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Monitoring of lightning from the April–May 2010 Eyjafjallajökull volcanic eruption using a very low frequency lightning location network

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Abstract

The April–May 2010 explosive eruption of the Eyjafjallajökull volcano in Iceland produced a tephra plume extending to an altitude of over 9 km. During many, but not all, of the periods of significant volcanic activity the plume was sufficiently electrified to generate lightning. This lightning was located by the UK Met Office long-range lightning location network (ATDnet), operating in the very low frequency radio spectrum. An approximately linear relationship between hourly lightning count rate and radar-derived plume height was found. A minimum plume height for lightning generation of sufficient strength to be detected by ATDnet was shown to be 5 km above sea level. It is not clear why some plumes exceeding 5 km did not produce lightning detected by ATDnet, although ambient atmospheric conditions may be an important factor.

Keywords: volcanic eruptions, lightning, Eyjafjallajökull

1. Introduction

The recent eruption of the Eyjafjallajökull volcano in southern Iceland first began as a 500 m long fissure on 20 March 2010. The eruption was in the form of fire fountains and located to the east of the main Eyjafjallajökull ice cap. A new phase of the eruption began at approximately 01:00 UTC on 14 April, when magma entered the main crater beneath the glacier at Eyjafjallajökull (63.63°N, 19.62°W), resulting in ice melt and consequent explosive eruption³. This eruption produced a tephra plume that reached a height exceeding 9 km [1], with the south-eastward advection of ash causing widespread closure of European airspace. The eruption continued throughout April, although the plume height above the crater was lower than during the most intense stage of 14–17 April. The explosive component of the eruption intensified again on 3

May, heralding a return to plume heights exceeding 5 km that lasted until the 21–23 May.

During the more vigorous periods of explosive volcanic activity, the plume was observed to produce vivid flashes of lightning as it ascended from the mouth of the crater⁴. Electrification of volcanic plumes has been reported for hundreds of years, with evidence dating back to the geological past [2], although explanation of the mechanisms that generate this intense electrification is still subject to scientific debate [2–5]. The UK Met Office owns and operates a long-range lightning location network called ATDnet, abbreviated from ‘Arrival Time Difference’ which describes the location technique employed [6]. The network has been in continuous operation since initiation in 1987 and has undergone significant expansion and development in recent years [7, 8], with

³ Institute of Earth Sciences, University of Iceland (www.earthice.hi.is).

⁴ Stromboli online (http://www.swisseduc.ch/stromboli/perm/iceland/eyafallajokull_20100416-en.html).

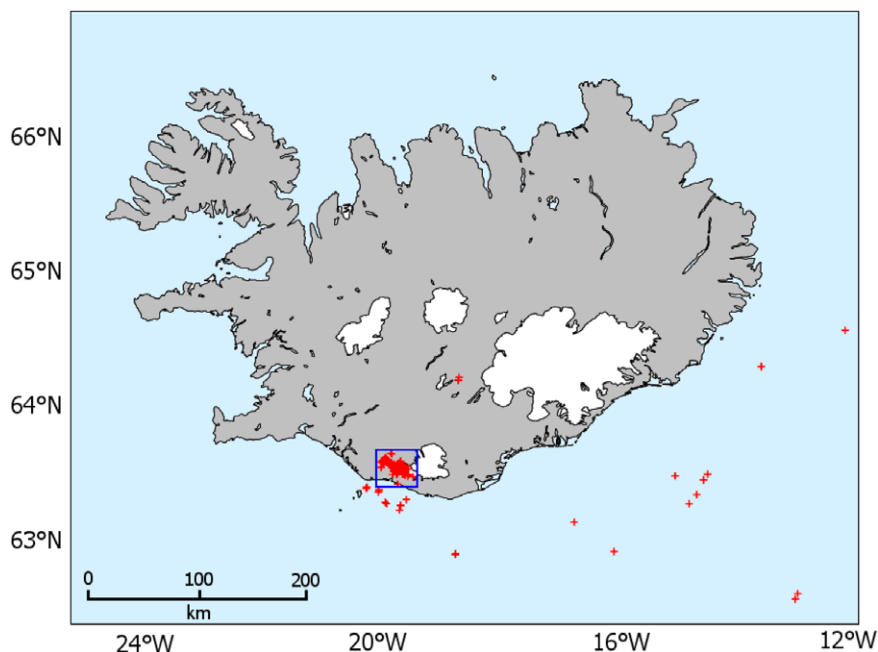


Figure 1. Location of lightning strokes (red crosses) over Iceland throughout April and May 2010. The stroke distribution for the Eyjafjallajökull region (blue rectangle) is shown in more detail in figure 3. White zones denote major glaciers.

the network currently consisting of 11 operational sensors deployed across Europe and Asia, including one in Iceland. The network exploits very low frequency (VLF) radio pulses emitted by lightning return strokes (hereafter referred to simply as strokes), locating the source by the accurate timing of when the peak energy of the emitted waveform arrives at each sensor site [6]. As VLF signals propagate over thousands of kilometres with low attenuation [9], ATDnet can locate lightning over 10 000 km from the network centre in north west Europe. The network locates approximately 10 million lightning strokes per month during Northern Hemisphere summer and although the network is optimized for the European region, lightning is also located over a longitude range extending from the North American Midwest to eastern China, and a latitude range from the Arctic to Southern Africa. The location of the Eyjafjallajökull volcanic eruption was therefore well within range of ATDnet, having previously been used to monitor the electrical activity generated by the tephra plume of Iceland’s last subglacial explosive eruption at Grímsvötn in 2004 [10]. Volcanic lightning was even detected by ATDnet from the May 2008 Chaiten eruption in southern Chile, nearly 13 000 km from the network centre.

ATDnet was designed to be a long-range lightning location network, so the network configuration and principle of operation limits the sensitivity to the detection of lightning which generates a peak current of at least 3 kA, with a stroke detection efficiency estimated at 60% for Iceland for strokes generating 15 kA or more [11]. This sensitivity threshold means that weak electrical discharges such as those observed immediately above or within the volcano’s crater (see footnote 4) are unlikely to be reported by ATDnet. Detection of these weak discharges would instead require short-range lightning location systems positioned within visual range of the volcano

and using techniques exploiting higher radio frequencies such as very high frequency (VHF) mapping [12]. Large ash-rich tephra plumes such as that present during the most active phases of the Eyjafjallajökull explosive eruption readily produce lightning with sufficiently high peak currents to be detected by ATDnet.

2. Spatial and temporal distribution of volcanic lightning

A total of 790 lightning strokes were detected by ATDnet in the vicinity of Eyjafjallajökull during the April–May eruption of the volcano. The first stroke over the volcano was detected at 18:31 UTC on 14 April, approximately 18 h after the onset of the explosive phase of the eruption. The last stroke was detected on 20 May at 12:46 UTC, with subsequent days experiencing only minimal explosive volcanic activity [1].

The high latitude and ocean surrounds of Iceland means that thunderstorm activity is relatively weak and infrequent [13], making the volcanic lightning easy to identify when analysing the ATDnet lightning dataset for April and May. There were only 25 lightning strokes recorded at distances greater than 20 km from the volcano during April and May in the entire Icelandic region shown in figure 1, compared to the 790 in the immediate vicinity of Eyjafjallajökull. Of these 25 ‘remote’ lightning strokes, all occurred away from the main volcanic plume and were identified from satellite imagery to be either due to thunderstorm activity or mislocated by the network as they were neither in the plume or associated with deep convective cloud. Examples of lightning produced over Eyjafjallajökull, from nearby shower clouds and lightning mislocated by the network are provided in figure 2.

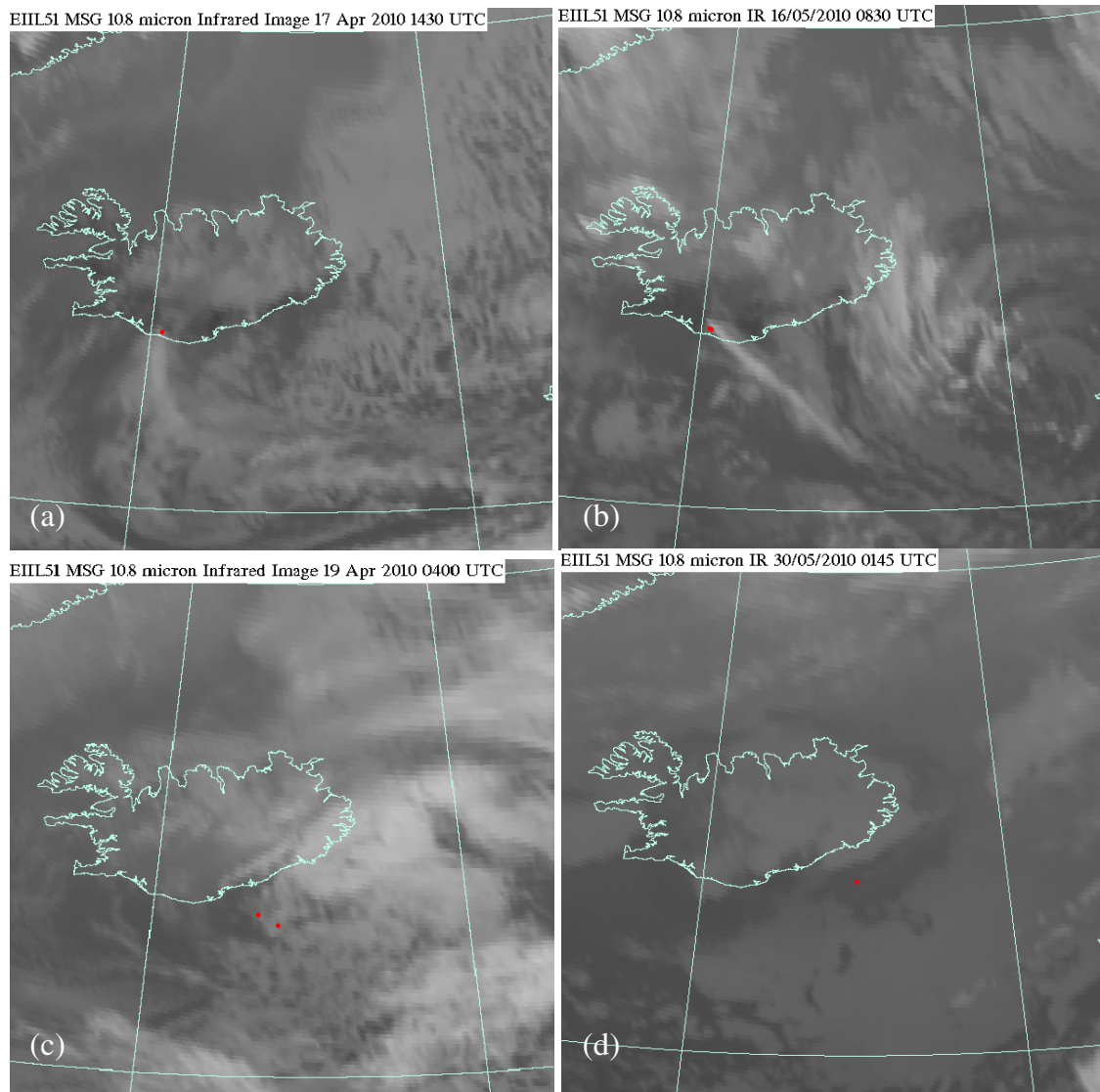


Figure 2. Lightning locations (red circles) overlaid on Meteosat infrared imagery. Lightning originating from the Eyjafjallajökull eruption on (a) 17 April and (b) 16 May are shown, along with lightning associated not with the volcano but instead from (c) shower clouds and (d) mislocation by the network.

A map of lightning stroke locations over Eyjafjallajökull during April and May is shown in figure 3. The majority of strokes occurred in a small region within or immediately due south of the central crater. Many of the strokes positioned in a broad line extending from the northwest of the crater are likely to be mislocated, as this direction does not correspond to the dominant plume direction during the main eruptions, but corresponds instead to the direction of greatest location uncertainty for the Iceland region when the ATDnet sensor network geometry is considered. When the sensor at Keflavik airport in west Iceland was not able to be used to locate the stroke the location accuracy was estimated to be 11.8 km, although with the Iceland sensor included in the location determination (as for most of the strokes) the estimated accuracy was improved, at 2.8 km. The tight grouping of volcanic lightning strokes over Eyjafjallajökull throughout the two months suggests that the lightning detected by ATDnet was mainly initiated by charge generated in the first 3 km of the

plume (or at most 15 km allowing for the maximum location error). Assuming a typical wind speed of $10\text{--}20\text{ m s}^{-1}$ and an atmospheric electrical relaxation time of $100\text{--}1000\text{ s}$ [14] the plume charge originating from within the crater alone will be reduced by 95% a few tens of kilometres downwind, depending on the actual air conductivity adjacent to the plume. Consequently, the short travel distance of any initial (vent) charge suggests that a charging mechanism operates outside of the immediate vicinity of the vent in order to account for the occurrence of lightning observed several kilometres from the volcano. Any initial charge on the plume upon exiting the vent may however account for the weaker lightning observed visually closest to the crater (see footnote 4). The delay of several hours between initiation of the explosive eruption and the first lightning stroke detected by ATDnet also suggests that conditions for generation of lightning of sufficient strength to be detected by ATDnet ($\sim 3\text{ kA}$) requires the establishment of a tall, ash-laden plume and appropriate atmospheric conditions

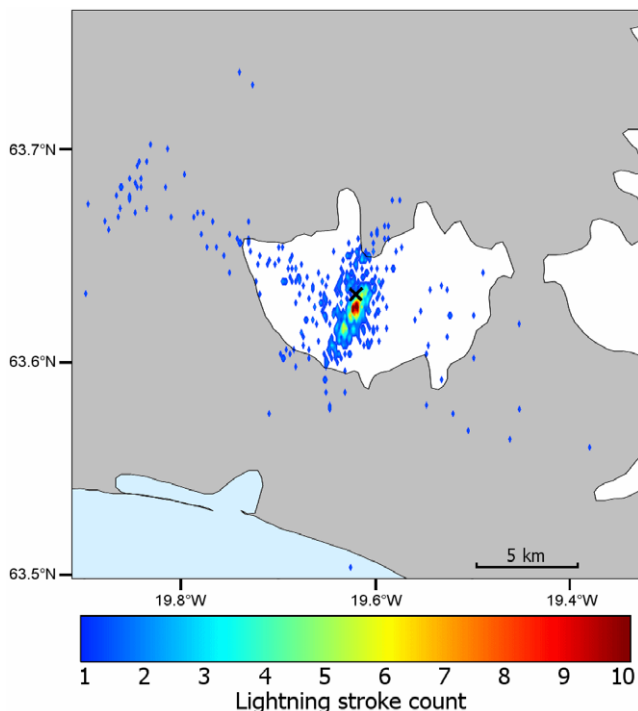


Figure 3. Distribution of lightning strokes during April and May 2010 over Eyjafjallajökull (this region is identified by the blue rectangle in figure 1). The black cross in the middle of the map represents the crater centre (63.63°N, 19.62°W), with the surrounding glacier shown in white and light blue is the Atlantic Ocean.

(section 4). It is likely however that plume electrification would be first identified from weaker lightning near the crater which had insufficient peak currents to be detected by ATDnet and may be produced by a different charging mechanism. A comprehensive review of the observation and mechanisms suggested for the electrification of volcanic plumes are provided by [2, 3].

Self-charging of the Eyjafjallajökull volcanic plume was reported several hundred kilometres downwind over Scotland [14], although it would appear that the self-charging mechanisms in operation here were insufficient to produce any lightning, or at least none sufficiently strong to be detected by ATDnet.

During the first few days (approximately 14–23 April) the eruption was phreatomagmatic (interaction of magma and the ice meltwater) and there appeared to be more steam in the plume⁵. During the phase from 3 May until the end the eruption was mainly semi-vulcanian explosions (see footnote 5), so the ash production was driven by gases in the magma. From the temporal distribution of volcanic lightning shown in figure 4 the electrical activity can be grouped into two main periods; 14–19 April and 11–20 May. The April volcanic lightning period corresponds closely to the duration of UK airspace closure from 15–20 April. During May, the airspace closed again on 4, 16 and 17 May, with the latter two days occurring during the peak of lightning activity. The close

⁵ <http://en.keilir.net/static/files/conferences/eyjaaviation/session6/armann-hoskuldsson-uniiceland.pdf>.

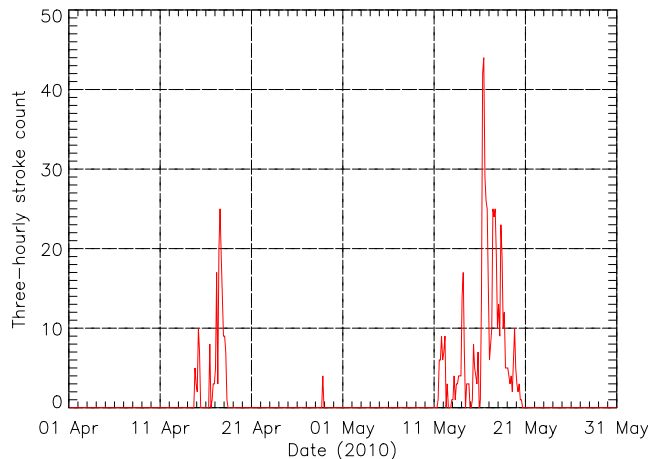


Figure 4. Lightning stroke count for the Eyjafjallajökull region (<20 km from crater) over three-hourly bins during April and May 2010.

association between airspace closure and volcanic lightning is suggested to be due to a common association with significant ash production. The April eruption period produced a total of 171 strokes, compared to 615 during May. A histogram comparing the horizontal distances between the crater and lightning strokes for these two periods of volcanic lightning is shown in figure 5. Apart from intensity, the two periods of electrical activity also differ in their location of maximum stroke count relative to the crater centre, with the April period having a mean distance (with standard error) between the lightning stroke and crater centre of 4.2 ± 0.4 km, compared to only 2.0 ± 0.1 km during May. April also had a larger standard deviation, at 4.8 km compared to 3.2 km for May. The most common stroke locations during April and May are shown by the peak of the histograms in figure 5. The April and May peaks can also be seen in a two-dimensional context by the secondary and primary stroke count maxima in figure 3 respectively. Although both the means are within the expected ATDnet location accuracy, they are statistically different (at 99% confidence) so cannot be attributed to location error alone, assuming no artificial location bias introduced by the network existed between the two periods.

A possible source for the difference in the mean lightning location during April and May is plume advection, with stronger wind speeds blowing the lightning generation process further downwind. The wind speed and direction above the volcano was estimated using the UK Met Office Global Unified Model [15]. An altitude of 3 km was chosen to represent the steering winds of the plume as it ascended above the crater, given a typical plume top height of 6 km (section 4). During the lightning activity of 14–19 April the mean wind speed was estimated to be 18 m s^{-1} and predominately from the north or west, compared to only 5 m s^{-1} with variable direction during the 11–20 May. The location of the majority of lightning strokes to the south of the crater is in agreement with the dominant northerly wind direction during the electrified phases of the eruption. The modelled reduction in wind speed between these two periods is consistent with observed wind speed profiles from radiosondes at Keflavik international airport,

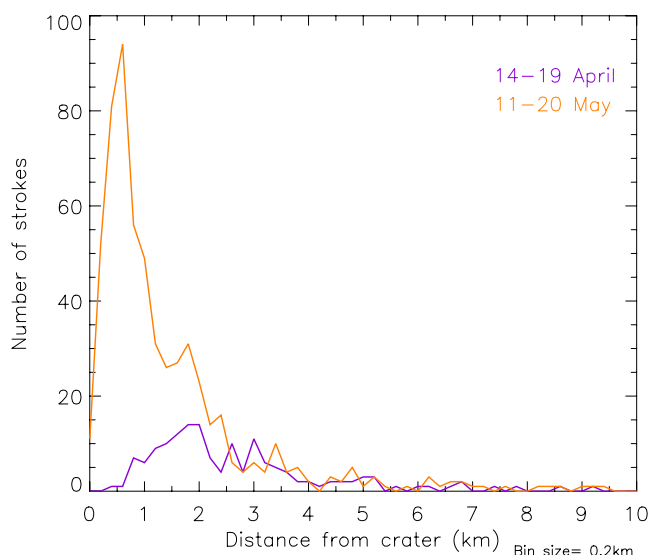


Figure 5. Histogram of lightning stroke distance to the Eyjafjallajökull crater for the two main periods of volcanic lightning on 14–19 April (purple) and 11–20 May (orange).

approximately 150 km to the west of Eyjafjallajökull [1]. It is suggested therefore that the difference in mean lightning location during the April and May volcanic lightning periods was due to changes in mean wind speed, altering the horizontal advection rate of the plume as it ascended from the crater. A similar correspondence between wind and the location of volcanic lightning was found during the Mount Spurr eruption [16].

3. Flash multiplicity for volcanic lightning

Flash multiplicity is defined here as the number of lightning return strokes present in an individual lightning flash [17]. The volcanic lightning strokes were grouped into lightning flashes using an inter-stroke time limit of 0.5 s [18]. The results show that only 14 flashes had a multiplicity of 2 (representing 1.8% of the total), with the remainder being of single stroke. This low multiplicity was surprising considering the typical number of flashes detected by ATDnet over Europe with a multiplicity of at least 2 is ~20%. Although the sample size of volcanic lightning was small, the anomalously low flash multiplicity may suggest a characteristic difference between the multiplicity of the volcanic lightning flashes compared to that generated by thunderstorms. ATDnet does not currently record lightning polarity or peak current so these parameters cannot be analysed. For lightning produced by thunderstorms, a general relationship exists between these two parameters and multiplicity, with low multiplicities most likely for either positive cloud-to-ground flash polarities or, in the case of negative polarity, low peak currents [19]. Evidence from previous Icelandic eruptions supports this suggestion, with volcanic lightning monitored by the location network of the Icelandic Meteorological Office from the subglacial eruption at Grímsvötn in 1998 having a mean peak current less than half the mean strength of lightning detected from Icelandic ‘meteorological’ thunderstorms [20].

4. Lightning generation rate in relation to plume height

The Icelandic Meteorological Office (IMO) operates a C-band weather radar which can be used to monitor and track tephra plumes. Previous studies [10, 22] have shown a correlation between volcanic lightning detection rate and plume height from Icelandic subglacial eruptions. This association was investigated in relation to the Eyjafjallajökull eruption using plume height data from the IMO weather radar and the number of lightning strokes detected each hour by ATDnet over Eyjafjallajökull between 14 April and 23 May. The lower limit of radar observation at ~2.5 km is due to viewing constraints imposed by the surrounding terrain. Instances when the plume was not detected by radar either due to the plume being below surrounding terrain or horizon or obscured by precipitation, were omitted from the dataset. Due to the volume and complexity of the radar measurements, a detailed account of the radar reflectivity data will be communicated separately. The comparison between plume height and the number of lightning strokes detected per hour is presented in figure 6 and indicates a general correspondence between lightning activity and plume height, except during the elevated plume at the beginning of the eruption early on 14 April and further discrepancies during 25–26 April and 3–10 May. ATDnet was operating correctly throughout all of April and May, so the lack of reported lightning is not due to network interruptions but instead suggests a change in the plume composition, structure or environmental conditions which made >3 kA lightning production unfavourable, as the reported plume heights (up to 8 km on 5 May) were just as high and prolonged as during the occasions that generated volcanic lightning. It is currently unclear why such plumes did not generate lightning capable of being detected by ATDnet, where as other seemingly similar plumes were highly electrified. One suggestion is that changes to the relative concentration of ash and steam in the plume effected the number of cloud-to-ground lightning strokes, with previous Icelandic plumes producing lightning originating from the ash and not from the steam [22], although high plume water content and availability of ice in the plume are thought to be factors in lightning production in the case of self-charging from the proposed ‘dirty thunderstorm’ mechanism [5, 23]. According to the volcanic activity reports issued by the IMO and the Institute of Earth Sciences, University of Iceland (see footnote 3) there was no obvious indication (e.g. from reported plume colour or ash fall) that the plume composition differed significantly between 3–10 and 11–21 May, so changes in the ambient atmospheric conditions are likely to have been an important factor. In particular, initial analysis of the ambient temperature profile during the eruption has indicated that the electrically active plumes were colder and more likely to have contained a larger proportion of ice than those which did not produce lightning, supporting the ‘dirty thunderstorm’ analogy of plume electrification [5, 23]. The relationship between plume electrical activity and temperature structure will be the subject of future research by the authors. Although the ‘dirty thunderstorm’ charging mechanism may account for the large lightning strokes detected by ATDnet, it is possible that

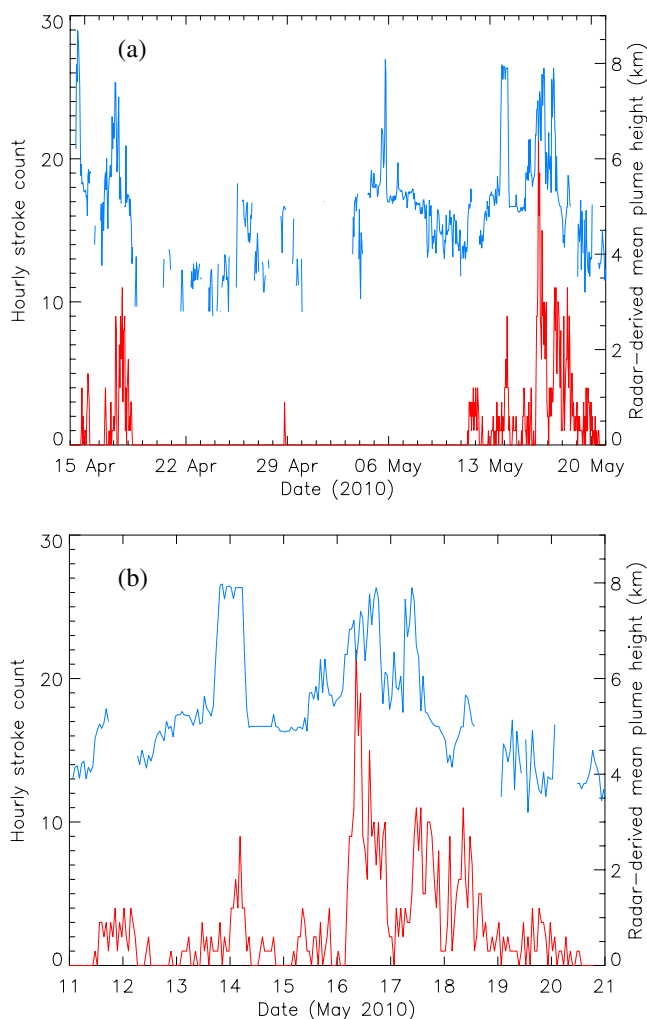


Figure 6. Hourly lightning stroke count (red) and radar-derived plume height above mean sea level during (a) the April–May explosive eruption phase of Eyjafjallajökull and (b) the May eruption which produced the most lightning.

the smaller electrical discharges (too weak to be detected by ATDnet) are produced by a different mechanism occurring close to the crater. Such a mechanism may be active in the vent, with charge separation occurring due to magma–water interactions or break up of the magma into ash [2, 3]. A distinction between source mechanisms responsible for the numerous weak lightning strokes observed at the crater and those responsible for the large, high peak current lightning strokes (capable of being detected by ATDnet) further downwind may therefore be required [24].

The discovery that the plume was weakly electrified several hundred kilometres downwind after the lightning-producing mid-April eruption [14], provides insight into the physical properties required for volcanic lightning. The recent suggestion that particle clouds such as volcanic plumes can become highly charged by collision of identical dielectric particles in the presence of an electric field [4] requires the ability of the particles to be polarized, the effectiveness of which will be a property of the particles in the plume. The necessity of an initial electric field could be satisfied by either

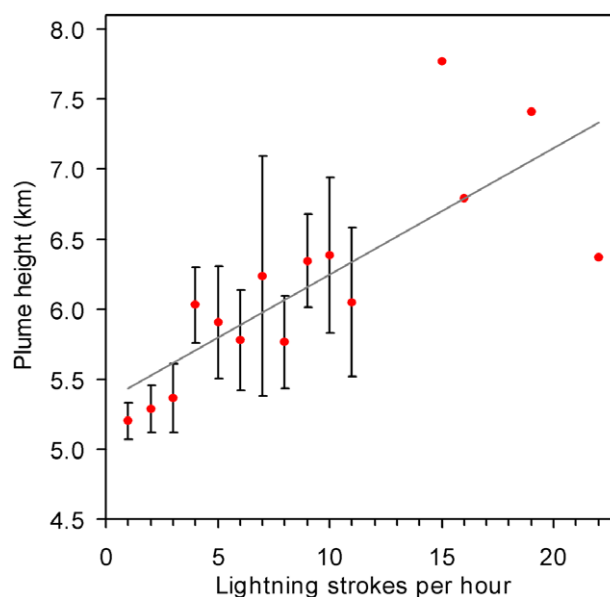


Figure 7. Mean plume height (above sea level) compared to number of lightning strokes per hour (red circles) detected by ATDnet, with standard error of the mean shown by error bars. The grey line represents the least squares fit for the mean values. Points with no error bars indicate hourly counts which occurred only once during the 14 April–21 May interval.

residual charge of the plume upon leaving the vent from magma–water interactions or break up of the magma into ash, in the case of near-crater electrification. An initial electric field will also be present from accumulation of charge at the edges of the whole plume resulting from the continuous current of the global electric circuit [25, 26], such a field could be enhanced by the inductive charging mechanism in the case of observed self-charging further downwind. This inductive mechanism for charge separation may contribute to charging in regions of the plume where there is insufficient ice for the ‘dirty thunderstorm’ mechanism to operate, such as for plumes too low or dry for ice formation, although it appears that such inductive charging may not be sufficient to produce >3 kA lightning strokes on its own.

For the cases when the plume was producing lightning, a statistically significant correlation (at 99% confidence) between hourly mean plume height and the number of lightning strokes was found, with the mean plume height compared to hourly stroke count shown in figure 7. There is a relationship which appears to be approximately linear between the IMO radar-derived plume heights and the number of strokes per hour detected by ATDnet up to at least 22 strokes, although more confidence is attributed to count rates of less than 11 owing to the greater number of occurrences. The regression line gradient and y-intercept are 0.09 km per stroke and 5.35 km respectively, with a correlation coefficient of 0.79. The observed relationship between plume lightning frequency and volcanic activity has also been found in previous studies [10, 16, 21, 22, 27, 28]. From this analysis the plume height threshold before lightning strong enough to be detected by ATDnet was initiated is 5 km, although from figure 6(a) it is clear that this relationship between plume height and lightning

production rate does not hold for all plume conditions, possibly relating to the presence of ice in the plume.

The only lightning strokes within 20 km of Eyjafjallajökull that occurred outside of the two main periods of electrical activity were on 28 April (figure 4). A total of three flashes (one of which had a multiplicity of 2) were detected between 19:47 and 20:04 UTC between 2 and 5 km northwest of the crater centre. From figure 6(a) the radar indicated an increase in plume height during the afternoon of 28 April, rising to a consistent 5 km with occasional increases to 8 km before reducing again the following day, although rain and low cloud from an occluded front prevented continuous observation of plume height. The wind direction during the evening of 28 April was southeast, so although the possibility of mislocation due to ATDnet location error cannot be entirely neglected, this wind direction is consistent with lightning strong enough to be detected by ATDnet being generated 2–5 km downwind of the crater, consistent with that observed during the main periods of volcanic lightning. It is emphasized however that weaker lightning such as that observed visually near the crater but not detected by ATDnet could still be present under different plume conditions.

5. Summary

The explosive eruption phase of the Eyjafjallajökull volcano produced an extensive tephra plume which in many (but not all) instances produced lightning of >3 kA peak current. The time and location of lightning strokes were monitored by the UK Met Office VLF lightning location network, ATDnet. Plumes producing lightning detected by ATDnet were generally at least 5 km in height, although exceptions did occur, with plumes estimated to be as low as 2.5 km producing detectable lightning on 19–20 May. It is not immediately clear why differences in lightning generation existed between plumes of similar size, although differences in the physical properties of the plume particles, composition, plume structure or changes to the ambient atmosphere are likely to be important factors. The presence of ice in the plume may be an especially important factor in the generation of lightning strokes with sufficiently high peak current to be detected by ATDnet, which will be the subject of further investigation.

The location of volcanic lightning varied in distance and direction from the crater centre according to the wind conditions, supporting the suggestion that the charge separation process occurs within the plume and not only at the vent [28], although smaller electrical discharges which may have had a peak current insufficiently large (<3 kA) to be detected by ATDnet appear to have been present at the crater edge (see footnote 4). Whilst lightning stroke data has been used in this study instead of flashes (ATDnet does not currently implement a stroke grouping algorithm operationally), the assessment that 98% of the strokes would also be considered flashes mean that the results are valid for either.

The marked difference in electrification of tephra plumes of similar heights shown during the April–May 2010 Eyjafjallajökull eruption presents an excellent opportunity for further research into charging mechanisms of volcanic plumes,

especially once more scientific data becomes available for analysis. When a plume becomes sufficiently electrified to produce lightning, the rate of lightning generation provides a method of remotely monitoring the plume height, offering clear benefits to the volcanic monitoring community [10, 16, 21, 22, 27, 28] especially as part of an integrated monitoring programme [29].

Acknowledgments

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