions: (1) lightning occurred in the WA OR the electric field reached ±2 kV/m, or (2) lightning occurred in the WA AND the electric field reached ±2 kV/m. Note that the only difference between these two is the boolean condition related to the use of the electric field. If the first occurrence of lightning within the AOC was due to a CG stroke, a warning was triggered automatically and was considered a failure to warn. In practice, in storms over the Vaisala facility, this situation only occurred when the second condition above (the "lightning AND electric field rule") was applied, but it did occur in the lightning-only analysis at the 3200-m site in the nearby mountains.

To assess the performance of warnings, we use standard contingency-table metrics of the type used in our past studies. Cases in which CG lightning was observed in the AOC are assessed by the probability that at least 2 minutes of lead time were provided prior to the first CG stroke in the AOC, the so-called "POD2" used in Holle et al. (2014) and other prior studies. Cases in which fewer than 2 minutes of lead time were provided are classified as failures to warn (FTW). The false alarm ratio (FAR) is the usual metric of the percentage of warnings in which no CG lightning was ultimately observed in the AOC.

III. RESULTS

A. *Warnings at the Vaisala Louisville faciliity with and without EFM*

During the period of analysis, there were 17 separate episodes when CG lightning was observed over the AOC around the Vaisala facility. The three essential metrics of warning performance, POD2, FTW, and FAR, are summarized in Table I, based on three warning triggering rules: (1) lightning in the WA OR electric field reaching ±2 kV/m, (2) lightning in the WA AND electric field reaching ±2 kV/m, and (3) lightning only. The 100% POD2 value in the lightning-only case shows that all storms that produced CG lightning within the AOC had at least some lightning activity in the WA at least 2 minutes prior to the first CG stroke in the AOC. Thus, in these 17 storms, the EFM was not able to improve upon the POD2. Rather, when the electric field was required to reach ±2 kV/m in addition to lightning in the WA, the POD2 was reduced significantly. Of course, the FAR is also reduced significantly when the electric field and lightning are both required, as opposed to the lightning-only and lightning or electric field cases.

TABLE I. WARNING PERFORMANCE METRICS AT THE VAISALA FACILITY WITH AND WITHOUT EFM DATA

	Lightning in WA OR EFM	**Lightning in WA AND EFM**	**Lightning only**
POD2 (%)	100.0	70.6	100.0
FTW (%)	0.0	29.4	0.0
FAR (%)	78.2	43.3	71.2

Although the POD2 was obviously unchanged in going from the lightning-only to the lightning OR electric field rule, the warning lead times were improved in the latter case. In eight of the 17 storms with CG lightning in the AOC, the lead time increased between 1 and 5 minutes in the lightning OR electric field case relative to the lightning-only case. Overall, the median lead time over the entire set of 17 storms improved by one minute, from 19 to 20 minutes.

The addition of the electric field in the lightning OR electric field case also raised the FAR from 71.2% to 78.2%. That deceptively small increase in terms of percentage points is actually associated with an increase in the total number of false warnings from 42 in the lightning-only case to 61 when the electric field threshold is included. Most of the additional false alarms occurred on days when there were already false alarms due to lightning in the WA but not the AOC, suggesting that electrified clouds were either sufficiently close or sufficiently sheared to produce high electric fields that led to additional false alarms on days when thunderstorms were already in the area. Three of the additional false alarms occurred in the month of November and were all associated with wet snow events that did not produce lightning anywhere within 20 km of the Vaisala facility.

B. *Lightning-only warnings between the Vaisala facility and the nearby high-altitude site*

Table II compares the warning performance metrics using only lightning data at both the Vaisala facility (a repeat of the final column of Table I) and at the nearby recreation area at 3200 m altitude. At the latter site, there were 29 storms that produced CG lightning within the AOC during the same time period of analysis. In the high terrain, the occurrence of lightning within 20 km is much less likely to provide at least 2 minutes of warning than at the lower-altitude site, but also substantially less likely to result in a false alarm. This suggests that thunderstorms more often develop directly overhead in the high terrain, but that they are also less likely to produce lightning only within the WA on many thunderstorm days. The higher FAR at Louisville may also be partially attributed to the fact that it is often to the west or northwest of the convergence line associated with the Denver cyclone (see, e.g., Wilczak and Glendening, 1988 and Wilson et al. 1992), leading to thunderstorms that develop over the eastern part of the WA but then propagate away from the site without generating any lightning in the AOC.

TABLE II. WARNING PERFORMANCE METRICS USING LIGHTNING DATA ALONE

	Vaisala facility (1640 m)	**Recreation area (3200 m)**
POD2 (%)	100.0	65.5
FTW (%)	0.0	34.5
FAR (%)	71.2	51.7

The cumulative distributions of lead times between the Vaisala and mountain sites are presented in Figure 1. The comparison is very interesting, showing that not only does the high-terrain site have a much larger proportion of near-zero lead times (failures to warn), but it also has a much longer tail of very long lead times than the Vaisala facility. The latter behavior suggests that, in addition to the days when thunderstorms develop nearly simultaneously in many places within 20 km, there is also a sizable population of days on which the storm development progresses very slowly from some portion of the WA into the AOC. In both the very short and very long lead-time cases, it seems that the mountain site would benefit greatly from the combination of electric field measurements with lightning data. Our future plans are to extend this study by deploying an EFM at a mountain recreational area or ski resort at the same time as we continue measurements of electric field at the Vaisala facility in order to ascertain the relative importance of electric field data in the high mountains.

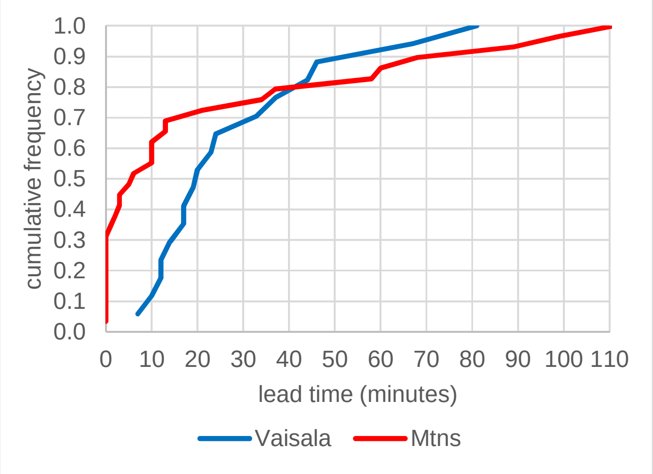

Fig. 1. Cumulative distributions of lead times in storms over the Vaisala facility and the mountain site

In only two cases did a long lead-time storm and a short lead-time storm occur on the same day at the site in the mountains. On 14 August, a failure to warn case occurred at 20:41 UTC, followed at 23:34 by a second period of CG lightning in the AOC where the lead time provided by lightning in the WA was 99 minutes. As indicated by the 12:00 UTC sounding from Denver (70 km ESE of the mountain site), the winds from 3200 m up through the mid-troposphere were around 2.5 m/s from the north (nearly parallel to the mountains), and the convective available potential energy (CAPE) from the 700-mb level (roughly 3200 m) up was fairly weak. Thus, 14 August case was likely a case of off-and-on air-mass thunderstorm activity over the whole area that happened to result in an extended break in lightning within the AOC itself, and the episode at 23:34 UTC happened to be preceded by a long period when lightning occurred somewhere within the WA. On 29 September, the first episode of CG lightning in the AOC actually had 60 minutes of advance warning from lightning in the WA, and this was followed a few hours later by two more episodes with lead times of 3 and 0 minutes. By contrast with 14 August, the 12:00 UTC sounding on 29 September indicated 15-20 m/s westerly winds (perpendicular to the mountains) at and above the 3200 m level and a nearly saturated, moist adiabatic atmosphere. By 00:00 UTC on 30 September, closer to the time of the late-afternoon thunderstorms, the mid-troposphere was significantly destabilized and the westerly winds increased to between 20-30 m/s in the mid-levels. Thus, all three of the episodes of lightning in the AOC on 29 September were due to propagating storms, and a simple analysis of the soundings does not reveal an immediately obvious meteorological explanation of the difference between the long and short lead-time episodes.

Only three additional cases of very long lead time storms at the mountain site were noted, and all occurred in July and August. Similar to the 14 August case, the 12:00 UTC sounding suggested fairly weak CAPE above the 700 mb level in all three of these cases, and in two of the three, mid-tropospheric winds were quasi-parallel to the highest terrain, although somewhat faster than on 14 August.

The remaining cases of very short lead time (0-2 minutes) were split between four summer days (18 July, 2, 15, and 31 August) and three autumn days (23 September, 2 and 20 October). Based on the Denver sounding data, the common feature of all but one of these days (23 Sept.) is that the winds at and above the 3200-m level were nearly perpendicular to the highest terrain, although with speeds ranging anywhere from about 5 to about 30 m/s. Although our sample size is obviously quite small, we can at least tentatively suggest that near-zero lead times at the 3200-m site are more likely to be associated with winds perpendicular to the highest terrain, while long lead times are typically associated with winds nearly parallel to the highest terrain. Such tentative conclusions definitely need to be confirmed with additional data from additional storm seasons, but they nevertheless may help to clarify under what circumstances an electric field measurement might be most useful in the high terrain.

C. Comparison with prior literature

López et al. (2012) found that when they included the various electric field criteria (threshold of ±2 kV/m, plus rate of change of field, plus field changes due to lightning), the number of false alarms increased by more than a factor of 2, while the number of effective alarms increased by only 4 (from 24 to 28). They found that a much better balance between POD and FAR could be achieved by dropping the electric field threshold and considering only the electric field rate of change and the field changes due to lightning. Although we cannot compare our results directly with those of López et al. (2012), we note that the total number of false alarms in our case increased less dramatically than in López et al.: somewhat less than 50% in our case in going from the lightning-only case to the case where we used lightning or the electric field threshold of ±2 kV/m.

In an analysis of warnings based solely on lightning data over Colombia, Inampués et al. (2009) found that the highest terrain areas of northern and central Colombia were associated with a distinct maximum in FAR and minimum in POD. The POD values over the high mountains in that study were consistently between 30-50%, and FAR was generally 90% or greater. Though not called out specifically, the area around Medellín appeared to have POD values in the 60s and FAR values in the 70s in the analysis by Inampués et al. (2009), consistent with the values denoted as the “Classic” method in López et al. (2012). In our case, we find a reduction in POD2 in going from 1640 m to 3200 m. This reduction is associated with the nearly simultaneous development of thunderstorms over the AOC and the WA. However, we also find that the FAR is almost 20 percentage points lower at 3200 m than at 1640 m, in contrast with Inampués et al. (2009). At least part of the difference is almost surely attributable to the larger size of the WA (30 km) used by Inampués et al. (2009) vs. our 20 km, but it would also be reasonable to assert that differences in the climatology of thunderstorm development and propagation between the deep tropics and mid-latitudes also exert an influence over the FARs in the two locations. That effect remains to be quantified.

At the NASA Kennedy Space Center, Murphy et al. (2008) found that the best combination of POD and FAR was obtained when the electric field threshold was set to ±1 kV/m and when the 50-Hz electric field values were smoothed using a 10-second running average. When they required at least one electric field value to cross the threshold of ±1 kV/m in addition to lightning in the WA, the POD dropped (as expected) but the FAR actually increased relative to the lightning-only case. However, many of the extra false alarms in that study were found to be associated with the fact that warnings were also allowed if two neighboring electric field measurements both crossed the threshold of ±1 kV/m. When that additional allowance was dropped, both POD and FAR were found to be lower under the lightning-and-electric field rule than under the lightning-only rule: 30% POD and 60% FAR vs. 67% POD and 68% FAR, respectively. When we apply the lightning-and-electric field rule at 1640 m and nearly 40° latitude, we attain a higher POD of 70.6% and lower FAR of 43.3%. The latter result is consistent with the anticipation by Murphy et al. (2008) that the FAR might be lower at a high-altitude location where the EFM is physically closer to the thunderstorm charge center and a higher electric field threshold than at KSC could be applied.

Consistent with the KSC results, when an electric field threshold was used as the warning-triggering mechanism by Aranguren et al. (2009), they found that a low threshold (0.8 kV/m in their analysis) was required to produce optimal warning performance at their location, which was at 300-m altitude. However, they also noted that better warning performance overall was achieved by switching from the use of a simple threshold to the use of polarity reversals to trigger warnings.

IV. CONCLUSIONS

In this study, we have used electric field measurements at an altitude of 1640 m at a mid-latitude station to add some geographic diversity to the study of how lightning warning performance is affected by the use of electric field data in combination with lightning location data. Compared with Medellín, Colombia, a tropical site with similar altitude (1600 m), we find that the use of an electric field threshold does not raise the FAR as dramatically at our mid-latitude site as it does at Medellín. Similarly, we find that using lightning data alone at an even higher-altitude site does not increase the FAR, as it does in Colombia, but rather decreases it relative to the site at 1640 m. With respect to a site at sea level, the combination of an electric field threshold and lightning data in the WA produces a much lower FAR at 1640 m, consistent with the expectation that when the thunderstorm charge centers are closer to the EFM, the FAR can be reduced by the use of a higher electric field threshold.

The current study suffers from a low sample size, because only 17 thunderstorms with CG lightning in the AOC were observed at the 1640-m site while the EFM was operational, and all of these are from just a portion of one thunderstorm season. Over the same time period, only 29 storms with CG lightning in the AOC were observed at the 3200-m site. Future studies will expand upon this preliminary analysis by having continuous operation of the EFM over a longer time period. In addition, we will also deploy a second EFM in the highest terrain near the Vaisala facility in order to evaluate the effect on warning performance there.

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