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Charge mechanism of volcanic lightning revealed during the 2010 eruption of Eyjafjallajökull

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[1] Volcanic lightning has intrigued observers through the centuries. Several likely processes have been proposed to explain the electrification of volcanic plumes, including quenching magma-water interactions, the fracturing or internal friction of fine grained ash, and the freezing of plume water at height. Scarce measurements of volcanic lightning have not been able to distinguish between proposed ideas. The Eyjafjallajökull volcanic eruption in Iceland in April–May 2010 may have revealed its charge mechanism. During its 39 days, the eruption went through a few phases while the conditions of the ambient atmosphere also changed, but at different times. The most surprising change in the lightning activity occurred on 11 May, with no obvious change in the physical eruption character or strength. During 3–10 May there was no lightning recorded by long-range networks, followed by intense activity 11–20 May. The change in lightning activity coincided with a change in the conditions of the ambient atmosphere. At this time the altitude of the isotherms for droplet freezing (about −20°C) dropped drastically below the plume top. Therefore, it appears that the atmospheric conditions around the plume were influencing or even controlling some of the lightning activity. The critical plume top temperature, which appears to have turned on and off the observed lightning activity during the Eyjafjallajökull eruption is estimated to be between −20° and −24°C. We conclude that a significant charge generation process of the observed volcanic lightning is probably analogous to processes in meteorological thunderclouds.

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1. Introduction

[2] The presence of lightning in volcanic plumes has been known throughout history, and probably the oldest written accounts of volcanic lightning are from Pliny the Younger (Gaius Plinus Caecilius Secundus) during the catastrophic AD 79 eruption of Mount Vesuvius. However, human fatalities due to volcanic lightning are rather rare, but are an addition to other volcanic hazards. In Iceland there are two known fatalities due to volcanic lightning; a man and a woman in a single incident were killed by lightning some 30 km from the volcano Katla in 1755 [*Arason and Hardarson*, 2007]. The discovery in the middle of the 18th century that meteorological lightning is an electrical phenomenon, led soon to research on volcanic lightning. Several processes have been proposed to explain charge generation in volcanic plumes. However, direct measurements and observations of the microscopic processes in the plumes are almost impossible, and there has not been a consensus on which charge generation or redistribution processes are most important.

[3] *Volta* [1782] mentions volcanic lightning during the 1779 Mount Vesuvius eruption and demonstrated with experiments that by pouring water on an insulated plate heated by burning coals he could generate electricity. He concluded that there would be sufficient water in volcanic eruptions to produce the electricity for the observed plume lightning. In the 19th century *Faraday* [1843] made series of experiments to generate electric charge and to see which physical properties are most important. *Mather and Harrison* [2006] provide a good review of historical accounts, electrification, and the processes thought to be most important in charge generation of volcanic plumes.

[4] Triboelectrification, or frictional charging, has been suggested as one source of volcanic plume electrification. It results from collisions and internal friction between dry ash grains in the plume. The microscopic process is fairly well understood [*Pähtz et al.*, 2010], and is believed to be responsible for the electrification of dry sandstorms. However, the charge distribution of dry sandstorms with a negative charge at the top is different from the charge distribution observed in volcanic plumes [e.g., *Williams and McNutt*, 2005]. Another related process suggested as a charge mechanism of volcanic plumes is fractoemission, or the fragmentation of the magma

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into ash which appears to be powerful in generating charge in laboratory experiments [*Büttner et al.*, 2000; *James et al.*, 2000, 2008]. Fractoemission may be an important mechanism for generating the small sparks sometimes observed close to the vent.

[5] During the Surtsey submarine eruption in Iceland, 1963–1967 (63°18′N, 20°36′W), extensive measurements were made of the electric field around the plume from ships and airplanes. The plume appeared to be positively charged, even small steam plumes from lava that was flowing into the sea were positively charged. Some negative charge was observed downwind under the plume. Furthermore, controlled experiments indicated that charge generation was more efficient when salt water interacted with magma or hot surfaces compared to fresh water or glacial geothermal water. Steam and water droplets were found to be positively charged. These measurements from the Surtsey and later Heimaey 1973 eruptions and controlled experiments were interpreted to indicate that the charge generation was caused by magma-water interactions [*Blanchard*, 1964; *Anderson et al.*, 1965; *Björnsson and Vonnegut*, 1965; *Björnsson et al.*, 1967; *Blanchard and Björnsson*, 1967; *Brook et al.*, 1974, *Björnsson*, 1986].

[6] The charge distribution in ordinary meteorological thunderclouds is dominated by a positive top, below which is a negative layer. At the bottom there is usually an additional weak positive layer. The altitude of the interface between the main positive and negative layers varies, but is often close to the −20°C isotherm [e.g., *Uman*, 2001; *Rakov and Uman*, 2003]. This may indicate that the interaction between supercooled cloud droplets, ice crystals and falling graupel (soft hail) is responsible for the charge generation. Recently, *Latham et al.* [2007] presented evidence that graupel alone is responsible for the charge generation. However, for this study the most important observation is the connection between charge generation and this critical temperature, about −20°C in meteorological thunderclouds.

[7] During the Surtsey eruption, *Sigurgeirsson* [1965] observed the lightning activity and measured the plume height. He compared the plume height to radiosonde measurements of temperature profiles of the atmospheric column at Keflavík International Airport. He tried to measure and continuously record the frequency of occurrence of volcanic lightning, but was not successful. He noted that when the plume was over 8 km, the ambient plume top temperature was almost −50°C, and the similarities between the top of ordinary thunderclouds and the volcanic plume. Because of these similarities he supposed that similar processes, responsible for thundercloud charge generation, might be involved in the larger whole plume volcanic lightning that were observed during the Surtsey eruption. On the other hand he also observed that most of the lightning flashes were rather small and close to the base of the plume. These small lightning flashes close to the vent were also evident when the plume was very low, and they sometimes appeared in a fraction of a minute after the ejecta came out of the vent [*Sigurgeirsson*, 1965].

[8] Phreatic volcanic eruptions (under water or ice) supply abundance of water to the plume, but it was demonstrated by *Williams and McNutt* [2005] that the water content of magma (often 2–5% by weight) is very high compared to the atmospheric water content and more than sufficient to keep the plume water saturated. Plumes are often high enough so that the supercooled water droplets will freeze and there are many accounts of rain or hail under volcanic plumes. Furthermore, the charge structure of volcanic plumes appears to be similar to meteorological thunderclouds. Therefore, they suggested that the charge generation of volcanic plumes might be similar to meteorological thunderstorms [*Williams and McNutt*, 2004, 2005; *McNutt and Williams*, 2010].

[9] Only a few studies have been published where lightning activity during volcanic eruptions have been monitored with lightning location systems [e.g., *Hoblitt*, 1994; *McNutt and Davis*, 2000; *Arason et al.*, 2000; *Arason*, 2005a, 2005b; *Vogfjörd et al.*, 2005; *Thomas et al.*, 2007, 2010a; *Bennett et al.*, 2010a]. In most cases a correlation was observed between the frequency of occurrence of lightning and plume height or some other measure of the strength of the eruption.

[10] After a small nonexplosive effusive eruption at the Fimmvörðuháls pass lasting from 20 March to 12 April 2010, an explosive volcanic eruption started at the ice-capped Eyjafjallajökull volcano (63°38′N, 19°38′W) in southern Iceland on 14 April 2010 at about 01 UTC [*Sigmundsson et al.*, 2010], see location map in Figure 1. While the first eruption was picturesque and caused few problems for the population, the local ashfall from the second one had great impact on the rural communities of southern Iceland. Furthermore, the upper level northwesterly winds advected fine-grained silicic ash rapidly into the crowded airspace of Europe causing major disruption to air traffic in northern and western Europe. The eruption had two main explosive phases 14–18 April and 3–20 May. The activity then decreased slowly and on 23 May the magma inflow ceased. *Petersen* [2010] gives a brief meteorological overview, and *Bennett et al.* [2010a] describe the lightning recorded by the ATDnet lightning location network of the UK Met Office during the eruption. The altitude of the volcanic plume as well as activity was monitored in several ways, with the most important tool being a weather radar.

[11] In this study, lightning observations during the 2010 eruption of Eyjafjallajökull are compared to observations of the plume height and temperature profiles of the atmosphere. Previous volcanic eruptions have not afforded similar quality of data. What makes the data collected during the Eyjafjallajökull exceptional for this comparison is the relatively long duration of the eruption, 39 days, with varying strength of the plume, while independently the status of the ambient atmosphere was changing. The plume height was continuously recorded with high temporal resolution during the entire eruption and, fortunately, the plume height was varying above and below the height of the critical −20°C isotherm. Lightning locations of uniform quality were collected by the ATDnet network (performance detailed in next section), and during the eruption period there was no obvious occurrence of meteorological thunderstorms close to the volcano. Finally, access to atmospheric model outputs, showing details of the atmosphere in high spatial and temporal resolution was critical.

[12] There appears to be good correlation between the plume top temperature and the occurrence of lightning. Furthermore, the colder the plume top the higher the frequency of occurrence of lightning. The critical plume top temperature seems to be about −20° to −24°C, which is comparable to the critical temperature between the positive

Figure 1. Map of Iceland showing the location of the Eyjafjallajökull volcano (63°38′N, 19°38′W) and Keflavík International Airport.

and negative charge boundary in meteorological thunderclouds, with the strongest electrification occurring after the cloud top becomes glaciated. These correlations are interpreted to indicate that the charge generation and redistribution for the lightning in the volcanic plume, recorded by a long-range network, is analogous to the generation in ordinary thunderclouds.

2. ATDnet Lightning Location Network

[13] ATDnet is a long range lightning location network owned and operated by the UK Met Office [*Lee*, 1986; *Nash et al.*, 2006; *Gaffard et al.*, 2008]. The network operates 11 sensors receiving lightning emissions in the very low frequency (VLF) radio spectrum, with a center frequency of 13.7 kHz during the time of the Eyjafjallajökull eruption. ATDnet needs four sensors to detect the lightning waveform for unambiguous location using an arrival time difference technique. ATDnet or its predecessor (ATD) has been operating continuously since 1987 and, as an operational network of the UK public weather service, is supported 24 h per day by Met Office personnel. The sensors monitor waveforms from lightning return strokes from cloud-to-ground flashes and from currents produced by strong cloud-to-cloud or intracloud flashes. The sensors are mainly located in Europe, including one in Iceland (Figure 2). The network is therefore well placed to monitor lightning of peak current exceeding approximately 3 kA from Icelandic volcanoes. A technical summary of the lightning location method used by ATDnet is included in the work of *Bennett et al.* [2011]. The network provides a typical lightning location uncertainty of 3 km and detection efficiency of approximately 60% for strokes generating 15 kA or more over Iceland [*Bennett et al.*, 2010b]. In addition to the recent eruption of Eyjafjallajökull, ATDnet was successfully used to monitor lightning generated by Iceland's subglacial explosive eruptions at Grímsvötn in 2004 [*Vogfjörd et al.*, 2005] and the latest in May 2011.

[14] A total of 790 lightning strokes were detected by ATDnet in the vicinity of Eyjafjallajökull during the April–May eruption of the volcano. Curiously, all but 14 of these strokes occurred with time separations long enough to infer they were the only return strokes in the lightning flash of sufficient peak current to be detected by the network [*Bennett et al.*, 2010a], which the authors suggested may have been a result of the volcanic lightning flashes having a lower peak current or greater tendency for positive polarity than typical meteorological thunderstorms. This finding means that although lightning return strokes are referred to throughout this text as they are the basic units observed by ATDnet, the results of this investigation may also be considered applicable to lightning flash data.

[15] The first lightning stroke over the volcano was detected by ATDnet 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, after which the explosive phase of the eruption greatly reduced [*Petersen*, 2010; *Arason et al.*, 2011b]. The locations of all lightning strokes detected by ATDnet in the vicinity of Eyjafjallajökull during the eruption is shown in Figure 3. Some outliers may be mislocated due to poor configuration of stations detecting the event [*Bennett et al.*, 2010a], although a general colocation of lightning with the volcanic eruption is evident. The distribution of lightning occurrence with time is given in Figure 4. Figure 4 shows the occurrence of lightning during the initial phase on 14–18 April, with the most lightning of this phase on 17 April, a few lightning strokes on 28 April and a renewed

Figure 2. The ATDnet lightning out stations network (circles) and the Eyjafjallajökull volcano (triangle). The long-range VLF network uses arrival time differences of a 10–14 kHz vertical electric field signal to locate lightning.

phase on 11–20 May, with an overall peak in lightning activity on 16 May. Although the ash plume was shown to be electrically charged over 1200 km from the volcano [*Harrison et al.*, 2010], the majority of lightning strokes with peak currents exceeding ~ 3 kA (the lower limit of detection by ATDnet) occurred within 3 km of the crater. Both the spatial and temporal distribution of this volcanic

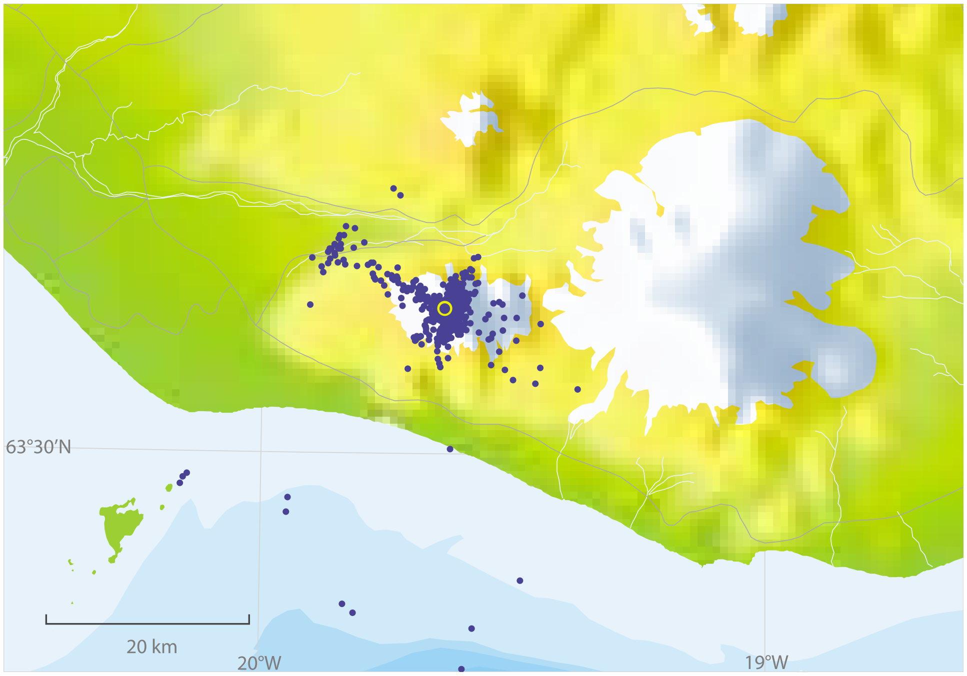

Figure 3. Located lightning in the vicinity of Eyjafjallajökull during the eruption. Some outliers may be mislocated because of poor configuration of stations detecting the event. Circle shows the location of the crater.

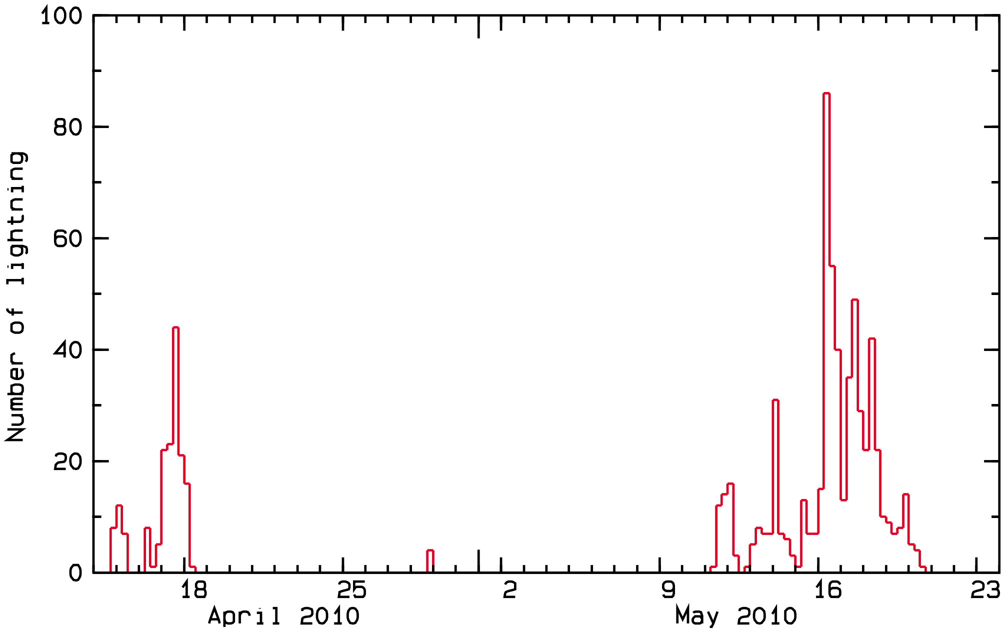

Figure 4. Number of lightning strokes located by the ATDnet system of the UK Met Office during the eruption, in 6 h bins. Lightning within 20 km of the volcanic crater were included in this collection.

lightning has been described in detail by *Bennett et al.* [2010a].

3. The Plume Top Altitude Time Series

[16] The volcanic plume was monitored during the eruption by a weather radar at Keflavík International Airport in southwest Iceland (64°02′N, 22°38′W), 153 km from the Eyjafjallajökull volcano, see Figure 1. This Ericsson C band radar, owned and operated by the Icelandic Meteorological Office, was the only operational weather radar in Iceland during the eruption. The radar has been successfully used for monitoring volcanic eruptions in Iceland: Hekla in 1991, only a few days after the radar became operational [*Larsen et al.*, 1992], Gjálp in 1996, Grímsvötn in 1998, Hekla in 2000 [*Lacasse et al.*, 2004], and Grímsvötn in 2004 [*Vogfjörd et al.*, 2005].

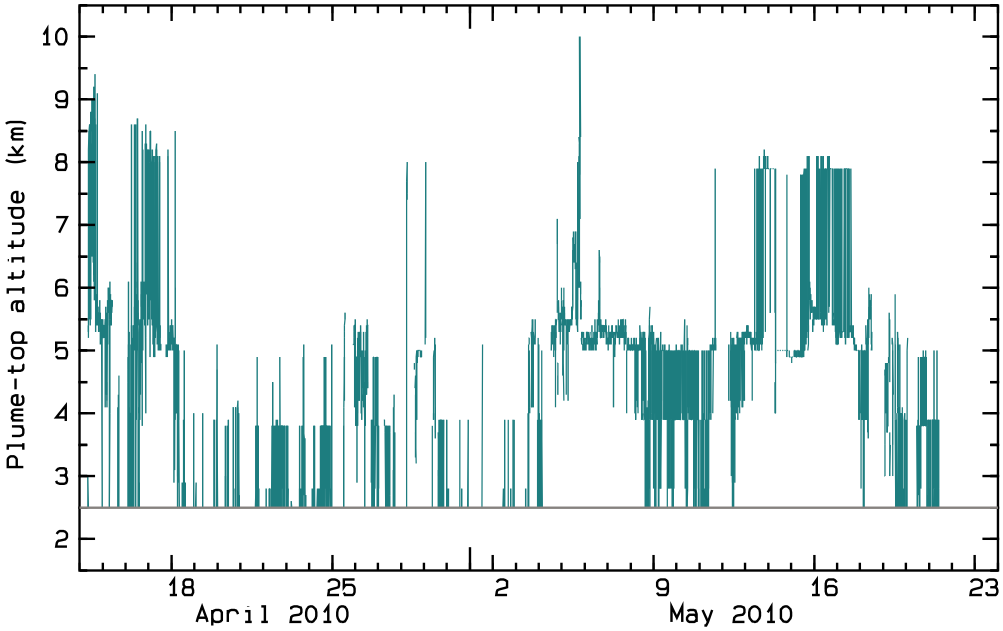

Figure 5. Height of the plume above sea level as measured by the weather radar of the Icelandic Meteorological Office. The radar could not detect the plume when below about 3 km because of orographic blockage and curvature of the Earth. This graph shows the raw 5 min data. The apparent stepping is due to discrete elevation angles of the radar.

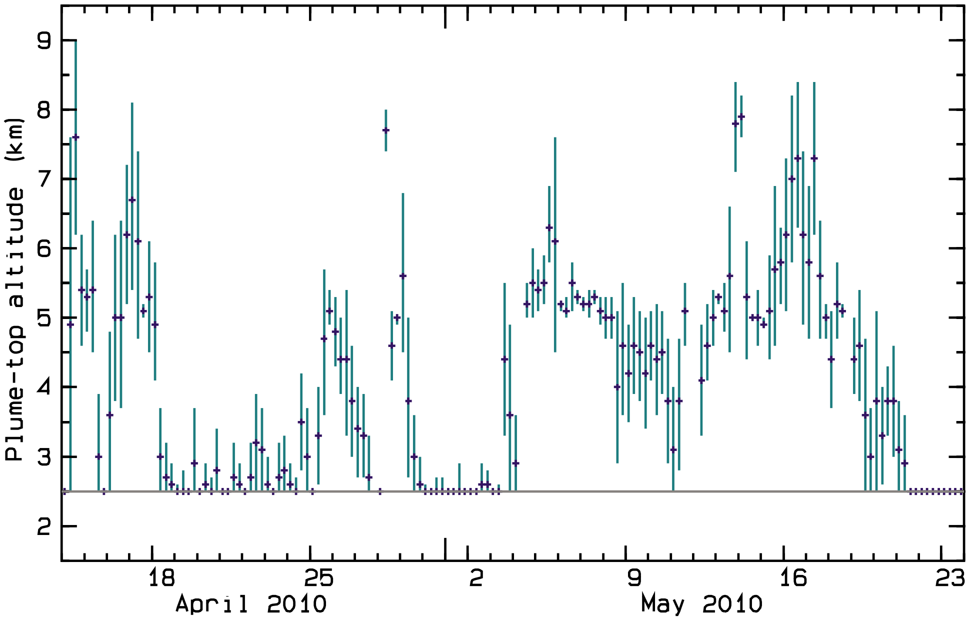

Figure 6. A 6 h mean height of the plume as measured by the weather radar along with standard deviations. By averaging, the apparent discrete stepping in Figure 5 is decreased.

[17] For this study the time series of the radar measured plume top altitudes were used, see Figure 5 [*Arason et al.*, 2011a, 2011b]. The radar plume top altitude estimates are available every 5 min during the eruption 14 April to 23 May. Because of the long distance to the volcano, the vertical resolution is rather poor. The lowest discrete elevation angles of the radar scans are 0.5°, 0.9°, 1.3°, and 2.4° (beam center), which correspond to the altitudes 2.8, 3.9, 4.9, and 7.9 km at Eyjafjallajökull. The half-power beam width of the radar is 0.9°, which translates to 2.4 km at this distance. The radar software provides linear interpolation of the reflectivity value of the highest beam exceeding the threshold (−20 dBZ), and the reflectivity value of the beam above to estimate the plume top altitude. Despite this interpolation, the estimates are noticeably grouped around the discrete altitude values. The lowest part of the 0.5° elevation beam does not reach Eyjafjallajökull. It is blocked by a mountain range, Brennisteinsfjöll (600 m asl), at a distance of 43 km from the radar. As a consequence the lowest angle of the beam reaching Eyjafjallajökull is 0.59° or 2.9 km in altitude. The partial beam blockage of the lowest elevation angle in the direction of Eyjafjallajökull is estimated to be at least 60%, using a 1 km digital elevation model [*Crochet*, 2009]. Because of this blockage, the low plume values are underestimated.

[18] To validate the radar time series, it was compared to web camera photographs of the plume from the village Hvolsvöllur, about 34 km from the volcano. Comparison of the radar and web camera time series shows that the radar is far superior in continuously monitoring the eruption plume. Due to poor visual conditions web cameras may not give any useful information for many consecutive days. However, the height resolution of the web camera images on a clear day are much better than of the radar. While the radar gave useful information about 80% of the time, the web camera was only useful about 20% of the time. The comparison of height estimates shows that the radar values are reliable on average in the 3–5 km range where both the radar and web camera data are available, despite the great discrete stepping between the radar beams [*Arason et al.*, 2011a, 2011b].

[19] In order to decrease the discrete stepping a six hour mean altitude is shown in Figure 6 along with standard deviations. Figure 6 gives a clear picture of the great variations in the eruption strength during the eruption. During the first few days the plume height varied mainly between 5 and 7 km followed by a period of lower activity on 18–24 April with plume height of 3–4 km. After almost a week of lower explosive activity the eruption gained some strength on 25–29 April, followed by another period with low plume height. On 3 May there was a sudden increase in the plume height with the initiation of a new phase of the eruption. During this last phase the plume rose to a maximum altitude of 7–8 km on 16 May, after which the plume decreased steadily. In Figure 7 the lightning activity and the plume height during the eruption are compared. The lightning activity is mainly confined to 14–18 April and 11–20 May, when the plume was relatively strong. However, the lack of lightning during 3–10 May, despite fairly strong plume was puzzling. In the search for an explanation of this, a change was noticed in the atmospheric conditions coinciding with this period.

4. Meteorological Data From the UK Met Office's Unified Model

[20] The meteorological data used here was derived from the UK Met Office's Unified Model (UM) [*Davies et al.*, 2005]. The UM is a suite of numerical modeling software developed and used operationally at the Met Office to provide forecasts of the state of the atmosphere for periods of a few hours to centuries ahead. In its current operational numerical weather prediction (NWP) configuration, the UM produces data over three nested domains, all with 70 vertical

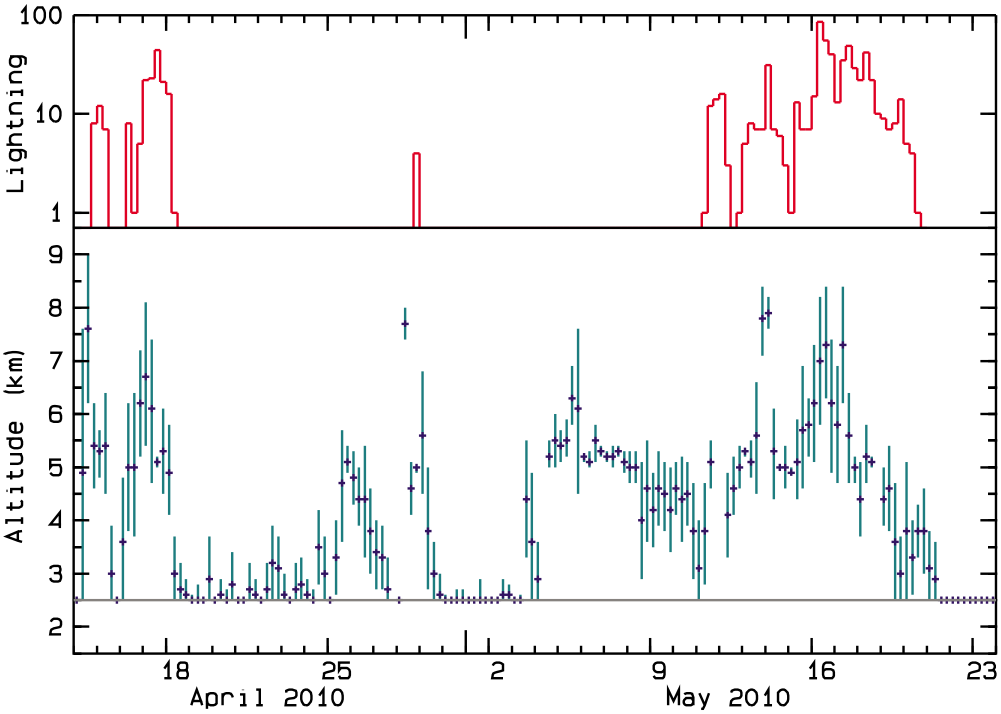

Figure 7. Comparison of the number of lightning per 6 h (on logarithmic scale) and the plume top altitude. A fairly good correlation can be seen most of the time, with the exception of the absence of lightning on 3–10 May.

levels: a global domain with 40 km horizontal resolution, a domain which covers the North Atlantic and Europe with 12 km horizontal resolution, and a smaller region which covers the UK with 4 km horizontal resolution. A typical run consists of a period of data assimilation followed by a period of prediction. The data assimilation scheme constructs the model state to be the best statistical fit to the observed data. Data from this analysis phase of the global model run was used here.

[21] The UK Met Office's Numerical Atmospheric dispersion Modeling Environment (NAME) [*Jones et al.*, 2007] was used to extract vertical profiles of temperature, wind speed and wind direction from the global domain of the UM. The NAME model was used by the London Volcanic Ash Advisory Centre (VAAC) during the eruption of Eyjafjallajökull to forecast the dispersal of the volcanic ash and is described in detail in other papers in this special issue [*Dacre et al.*, 2011; *Webster et al.*, 2011]. NAME linearly interpolated the data from the UM to the location of Eyjafjallajökull (63°38′N, 19°38′W) in vertical extent from the crater at 1667 m to an altitude of 10,167 m in 100 m intervals at a temporal resolution of 1 h.

[22] Figure 8 shows the wind speed and direction at 3, 5, and 7 km altitude above Eyjafjallajökull in the atmospheric hourly data from the UM. High wind speed may affect the height of the plume [e.g., *Petersen et al.*, 2011] and inhibit the accumulation of electric charge. If opposite charges accumulate at different heights, the distances between these regions will increase with increased wind speed, leading to decreased electric field and rate of lightning. Figure 9 shows the height of the 500 hPa pressure level, both the value of the UM data at Eyjafjallajökull and measurements at Keflavík radiosonde station, 151 km from the volcano. The graph shows variations in the height and a warm period (high values of the pressure level) 2–11 May is apparent. This warm period coincides with the period 3–10 May where the eruption was fairly strong, but no lightning were measured by the long-range ATDnet network. Figure 10 shows the variations in the temperature profiles of the atmosphere over Eyjafjallajökull. Note that the temperature scale is inverted, so that the highest profile is at the top of the graph. The lowest profile (blue) shows a lowland surface temperature of a close automatic station, Vatnsskarðshólar (63°25′N, 19°11′W), elevation 20 m asl. Figure 11 shows the variation in the height of a few isotherms in the UM output. Figure 11 shows that the altitude of the −20°C isotherm varied from about 3 to 6 km during the eruption, similar to the variations of the altitude of the plume.

5. Discussion

[23] The height of an atmospheric critical isotherm, close to −20°C, appears to control the charge distribution in meteorological thunderclouds. Generally, thunderclouds are positively charged above this isotherm and negatively below [e.g., *Uman*, 2001; *Rakov and Uman*, 2003].

[24] During a long eruption the height of this critical isotherm may vary independently of temporal variations in the strength of the eruption and height of the volcanic plume. If the charge generation process in volcanic plumes is similar to processes in meteorological thunderclouds, there might be a correlation between the occurrence of lightning and plume height compared to the height of a critical isotherm. However, we are not aware of any long volcanic eruption, where

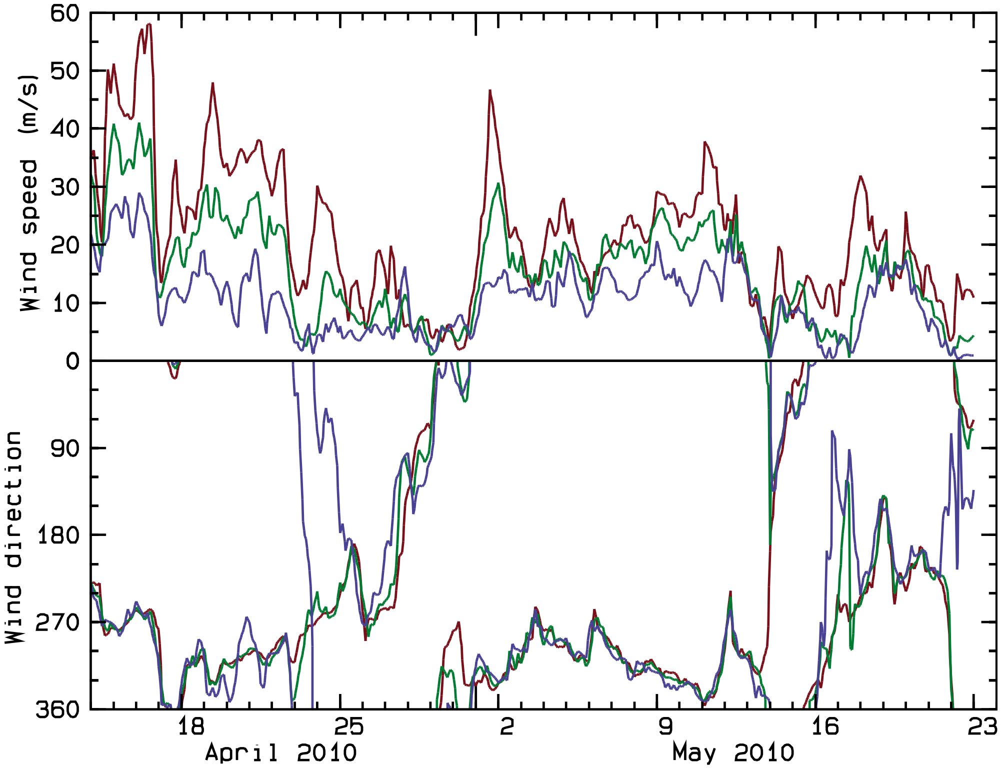

Figure 8. Wind speed and direction above Eyjafjallajökull. Atmospheric hourly data from the UM data. Wind at the 3 km (blue), 5 km (green), and 7 km (brown) altitude levels.

the plume height has been monitored continuously and where lightning activity has also been monitored. All the critical variables needed for such a comparison are available for the 2010 eruption of Eyjafjallajökull. Therefore, Figure 12 compares the temporal variations of the plume top altitudes and the height of the −20°C isotherm along with the lightning count per 6 h (on a logarithmic scale). Sometimes the plume did not reach the height of the −20°C isotherm, while at other times it went well above it. It is very informative to see that during the lightning free period in the beginning of May, the isotherm is relatively high, and above the plume.

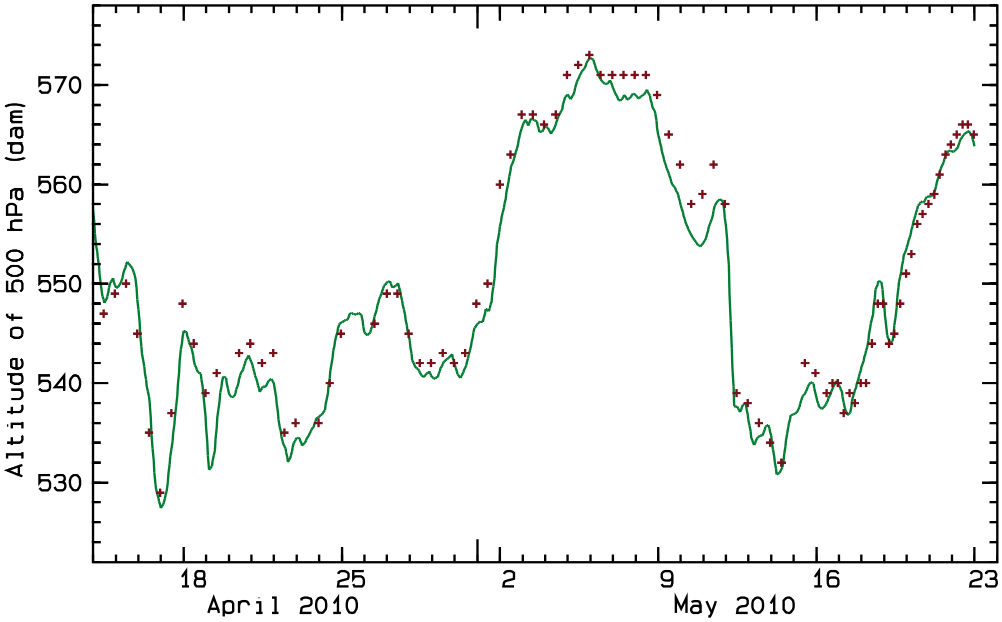

Figure 9. Height of the 500 hPa atmospheric pressure level. Comparison of the UM data at Eyjafjallajökull (green curve) and radiosonde measurements at Keflavík International Airport (63°58′N, 22°37′W) (dots).

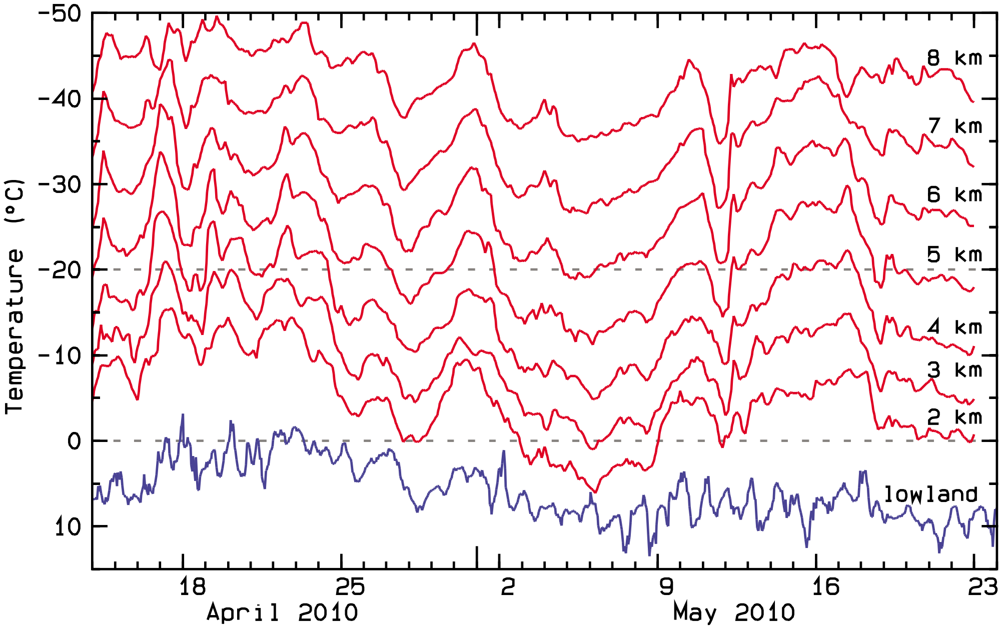

Figure 10. Variations in the temperature profiles of the atmosphere above Eyjafjallajökull. Note the inverted temperature scale. Lowland surface temperature (blue), and temperature time series of the UM data at 2, 3, 4, 5, 6, 7, and 8 km altitude (red).

[25] Figure 13 shows the calculated plume top temperature according to the UM data over Eyjafjallajökull. Here, the mean value and the standard deviation bars of the 6 h mean plume top altitudes (Figure 6) were transformed to the 6 h mean temperature at that height in the UM output. Note that the plume reached the coldest temperatures during the first days of the eruption and during the middle of May, synchronous to the greatest lightning displays. There are some notable discrepancies in the temporal correlation seen in Figures 12 and 13 which may be related to inaccurate plume altitude estimates or more likely to temporal variability in some other unknown but important properties of the plume. During the morning of the first day, 14 April, the plume was fairly high but no lightning was detected. After these first hours Figures 12 and 13 show good temporal correlation for the first two weeks. Three lightning flashes were detected on 28 April, but increased plume heights were observed slightly before and after the lightning. The

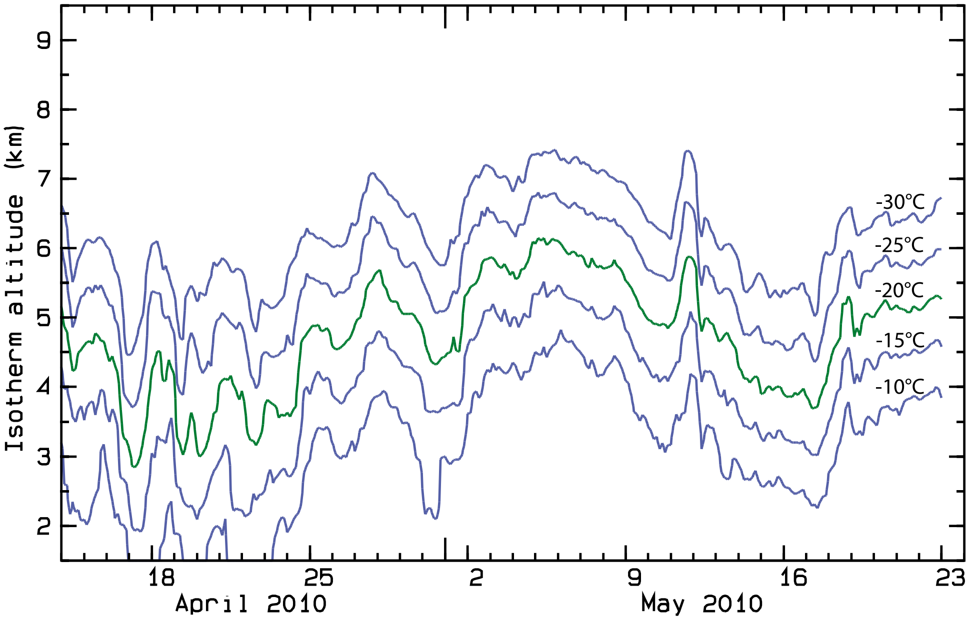

Figure 11. Variations in the height of the −10° (lowest), –15°, –20° (green), –25°, and −30°C (highest) isotherms.

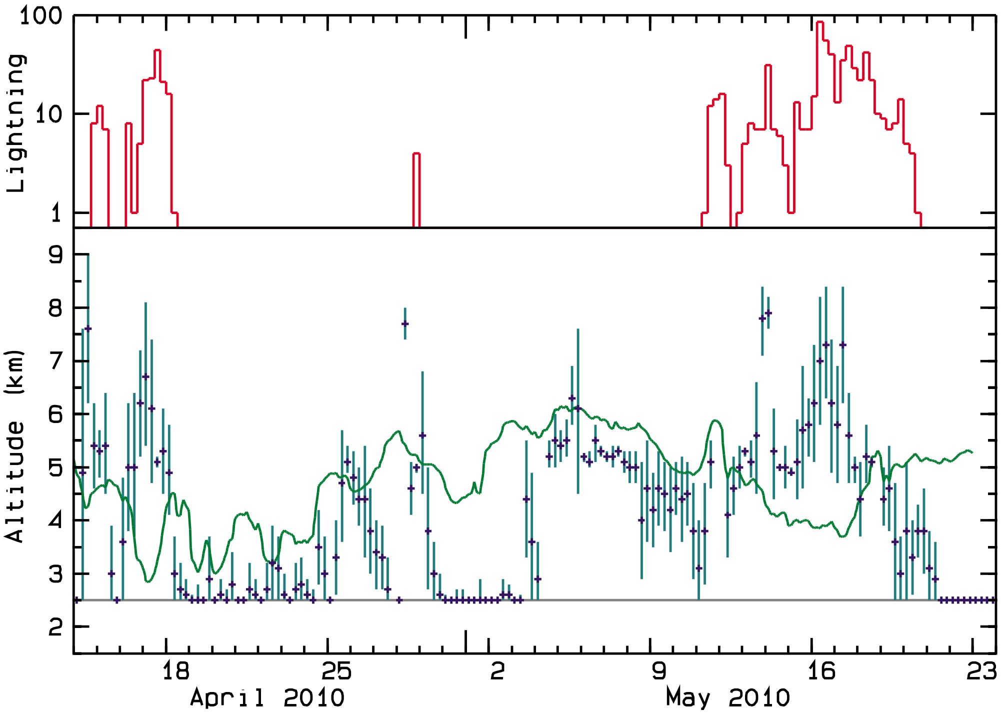

Figure 12. Number of lightning per 6 h (red) from Figure 4, plume top altitudes (blue) from Figure 6, and the height of the −20°C isotherm (green) from Figure 11. Lightning activity was observed when the plume penetrated significantly up into droplet freezing conditions.

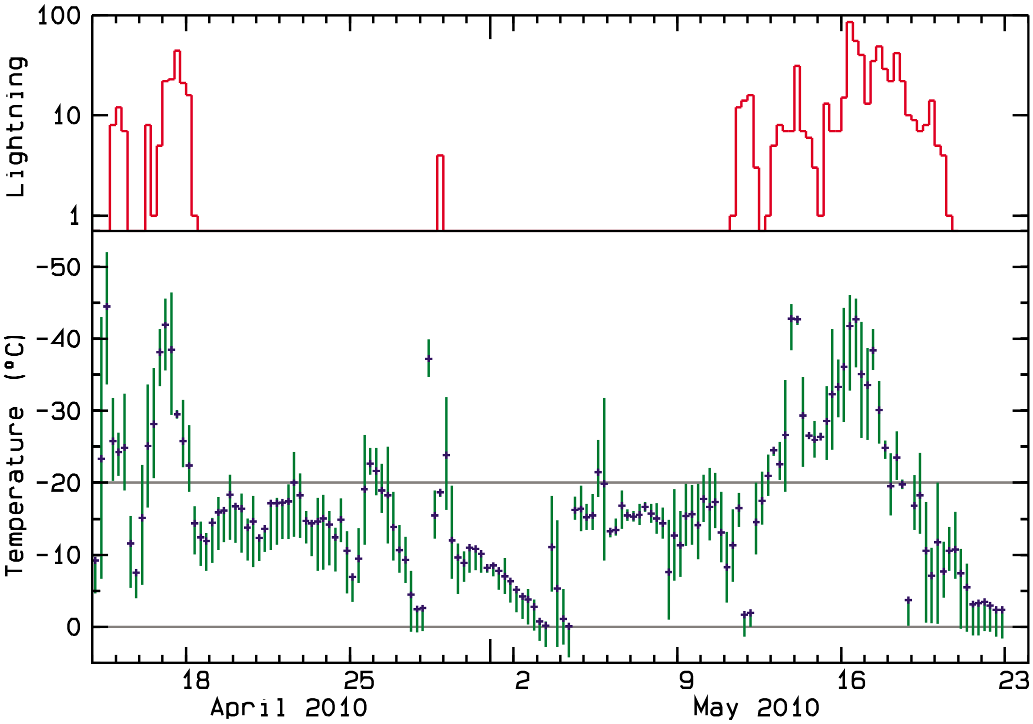

Figure 13. Number of lightning (red) from Figure 4, and plume top temperature (green) estimated from the height of the plume and the temperature of the UM data. The standard deviations of the plume top altitudes were used to estimate the corresponding variation in plume top temperatures.

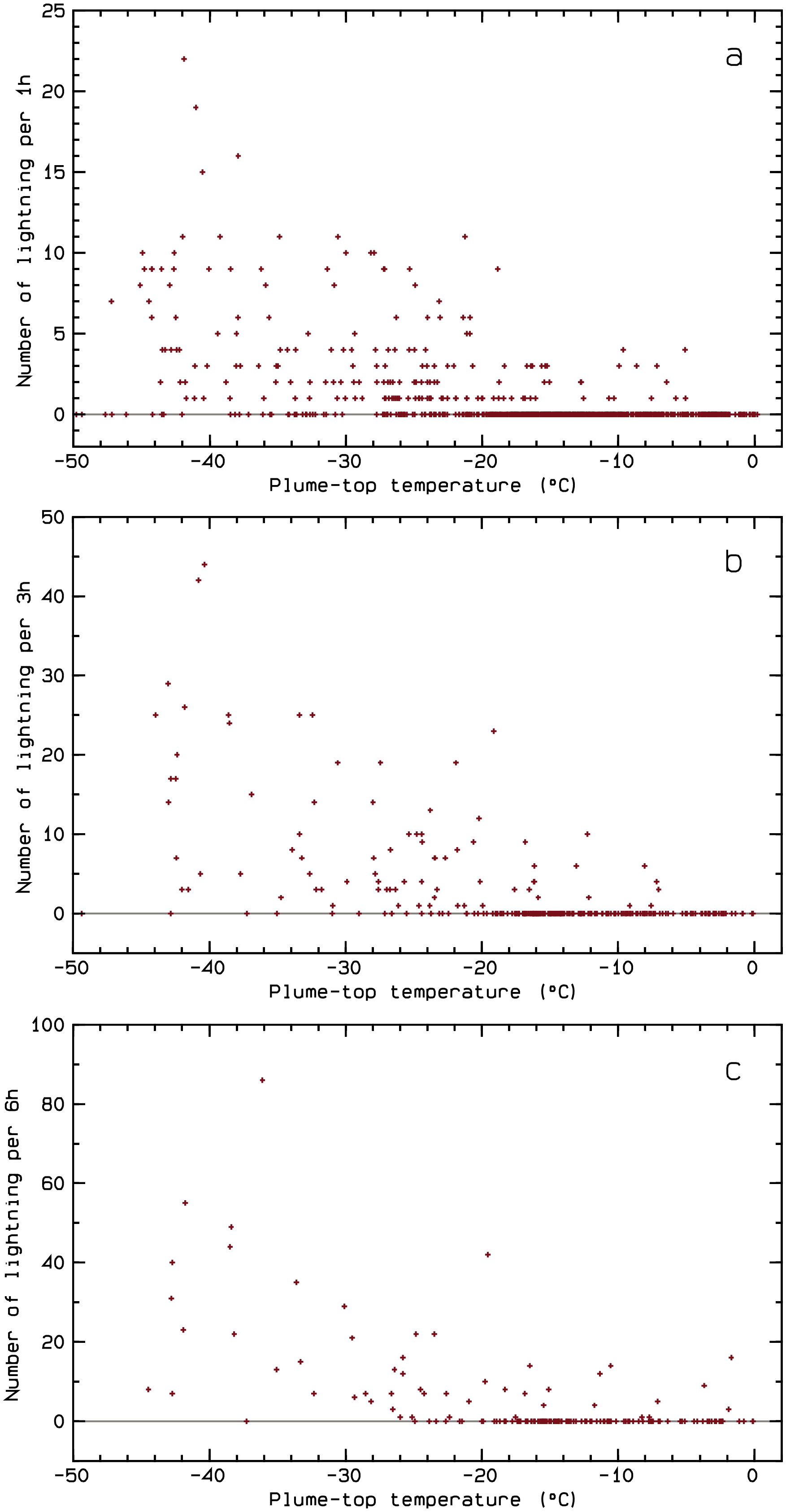

Figure 14. Comparison of the plume top temperature and the rate of lightning strokes for 1, 3, and 6 h bins. Lightning occurs seldom for the warmest cases, and the greatest rate of lightning strokes occurs for the coldest cases.

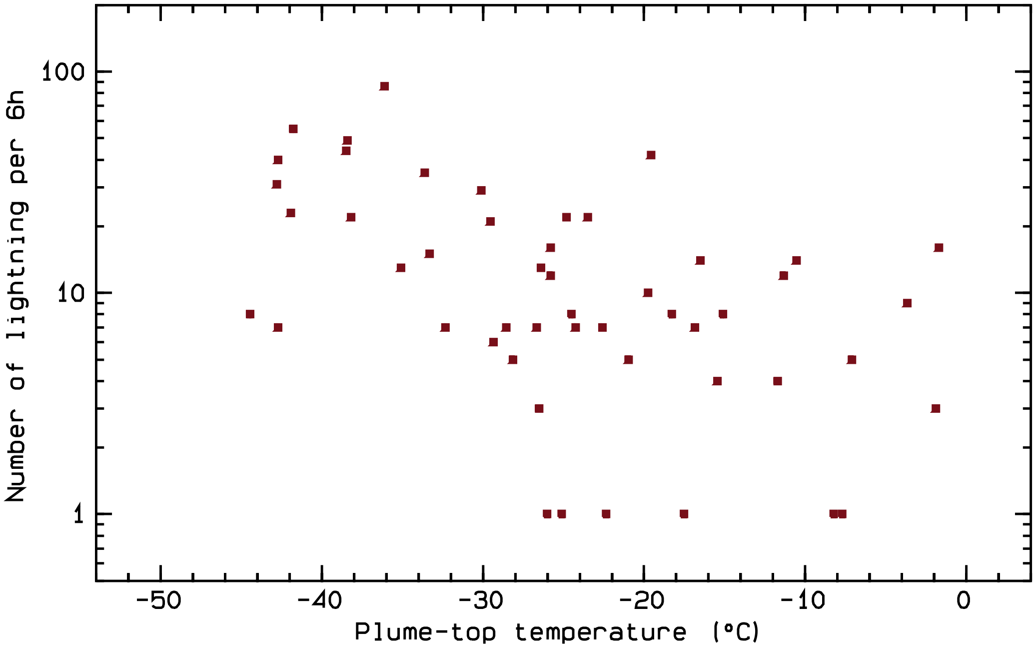

Figure 15. Number of lightning per 6 h (logarithmic count) versus 6 h mean plume top temperature, when lightning was observed. Frequency of lightning occurrence increases as the plume reaches colder temperatures. Coefficient of determination for a least squares line is $R^2 = 0.23$.

relatively high plume in early May with no lightning strikes is well explained by the high ambient temperature. The initiation of lightning on 11 May is not obvious in the temperature data and poor plume height estimates. However, there is good temporal correlation between the ambient temperature and lightning during 12–18 May. The last two days of lightning on 19–20 May, do not give good correlation between plume height and ambient temperature of the atmosphere. On the whole, Figures 12 and 13 indicate that the plume top temperature is closely correlated to the occurrence of lightning in the Eyjafjallajökull plume, and also that the rate of lightning occurrence, i.e., number of lightning per 6 h, appears also to be linked to the plume top temperature.

[26] The estimate used in this study of plume top temperature is derived from radar estimates of plume top altitudes and the atmospheric temperature at that level in the UM. This temperature of the ambient atmosphere may not fully reflect the actual temperature within the plume close to its top. Furthermore, for a graupel based charge generation process to work, a sufficiently large portion of the upper part of the plume must be elevated above some actual critical temperature. Therefore, the calculated critical plume top temperature of this study is probably shifted toward colder temperatures than the actual critical temperature within the plume. Although the magnitude of this bias is not known, it may not be important at this point.

[27] The calculated critical plume top temperature appears to be close to −20°C, but it is possible to estimate this critical temperature from the data. Furthermore, it is important to verify that the choice of a 6 h temporal averaging, is not influencing the results. Figure 14 shows scatterplots for three different time intervals, 1, 3, and 6 h, of the number of lightning strokes versus the mean plume top temperature. The time intervals correspond to the interval used for the lightning count bins, the time interval for the calculation of the mean plume top altitude, and for the mean temperature in the UM data. Figure 14 shows that there was usually no lightning when the plume top was relatively warm, and that lightning often occurred when the plume top was very cold. The agreement seems to be independent of the three averaging time intervals used. Furthermore, there appears to be a correlation between the rate of lightning strokes and the plume top temperature. Figure 15 is similar to Figure 14c, where the lightning count is shown on a logarithmic scale when lightning was observed. Higher frequency of lightning occurrence is apparent as the plume top gets colder. Figure 16 shows a further compilation of the data in Figure 14, where the frequency of lightning occurrence for each plume top temperature interval is calculated for the three averaging time intervals. The critical plume top temperature in Figure 16 appears to be between −20° and −24°C. In this study we have correlated temporal variations in lightning occurrence to a critical value of the plume top temperature, a process analogous to the charge generation in meteorological thunderstorms. However, other scenarios are possible involving different charge generation processes coupled with separation or redistribution processes linked to the critical temperature of the plume top.

[28] Time lapse photographs during the Eyjafjallajökull eruption reveal at least two types of lightning. Most of the photographs show small lightning sparks in the lower part of the plume, close to the crater. Much fewer images show large whole plume flashes. However, the photographs of the whole plume lightning have greater appeal and much wider distribution. Probably none of the small sparks were registered by the long-range ATDnet lightning network. The low level vent discharges must be due to processes at or very close to the vent, such as magma-water interactions or

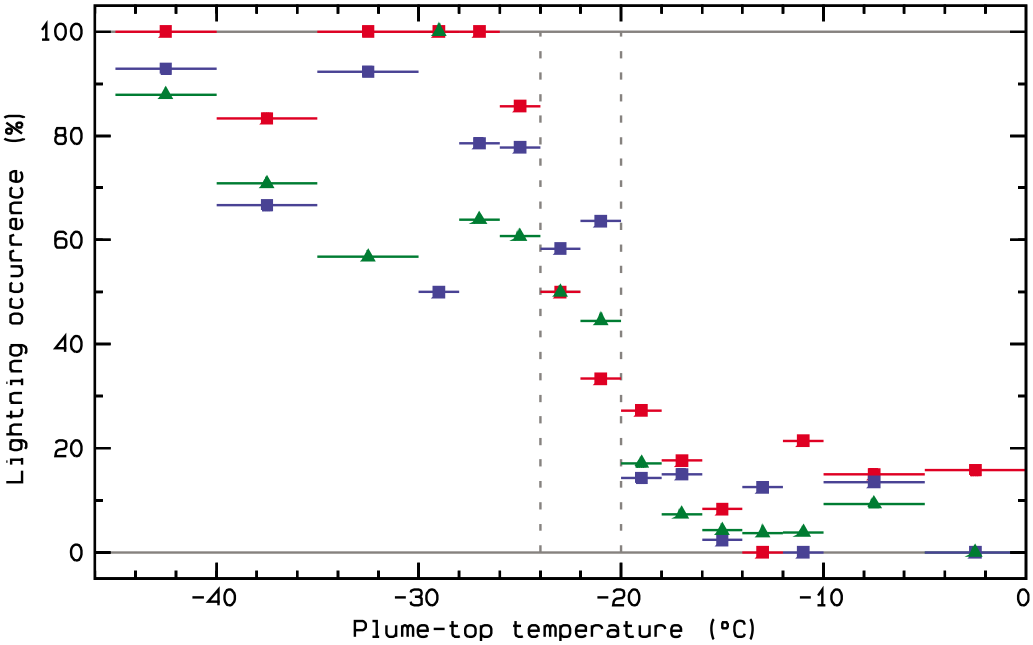

Figure 16. Comparison of the mean plume top temperature and the occurrence of lightning for 1 h (green), 3 h (blue), and 6 h bins (red). Lightning occurs seldom for the warmest cases, but frequently when the plume top is very cold. The critical temperature is between −20° and −24°C.

fractoemission. The separation of volcanic lightning into visually different types was noted during the Surtsey eruption by *Sigurgeirsson* [1965] and in Eyjafjallajökull by *Thomas et al.* [2010b], and in 3D mapping at the 2006 Mount St. Augustine eruption by *Thomas et al.* [2007, 2010a].

[29] Ash layers on the Eyjafjallajökull glacier, close to the crater were observed to include distinct layers of gray ash-

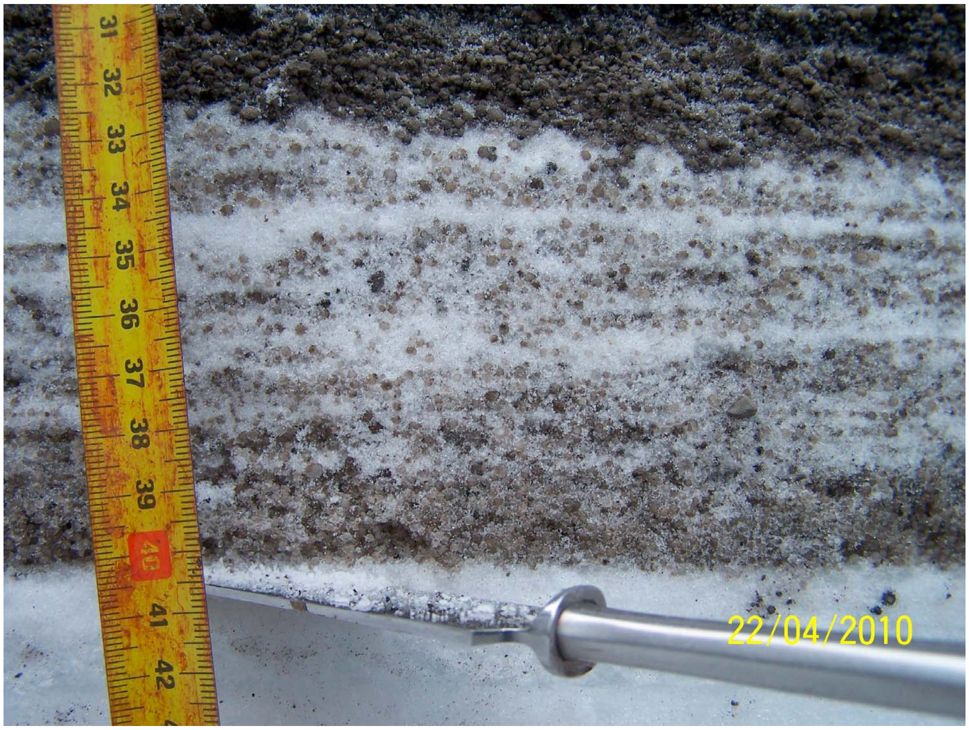

Figure 17. Initial ash layers of the eruption observed on the Eyjafjallajökull glacier about 5 km east of the vent, altitude about 1300 m. The initial layers, probably from 14 April, include a mixture of meteorological snow and 1–2 mm ash-infused hail from the volcanic plume. Photo Thor Thordarson, 22 April 2010.

Table 1. Frequency of Plume Top Temperatures and Occurrence of Lightning[a]

Temperature Range	N_0	N_L	N_T	Frequency of Lightning
1 h				
>−20°C	547	34	581	6%
−20° to −24°C	31	28	59	47%
<−24°C	56	117	173	68%
Missing	-	-	123	-
Total	-	-	936	-
3 h				
>−20°C	187	17	204	8%
−20° to −24°C	9	14	23	61%
<−24°C	11	48	59	81%
Missing	-	-	26	-
Total	-	-	312	-
6 h				
>−20°C	99	17	116	15%
−20° to −24°C	5	4	9	44%
<−24°C	2	29	31	94%
Missing	-	-	0	-
Total	-	-	156	-

[a] Number of time intervals during the 39 days of the eruption: With no registered lightning (N_0), with lightning occurrence (N_L), and total (N_T). Missing data is because of time intervals with no plume top altitude estimates.

infused hail [*Larsen et al.*, 2010; T. Thordarson, personal communication, 2010], indicating the presence of hail or graupel in the plume. Figure 17 shows the initial layers of ash about 5 km East of the vent, probably deposited on 14 April. The photograph shows a mixture of meteorological snow and ash-infused hail or graupel. Graupel is well known as the key element in the charge generation in meteorological thunderstorms [e.g., *Latham et al.*, 2007].

[30] Table 1 shows that when the plume top was warmer than −20°C, only 6–15% of the time intervals had any lightning occurrence, while when the plume top was colder than −24°C, lightning occurrences rose to 68–94%.

6. Conclusions

[31] Several possible charge generation mechanisms have been proposed for volcanic plumes, but it is very difficult to verify their existence or relative efficiency in real plumes, and to see to what extent they are responsible for the observed charge generation. However, visual observations and photographs of volcanic lightning indicate that there may be more than one charge generation process at work.

[32] During the 2010 Eyjafjallajökull volcanic eruption, which lasted 39 days, data were collected on plume lightning activity, plume height, and status of the ambient atmosphere. Because of the length of the eruption, the data collected provides a unique opportunity to assess influences of atmospheric properties on the plume and lightning activity. This study shows a very good temporal correlation between the ambient temperature of the atmosphere at the plume top and the occurrence of lightning as recorded by a long-range network. The critical plume top temperature appears to be between −20° and −24°C. Furthermore, as the plume became colder, the rate of lightning occurrence increased.

[33] This critical temperature, that seems to have turned on and off the observed lightning activity in the 2010 Eyjafjallajökull volcanic plume, is the same as the temperature level between the top positive charge and lower negative charge in ordinary thunderclouds. Therefore, we conclude that the larger whole plume lightning recorded by long-range networks is likely to be graupel generated, analogous to the charge generation in meteorological thunderstorms.

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