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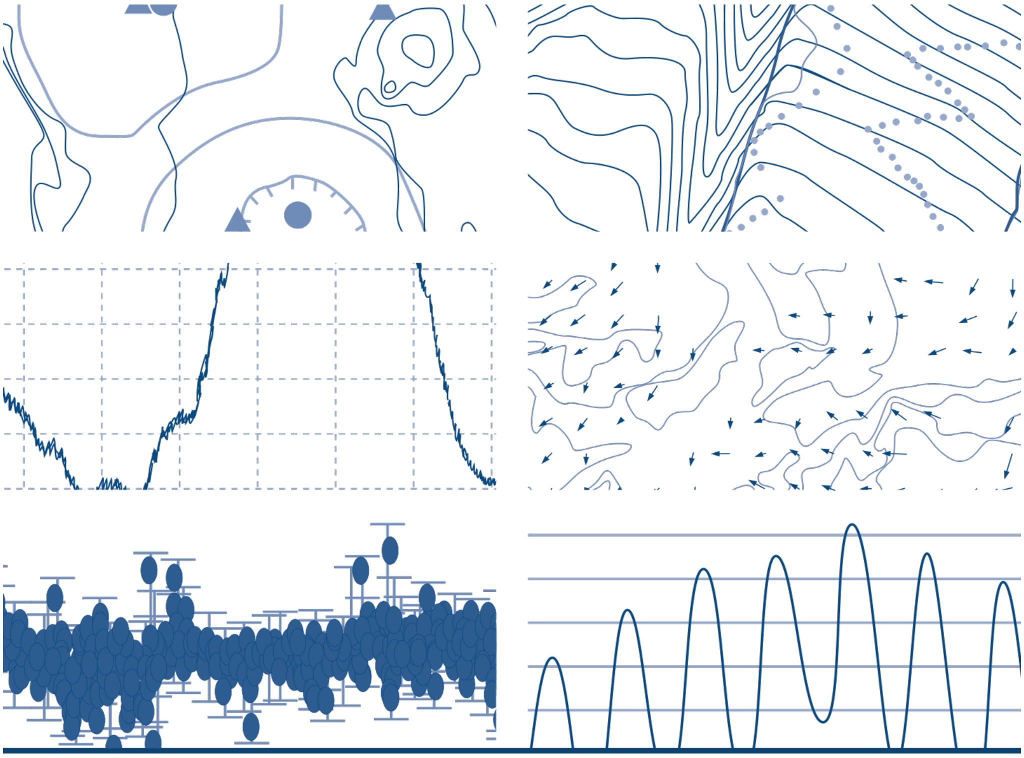

Estimation of eruption site location using volcanic lightning

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Guðrún Nína Petersen
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Report
VÍ 2013-006

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Summary:

An automatic monitoring system has been developed that predicts the location of a volcanic eruption site in Iceland using real-time lightning location data during the early hours of an eruption. The system delivers E-mail warnings and publishes location analysis on the web. Currently the analysis of the system is updated every 10 min. The essential elements of this prototype system are described in this report.

Keywords: Volcanic eruptions, Volcanic lightning, vent location	**Managing director's signature:** **Project manager's signature:** **Reviewed by:** TrJ

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Introduction

Eruption of subglacial volcanoes may lead to catastrophic floods and therefore early determination of the exact eruption site may be critical to civil protection evacuation plans. Poor visibility due to weather or darkness often inhibit positive identification of exact eruption location for many hours. However, because of the proximity and abundance of water in powerful explosive subglacial volcanic eruptions, they are probably always accompanied by early lightning activity in the volcanic column.

Lightning location systems, designed for weather thunderstorm monitoring are based on remote detection of electromagnetic waves from lightning and can provide valuable real-time information on location of eruption site. Important aspect of such remote detection is its independence of darkness and weather, apart from thunderstorms close to the volcano. However, the fact that individual lightning strikes can be over 10 km in length and are sometimes tilted and to the side of the volcanic column must be taken into account. This adds to the lightning location uncertainty, which is often a few km. Furthermore, the volcanic column may be swayed downwind, e.g. see Figure 1. Therefore, location of a single lightning can be misleading but by calculating average location of many lightning strikes and applying a wind correction a more accurate eruption site location estimate can be obtained.

A prototype of an automatic system at the Icelandic Meteorological Office (IMO) has been developed that analyses such real-time lightning location data and predicts the eruption site location. This report describes this system.

Development of this system was a part of the EU-FP7 Futurevolc project, WP7, Task 7.1:

> Lightning detection networks: Existing lightning detection networks will be used to locate eruption source and study plume dynamics. Lightning location data from explosive eruptions in Iceland during the last 15 years will be used to assess the prospects and estimate uncertainty in providing initial real-time estimates of location of volcanic vents, also using a wind correction from operational weather prediction models. A real-time processing system will be developed and made operational for this purpose.

A dormant automatic monitoring system waiting for a rare event, potentially for several years, is quite susceptible to degeneration during the waiting period, e.g. due to computer or other IT-system upgrades. However, ordinary weather thunderstorms in Iceland should initiate special monitoring and automatic analysis of this system in the same fashion as during a volcanic eruption. Such ordinary weather thunderstorms can be used to observe anomalies and malfunctions in the system.

Figure 1. Plume lightning during the Eyjafjallajökull 2010 eruption. The plume was blown southward (to the right on this photo) by strong northerly winds. Location of this lightning is far from the eruption site. Photo Þórður Arason from a 72 km distance on 17 April 2010 at 04:47:09 UTC (30 s exposure time).

Lightning location data

Lightning is an electric current through air which occurs when electric charges accumulate to a point where the electric charge difference and thus the electric field between two places becomes too high. The lightning current leads to an electromagnetic wave that can be observed over great distances (>10 000 km). The web site of the IMO includes lightning information from the ATDnet system (Arrival Time Difference) of the UK Met Office. This system is based on several out-stations in and around Europe and has been operational since 1988, see Figure 2. One of its stations at Keflavík airport in Iceland is supported by the IMO. Through an agreement between IMO and the UK Met Office, the IMO has full access to the real-time lightning data for internal applications but not for distribution.

The out-stations operate in the VLF frequency (13.7 kHz) and record the arrival time with great accuracy. Data from at least four stations are needed to locate a lightning. The ATDnet system observes both intracloud and cloud-to-ground lightning, but because it observes variations in the local vertical electric field, the system is more susceptible to vertical (cloud-to-ground) lightning. Detailed description of the ATDnet system and its use in monitoring volcanic lightning is given by Gaffard et al. (2008), Bennett et al. (2010), and Arason et al. (2011).

Figure 2. The out-stations of the ATDnet lightning location system in operation during the Grímsvötn 2011 volcanic eruption.

It is possible that an ordinary weather thunderstorm might coincide with a volcanic eruption, and this might affect the analysis of the system. However, thunderstorms are rare in Iceland and during the past 15 years of which lightning data are available, 1998–2013, there were no clear indications of weather thunderstorms in Iceland during volcanic eruptions. About 10% of the days during this 15-year period had lightning activity recorded somewhere in Iceland, and about 0.6% of the days involved volcanic lightning activity. Usually each weather thunderstorm in Iceland has only a few lightning strikes while many are recorded during eruptions. During this 15-year period 73% of the recorded lightning strikes in Iceland were volcanic in origin, but note that this number is greatly influenced by one eruption, Grímsvötn 2011.

Table 1 summarises the located lightning by the ATDnet system during volcanic eruptions in Iceland 1998–2011 (the Hekla 2000 data are from the local LLP system). The date and time of the initiation of the eruption is given, and the time from the initiation to the first recorded lightning. The number of lightning is given for the first 1–24 hours of the eruption, from the eruption onset. Grímsvötn 2011 eruption stands out in the number of lightning as well as in the early lightning activity.

Table 1. Number of lightning during volcanic eruptions in Iceland 1998–2011.

Volcano	Eruption initiation	First lightning	Number of lightning <1h	<3h	<6h	<12h	<24h	Total
Grímsvötn	1998-12-18 09:20	2 h	0	1	20	121	167	183
Hekla	2000-02-26 18:17	41 min	1	4	6	6	6	6
Grímsvötn	2004-11-01 21:50	4 h	0	0	15	59	142	251
Fimmvörðuháls	2010-03-20 23:34	-	0	0	0	0	0	0
Eyjafjallajökull	2010-04-14 01:15	17 h	0	0	0	0	10	790
Grímsvötn	2011-05-21 19:00	15 min	888	3340	6484	11729	16041	16195

The monitoring system

There are two main parts of the system; an E-mail warning system and a web site presenting results of the location analysis.

The real-time lightning data is retrieved by IMO from UK Met Office every 10 min and the mean location analysis recalculated. If an onset of a thunderstorm in Iceland or a significant increase in lightning activity is observed, then an E-mail warning message is sent to a group including the 24–7 watch at the IMO. These messages are also used by the IMO weather watch to monitor thunderstorms in Iceland. Weather thunderstorms during the summer of 2013 indicate that the response time of the system is 10–20 min. The response time reflects the total time from the first lightning strike until the web pages were updated and E-mail warnings sent.

The results of the analysis of the system are published on the web, as a map, graph and tables. The text and labels are in Icelandic, but an English glossary is provided. The web site is currently:

`http://brunnur.vedur.is/athuganir/eldingar/eldgos/`

The main page shows a map with the lightning locations in Iceland during the past 24 hours, color coded in 3 hour bins. Detailed explanations are provided on the web.

Additionally, a graph is provided showing the number of lightning per hour in Iceland for the past 24 hours (Fjöldi eldinga).

Also available is a table of lightning data for the past week (Eldingalisti). The list shows one line for each located lightning in the area 63–67°N, 13–25°W, the latest data first. It includes date and absolute time (UTC) of the lightning, a unique identification number (not really useful), latitude (decimal °N), longitude (decimal °W), location uncertainty (km), and a quality indicator (G=Good).

Three tables are provided showing mean and median locations of lightning for 1, 6 and 24 hour intervals during the past week (Meðalstaðsetningar). For each time interval (Tímabil) the following data are presented: Number of lightning in Iceland (Fjöldi eldinga), mean location, latitude °N and longitude °W (Meðalstaðsetning / Breidd Lengd), median location, latitude °N and longitude °W (Miðgildi / Breidd Lengd), radius of a circle around the median location which encloses half of the observed lightning (Helm fjarl), and distance (km) and direction (N=North, A=East, S=South, V=West) from a named reference place (Viðmið).

Currently, no wind correction is automatically included. Data from Grímsvötn 2004 and 2011 indicate that the wind at the 500 hPa level, backtraced for 500 s gives the best results. For Eyjafjallajökull 2010 this time constant was closer to 200 s.

The system has been described in posters and presentations at conferences in 2013 (Arason et al., 2013a, b; Petersen et al., 2013).

Review of lightning data during previous eruptions

Prior to the installation of the ATD station in Keflavík in 2001, the lightning location data was inferior in quality, both in the number of events recorded and also in poor constraints of stroke initiation time. Figure 3 shows the recorded locations during the Grímsvötn 1998 and Hekla 2000 eruptions. The poor determination of the stroke initiation time leads to a NW–SE location error evident in Figure 3b.

The Grímsvötn 2011 eruption started at about 19:00 UTC on 21 May. From its start it was known to be within the Grímsvötn caldera, but its specific location within the caldera could not be identified before the night. No eye witnesses were on site, and seismic data, GPS-data, radar data or satellite data could not determine the location of the actual eruption site within the caldera. Only 15 hours later the vent was determined to be at a similar/same place as the 2004 eruption.

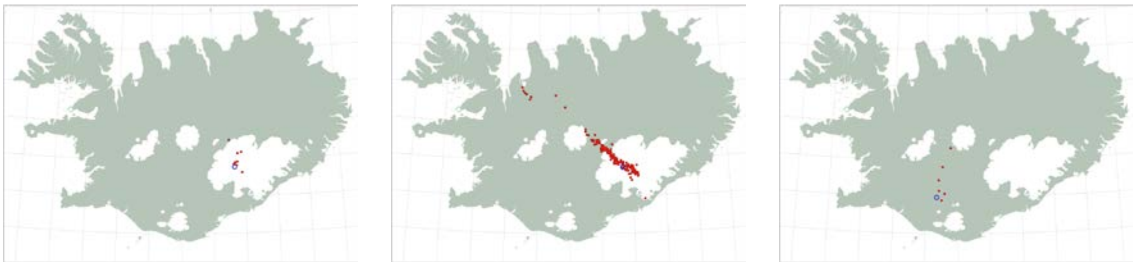

Figure 3. Located lightning prior to the installation of the Keflavík ATD out-station. (a) The Icelandic LLP locations during Grímsvötn 1998. (b) The ATD locations during Grímsvötn 1998. (c) the LLP locations during Hekla 2000. A blue circle is at the vent location.

Figure 4. Located lightning by the ATDnet system during (a) Grímsvötn 2004, (b) Eyjafjallajökull 2010 and (c) Grímsvötn 2011. A blue circle is at the vent location.

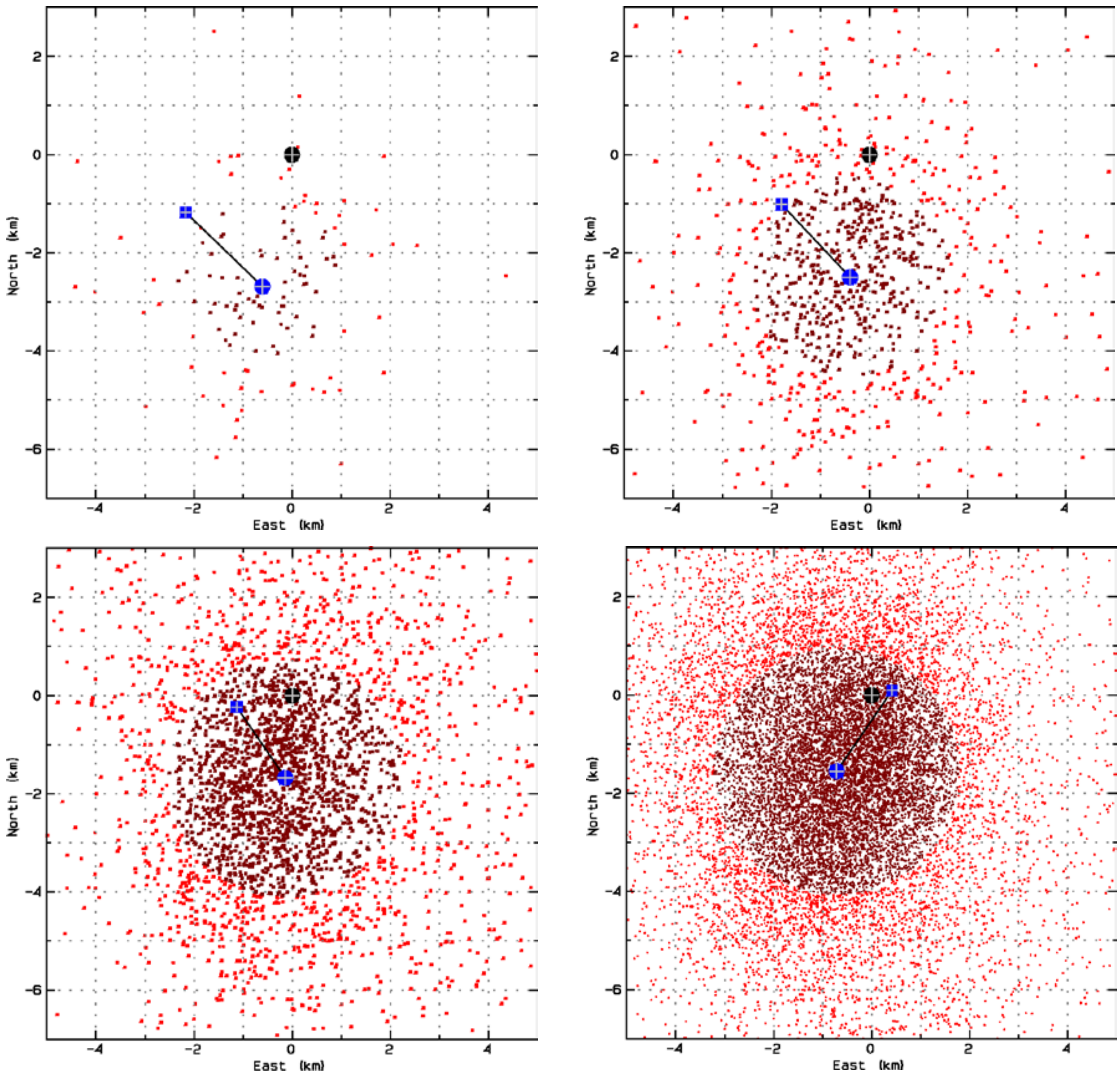

Figure 5. A map view, North (km) vs. East (km), of Grímsvötn 2011 lightning for the first 30 min (123 lightning), 1 hour (888), 3 hours (3340) and 24 hours (16041). The actual eruption site is marked with a black circle with a gray cross at the origin (0,0), the median location of the lightning with a blue circle. Individual lightning are red and brown dots, the closest half of the dots to the median are brown. A backtraced wind correction of the median is shown by the line and blue square. The wind at the 500 hPa level of a weather model was used and this wind backtraced for 500 s.

The best available data for the current analysis, Grímsvötn 2011, is shown in Figure 5. After only 30 min from the start of the eruption one could have seen from the lightning data that the median location was 2–3 km south of the correct location. With a simple wind correction the estimate would indicate 2 km WSW of the 2004 site. After 3 hours the estimate would have indicated that the eruption site was about 1 km W of the 2004 site. Four hours into the eruption (at 22:00 UTC) the wind corrected estimates are all within 1 km of the actual eruption crater, see Figure 6.

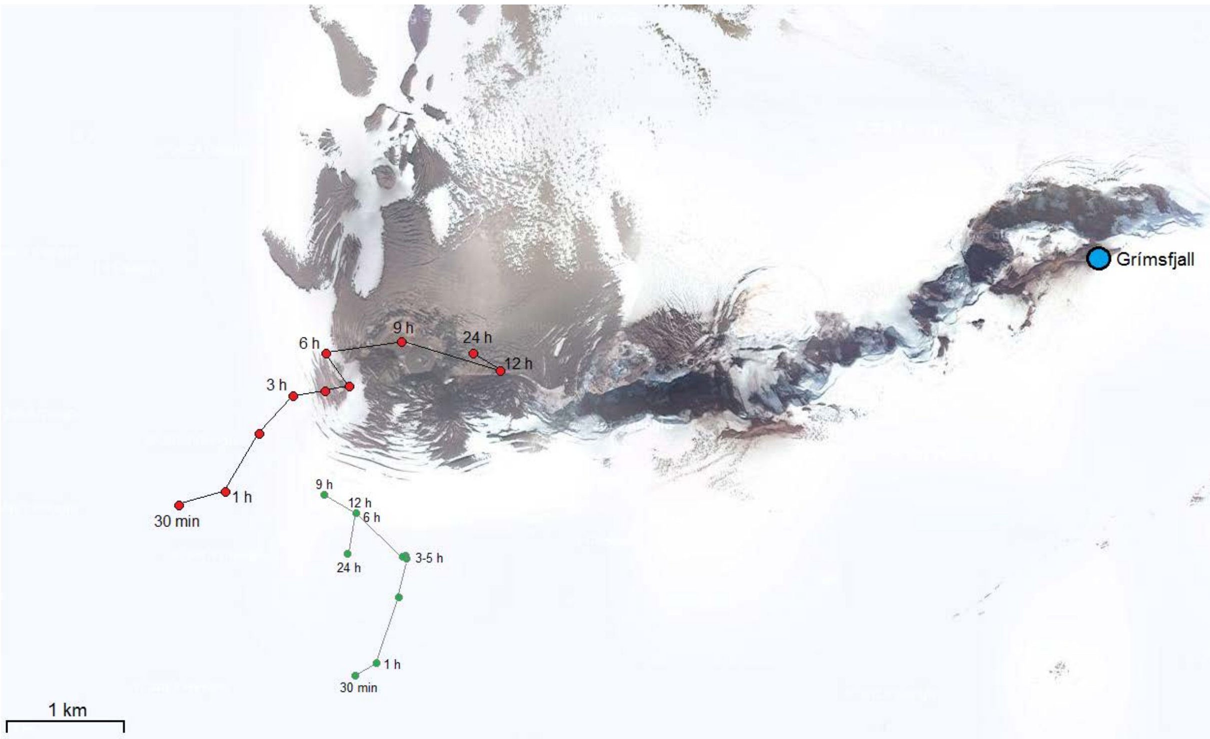

Figure 6. Aerial view of Grímsvötn after the 2011 eruption, with the eruption crater visible in the SW-corner of the caldera (close to the 9 h red dot) about 6 km W of the Grímsfjall station. The eruption site estimates are shown for the first 30 min, 1, 2, 3, 4, 5, 6, 9, 12 and 24 hours of the eruption. The green dots indicate the median lightning locations and the red dots the locations after a simple wind correction with a time constant of 500 s. Four hours into the eruption (at 22:00 UTC) the wind corrected estimates are all within 1 km of the actual eruption crater.

The lightning data from Grímsvötn 2004 and Eyjafjallajökull 2010 could not have given such timely estimates of the eruption site, but by analyzing longer time series one can see that indeed they include significant information on the eruption site.

Figure 7 shows the same map-view as Figure 5 for the initial 24 hours of Grímsvötn 2004 and one day (24 hours) well into the Eyjafjallajökull 2010. The high southerly winds during 2004 moved the lightning cluster 10–20 km to the north. The same wind correction as applied for 2011 moves the eruption site estimate to about 4 km WNW of the correct site. By applying a smaller wind correction (time constant of 200 s instead of 500 s) gives a perfect match for Eyjafjallajökull for the day with the highest frequency of volcanic lightning (16 May 2010).

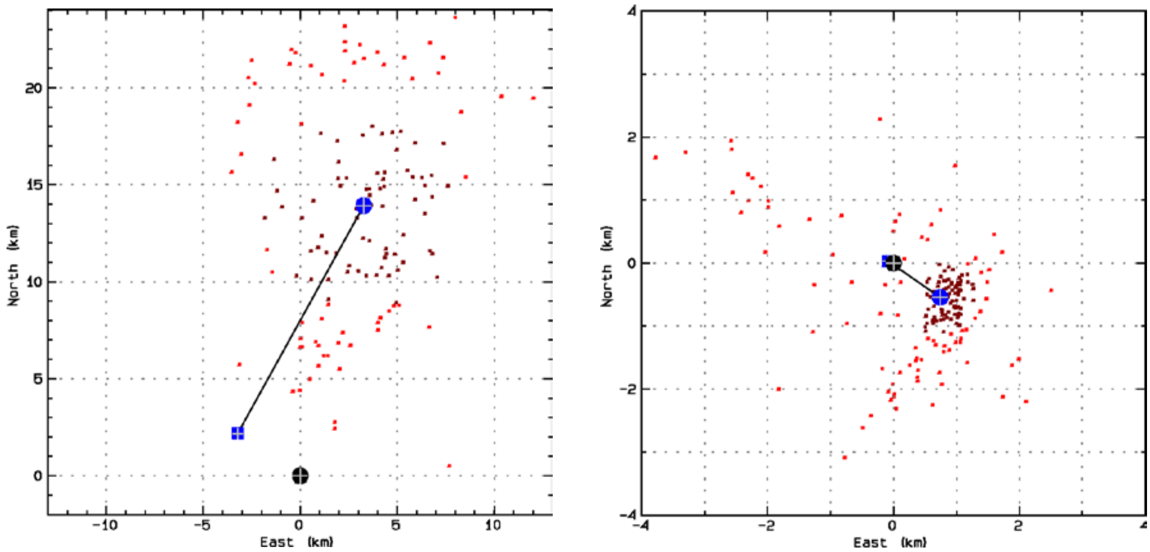

Figure 7. A map view, North (km), vs. East (km) of (a) Grímsvötn 2004 lightning for the first 24 hours (142 lightning) and (b) Eyjafjallajökull 2010 for one day with the highest lightning frequency, 16 May (196 lightning). Note that a different time constant was applied for Eyjafjallajökull wind correction. The labels are the same as in Figure 5.

Discussion

During the early hours of the Grímsvötn 2011 eruption it became evident that the real-time lightning data included important information on the vent location within the caldera. To be able to retrieve this information needed some processing. Early hours of an eruption do not usually afford meticulous analysis of data. Therefore, it is important to automate some of the analysis that might be useful.

There is not a consensus on how electric charge is generated in volcanic columns. Four main ideas have been proposed as charge generation processes: magma-water interaction, fractoemission, triboelectrification and dirty-thunderstorm. These processes can be produced in the laboratory, but the degree to which they are present in volcanic columns is not known, or if they are always the same (e.g., Mather & Harrison, 2006; Arason et al., 2011). Experience in Iceland indicates that subglacial and submarine eruptions usually produce more lightning activity than other eruptions. How the lightning is generated may not be critical for this work, as long as its intensity is sufficient in the volcanic column.

Table 1 indicates that some eruptions do not provide intense lightning activity during its early hours. It is therefore possible and even quite likely that the system, described here, will not give any useful information during the next volcanic eruption in Iceland. However, for the most hazardous powerful subglacial eruptions, early lightning activity is considered likely.

The frequency of weather thunderstorms in Iceland is very low. For instance where the ground flash density in Iceland is the highest, it is only about 1/1000 of the density in Florida. Therefore, weather thunderstorms are not interfering with this lightning monitoring of volcanoes. Even a moderate Icelandic weather thunderstorm would probably not matter during a powerful subglacial eruption.

Figures 5–7 show that a simple wind correction is probably useful, but unfortunately the data indicate different time constants for different eruptions (τ = 200–500 s). The lightning location data considered here provide no indication of the mean lightning altitude. The vertical speed of volcanic plumes in their buyoancy phase has been estimated to be on the order of 10–20 m/s (e.g., Petersen et al., 2012; Bjornsson et al., 2013). During 500 s such a plume would rise 5–10 km above the volcano, which is a reasonable value for the mean lightning height. It is possible that the different best fitting time constants reflect different plume heights. However, in the early hours of an eruption we would prefer to make no assumptions on the plume height. Further work on a suitable wind correction is needed.

The lighting data used by this system come from the ATDnet system of the UK Met Office. There are at least two other potential sources of useful lightning location data. The World Wide Lightning Location Network (wwlln.net) global system provides data to station and data providers. The IMO is currently in the process of joining this group. The quality of their data is not known. Four old ALDF lighting sensors (from about 1990) were installed by IMO in Iceland in 2006 and 2007 (Arason & Harðarson, 2007). In addition to lightning location, this local system potentially also provides lightning peak current and polarity, but is designed to exclude information on intra-cloud lightning. Whether the local ALDF system is more sensitive to low-current lighting in Iceland and has lower location uncertainty than the ATDnet remains to be seen. Unfortunately, automatic data collection to IMO was not finalized, but to fully implement the system is not thought to be costly.

This simple system of estimating eruption site could be reproduced in other countries or even as a global system using real-time global lightning data. However, in thunderstorm prone areas of the world one may need procedures to distinguish volcanic lightning from thunderstorms. It might be possible to use indices of atmospheric stability, e.g. CAPE, in global numerical weather prediction models to mask out potential thunderstorm areas. Such a global system might be useful to monitor large areas of poorly monitored volcanoes, e.g. the chain of volcanoes in the Aleutian Islands, with its heavy air-traffic above.

Conclusions

An automatic monitoring system has been developed that estimates eruption site location based on mean location of real-time volcanic lightning location data. The system delivers E-mail warnings and provides a web page with eruption site location estimate.

- It is possible that mean or median location of lightning may give the best estimate of the eruption site for the early hours of an eruption, especially if darkness, weather and visibility prevent direct observations.
- The initial lightning activity in the volcanic plume may not be sufficient to give useful information. However, for the largest and most dangerous subglacial eruptions, intense early lightning activity is expected.
- For a more accurate eruption site estimate, a wind correction is needed. More work is needed in developing a suitable wind correction.

Additional local ALDF lighting location data could be available at minor additional cost. This data has the potential of providing more accurate eruption site estimates. Therefore, it is important for IMO to finalize the installation of its ALDF lighting location system.

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