Earth, Water, Wind and Fire

On the Charge Generation of Volcanic Lightning

Þórður Arason

Veðurstofa Íslands

Icelandic Meteorological Office, Reykjavík, Iceland

USGS Cascades Volcano Observatory, Vancouver, Washington, USA, 7 December 2016

Icelandic Meteorological Office
Veðurstofa Íslands

Icelandic Met Office

- Government organization – National weather service. Founded in 1920; weather obs. since 1840s (1779). 130 employees
- Weather – Climate – Atm. Pollution – Seismology – Tectonics – Volcanics – Glaciology – Avalanches – Hydrology
- Natural Hazards: Observations – 24-7 Monitoring – Forecasting – Warnings – Research

Background

Icelandic Met Office

Education

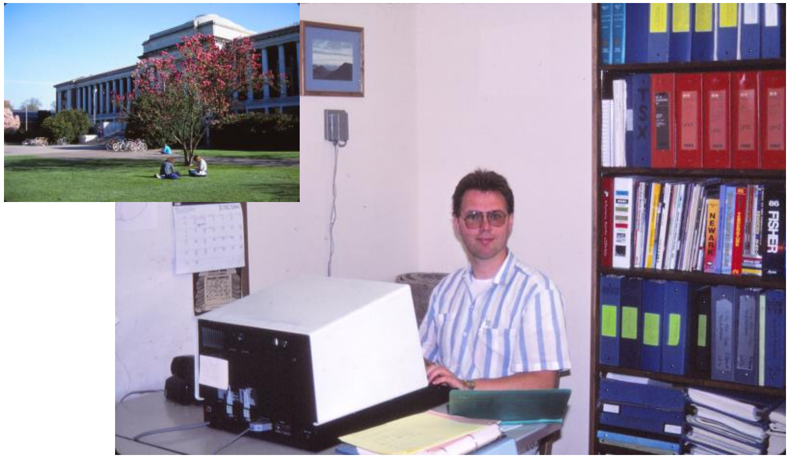
- BS-Physics, University of Iceland 1982
- PhD-Geophysics, Oregon State University 1991 – Paleomagnetism of deep-sea sediments

Work

- 1981-1984 High school physics teacher
- 1984-1991 Graduate geophysics student at College of Oceanography, Oregon State University, Corvallis
- 1991-1996 Geothemal reservoir physics
- Since 1996 IMO: Weather station operations – Lightning obs. & res. – Weather data base – Web – Avalanche risk assessment

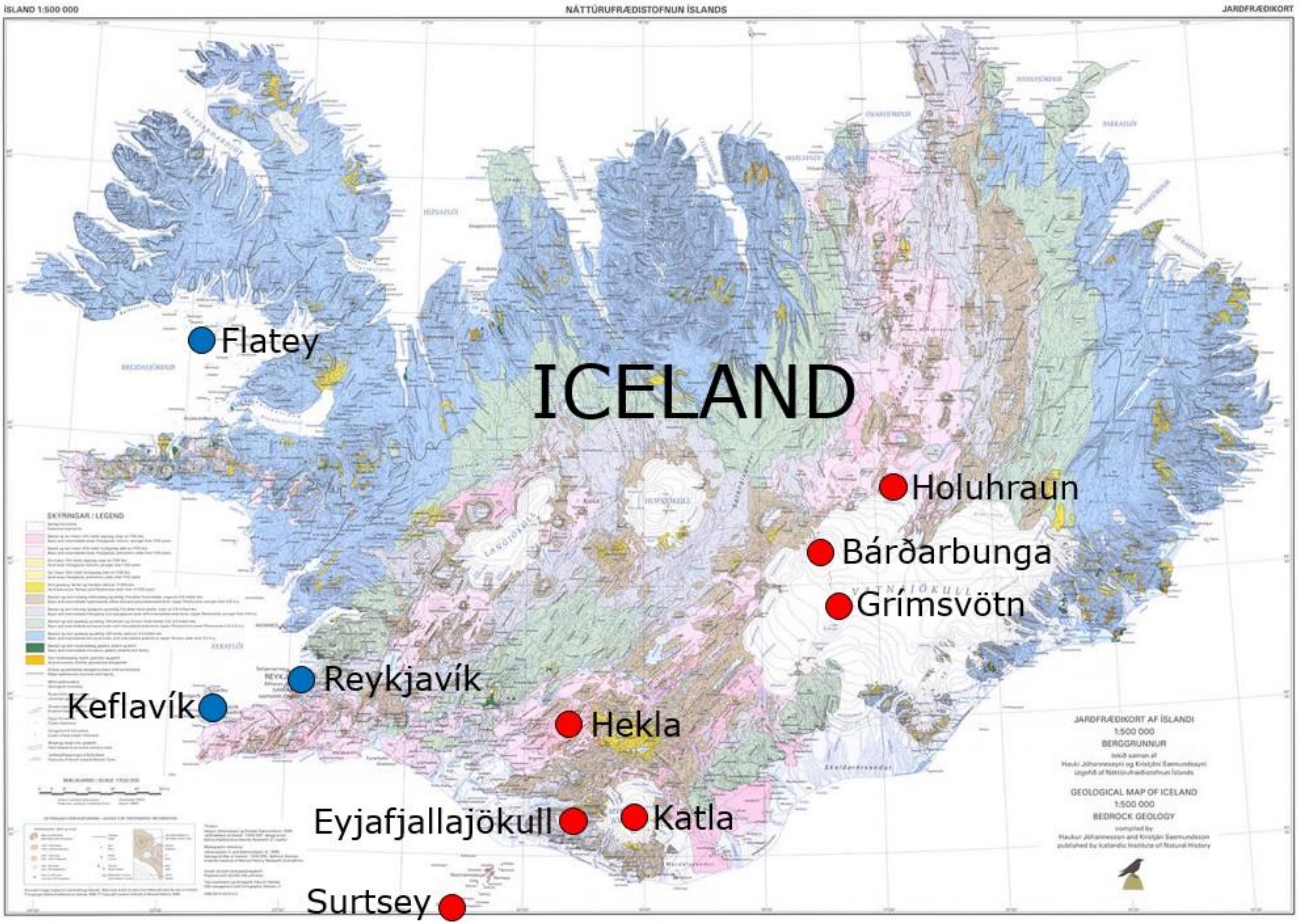
Current responsibilities

- Radars – Aurora – Lightning – Volcanics



At Oregon State University, Corvallis, June 1986.

At Washington Park Zoo, Portland, March 1987.


ÍSLAND 1:500 000
NÁTTÚRUFRÆÐISTOFNUN ÍSLANDS
JARÐFRÆÐIKORT
ICELAND
Flatey
Reykjavík
Keflavík
Holuhraun
Bárðarbunga
Grímsvötn
Hekla
Eyjafjallajökull
Katla
Surtsey
SKÝRINGAR / LEGEND
JARÐFRÆÐIKORT AF ÍSLANDI
1:500 000
BERGGRUNNUR
GEOLOGICAL MAP OF ICELAND
1:500 000
BEDROCK GEOLOGY

Charge generation in volcanic plumes

Icelandic Met Office

Electric charge can be generated by various processes

- magma-water interactions
- fractoemission – magma fracturing into ash
- triboelectrification – collisions of ash-grains
- plume water freezing – thunderstorms

It is difficult to distinguish between these proposed charging processes in real volcanic plumes

- All processes are possible – and more powerful eruptions are expected to produce more charge generation for all processes
- In situ observations are (almost) impossible
- Controlled laboratory experiments that generate electric charge, never fully represent the conditions in the more complicated natural setting
- More than one process may be responsible for the observed volcanic lightning

Is there more than one type of volcanic lightning?

Icelandic Met Office

Observers sometimes notice two distinct types

1. Frequent small sparks (~100 m) close to the vent
2. Whole-plume (5–10 km) thunderbolts

Lightning outside or on the edges of plumes are more easily observed visually than the ones deep inside the plume

Magma-water interactions

Icelandic Met Office

Earliest published scientific research on volcanic electric charge generation was by Volta in 1782, where he mentions lightning during the dreadful eruption of Mt. Vesuvius in 1779. He demonstrated that by pouring water on hot surfaces one could generate electric charge.

Alessandro Volta (1745-1827)

He concluded that there would be sufficient water in volcanic eruptions to produce the electricity for the observed plume lightning.

Volta, A. (1782), Del modo di render sensibilissima la più debole elettricità sia naturale, sia artificiale (Of the method of rendering very sensible the weakest natural or artificial electricity) (in Italian w. English translation), *Philosophical Transactions*, **72**, 237–280 (vii-xxxiii), doi:10.1098/rstl.1782.0018


Lightning in the plume of Mt. Vesuvius 8 August 1779.
Oil painting by J. P. Hackert (1737-1807)

Fragmentation and collisions of ash particles

Icelandic Met Office

Fractoemission

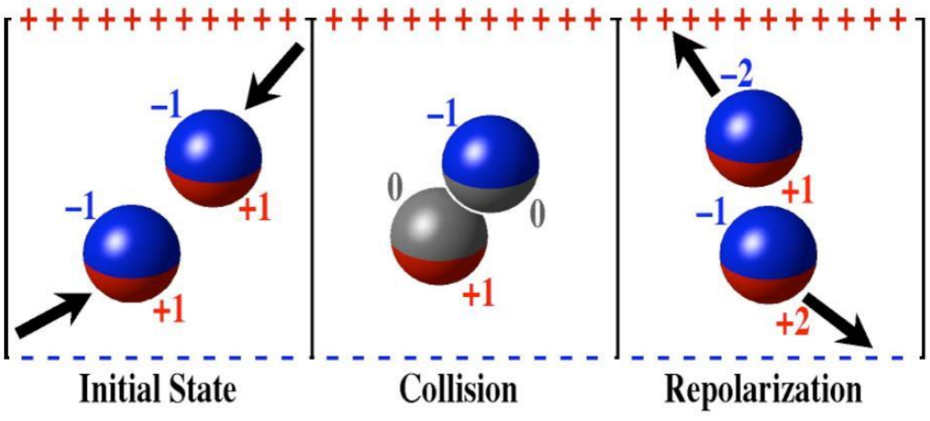
- Fragmentation of material (e.g. gas-rich magma) into ash is powerful in generating electric charge in laboratory experiments

Triboelectrification

- Charge separation after contact between particles of different properties

Inductive charging

- Small suspended grains polarized by external electric field may also get charged by collisions

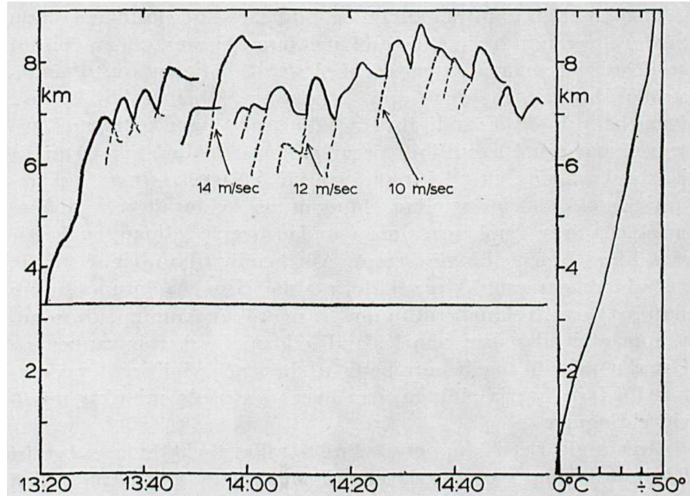


From Pähtz et al. (2010)

Cause of Surtsey volcanic lightning

Icelandic Met Office

Hreyfingin í efri hluta gosskýsins er mjög áþekk því, sem gerist í þrumuskýjum, svo að ætla má að sömu orsakir geti framkallað eldingar í báðum þessum tilfellum. Annars eru menn ekki á eitt sáttir um, hver sé frumorsök eldinganna í venjulegu þrumuskýi, en á einhvern hátt skiljast rafhleðslur að, þannig að efri hluti skýsins fær jákvæða rafhleðslu, en neðri hlutinn neikvæða. Sumir telja að aðgreiningin eigi sér stað þar, sem vatnsdropar og frosið hagl þyrlast saman í uppstreymi skýsins. Eftir snertingu við haglið fái hinir smágerðu vatnsdropar jákvæða rafhleðslu og berist upp með skýinu, en haglið flytji neikvætt rafmagn niður.



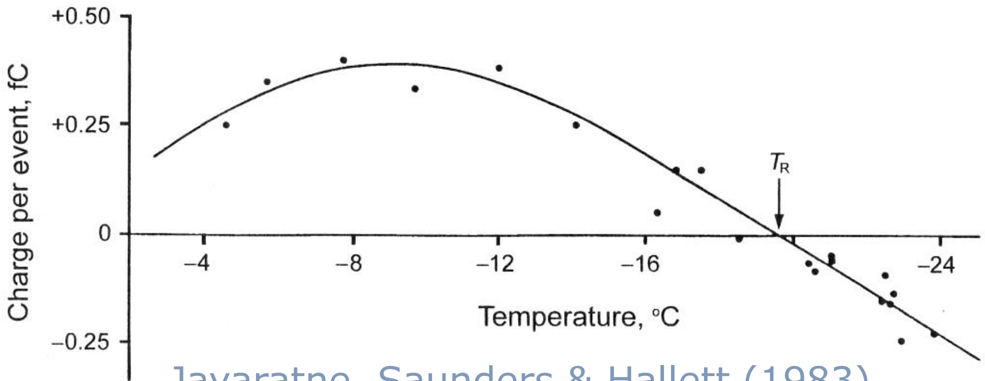
1. mynd. Hæð gosskýsins yfir Surtsey 1. desember 1963. — *Fig 1. Height of top of the volcanic cloud at Surtsey on December 1st, 1963.*

Prof. Þorbjörn Sigurgeirsson (1917-1988)

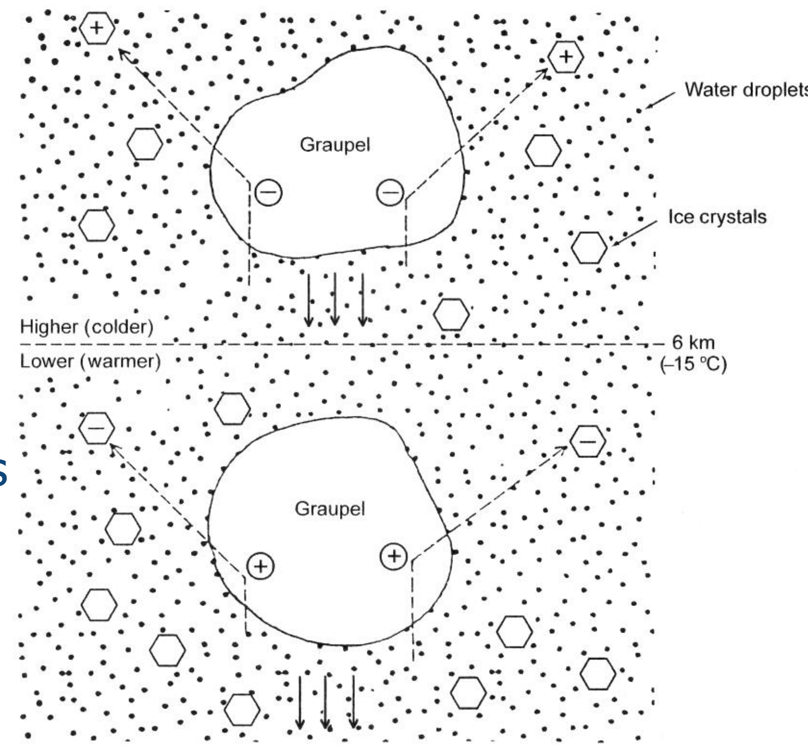
"The movement in the upper part of the volcanic cloud is very similar to the one in thunderclouds, so one may expect the same processes to cause lightning in both. … Some believe the separation [of charge in thunderclouds] occurs where water drops and frozen hail swirl together in the updraft of the cloud. After contact with the hail, the small water drops get positive charge and are carried aloft with the cloud, while the hail transports negative electric charge downward." (translation ÞA)

Sigurgeirsson, Þ. (1966), Jarðeðlisfræðirannsóknir í sambandi við Surtseyjargosið (Geophysical research in connection with the volcanic eruption at Surtsey), *Náttúrufræðingurinn*, **35**(4), 188-210, (in Icelandic).

Electrification in meteorological thunderclouds



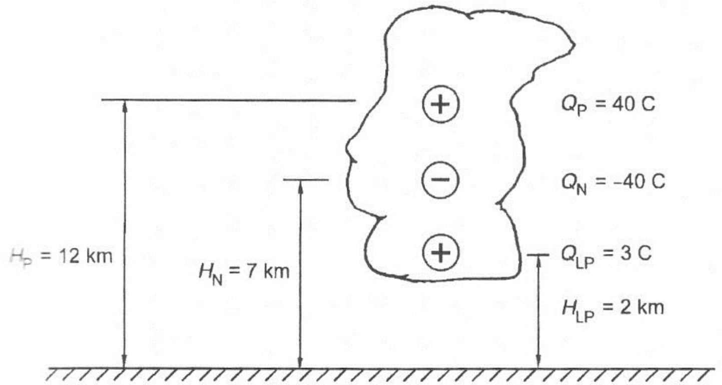
Jayaratne, Saunders & Hallett (1983)



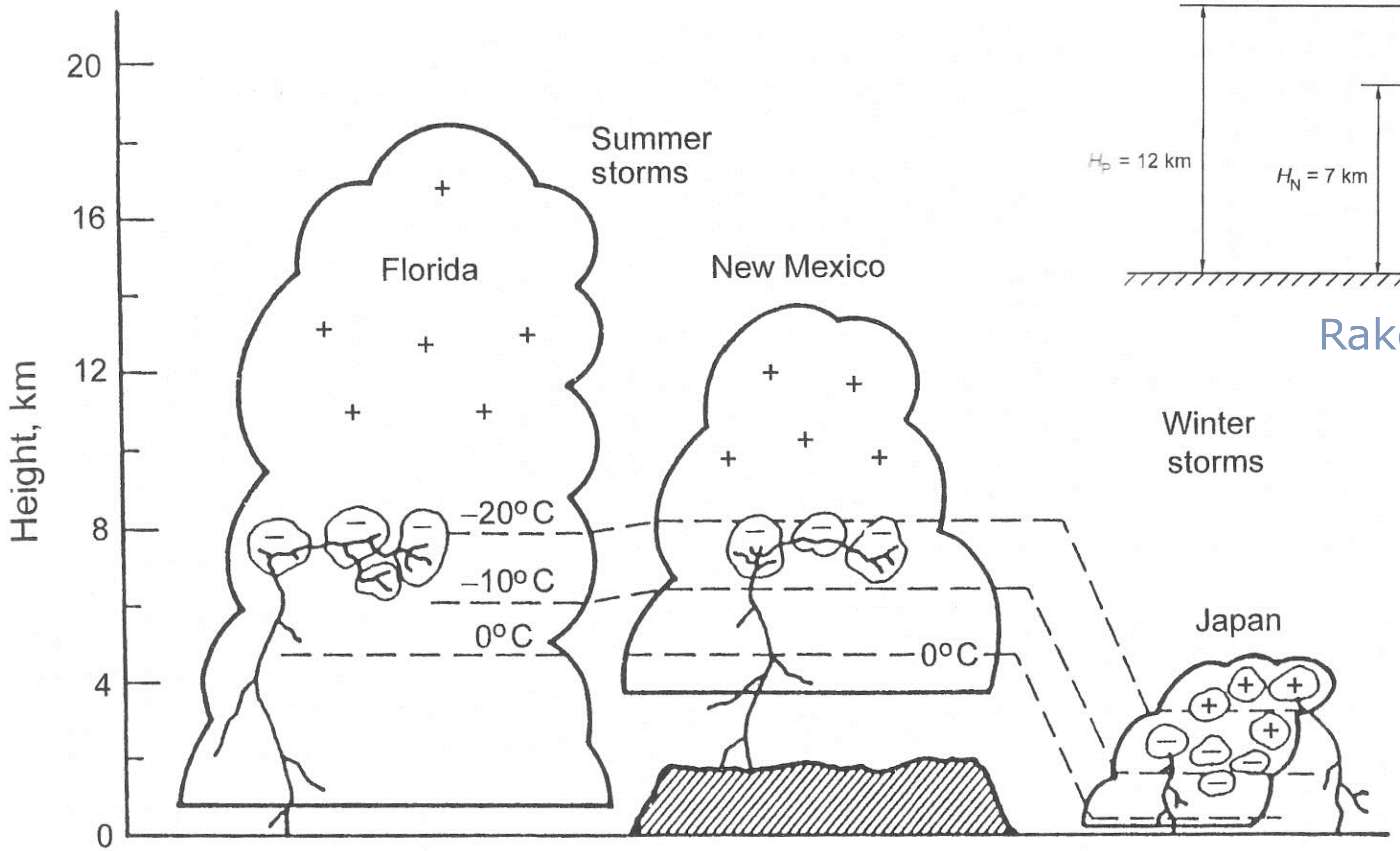
Rakov & Uman (2003)

- Due to their small size, cloud droplets stay supercooled well below 0°C. Usually they freeze at −15° to −20°C
- Both the polarity and charge generation efficiency of a falling graupel appears to be temperature dependent
- The temperature controls freezing of cloud droplets, charge generation and charge distribution in thunderclouds

General charge structure of meteorological thunderclouds



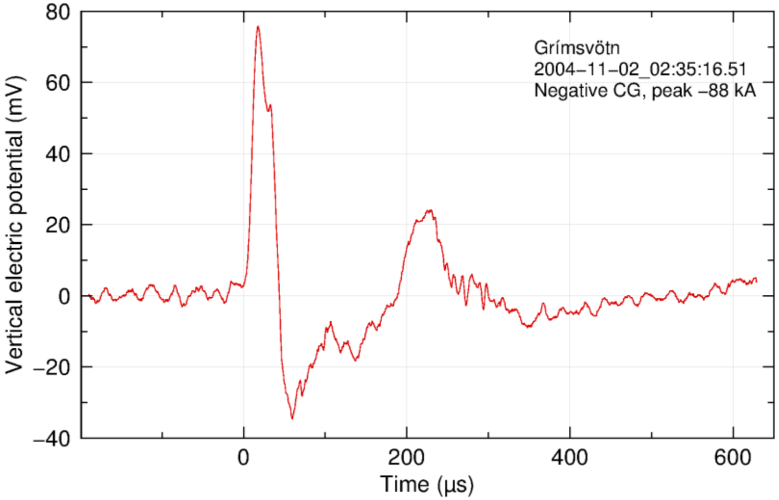
Rakov & Uman (2003)

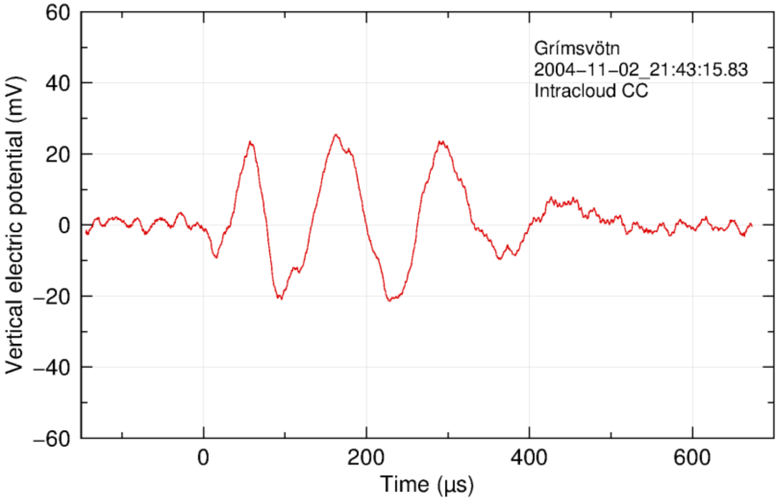


Adapted from Krehbiel (1986)

Vertical electric field from volcanic lightning

- Vertical electric field observed in Reykjavík, 220 km distance to Grímsvötn. Proxy: Two horizontal circular 40 cm plates 3.5 cm apart. Electric potential (mV) recorded every 0.2 μs.
- Three characteristic types of waveforms were observed during the Grímsvötn 2004 eruption: Cloud-to-Ground lightning (46%), Intracloud lightning (50%), and Precursors (4%).

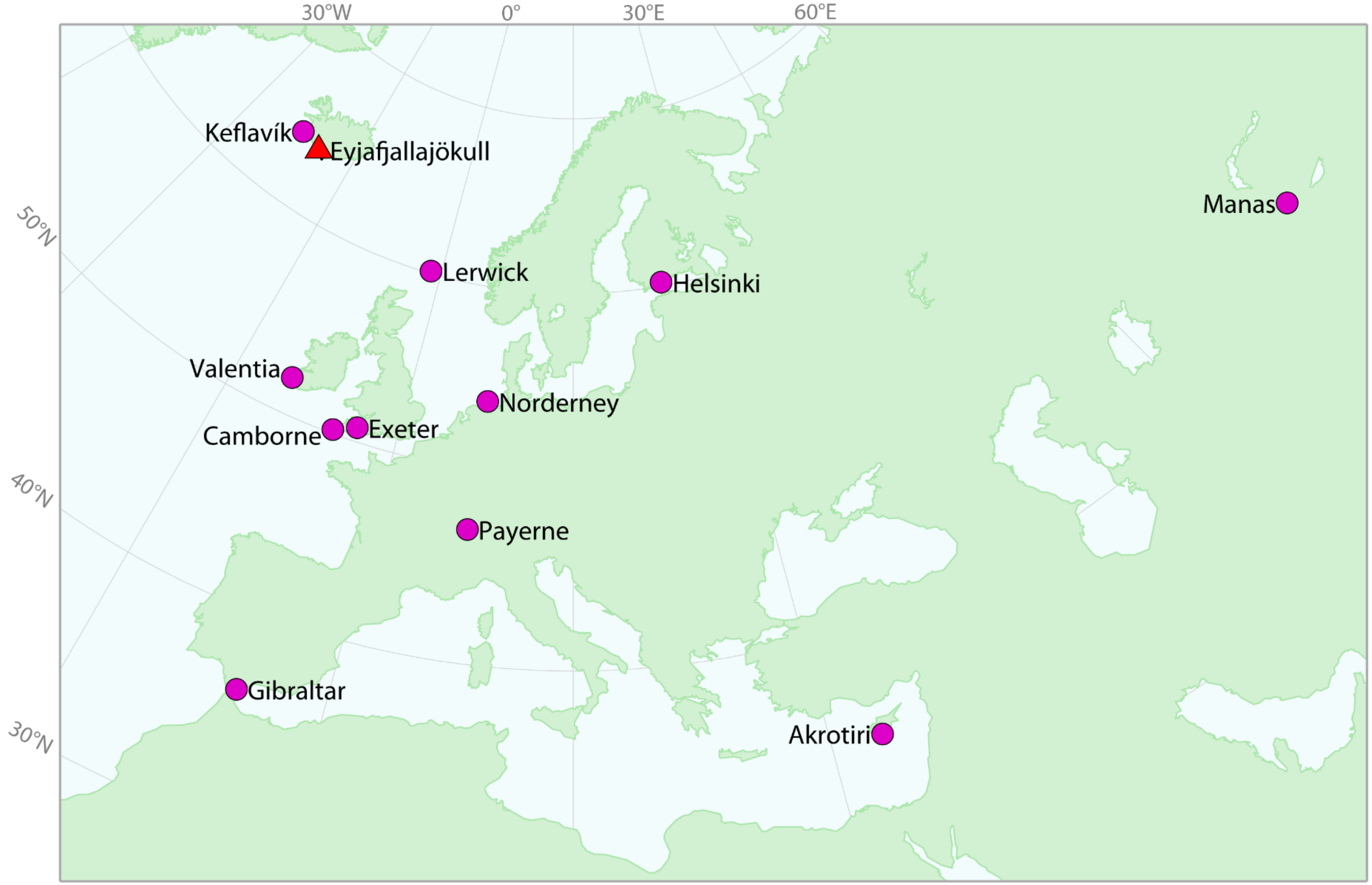




Eyjafjallajökull eruption. Photo Þórður Arason, 17 April 2010 at 16:35 UTC.

Lightning locations using the UK Met Office ATDnet

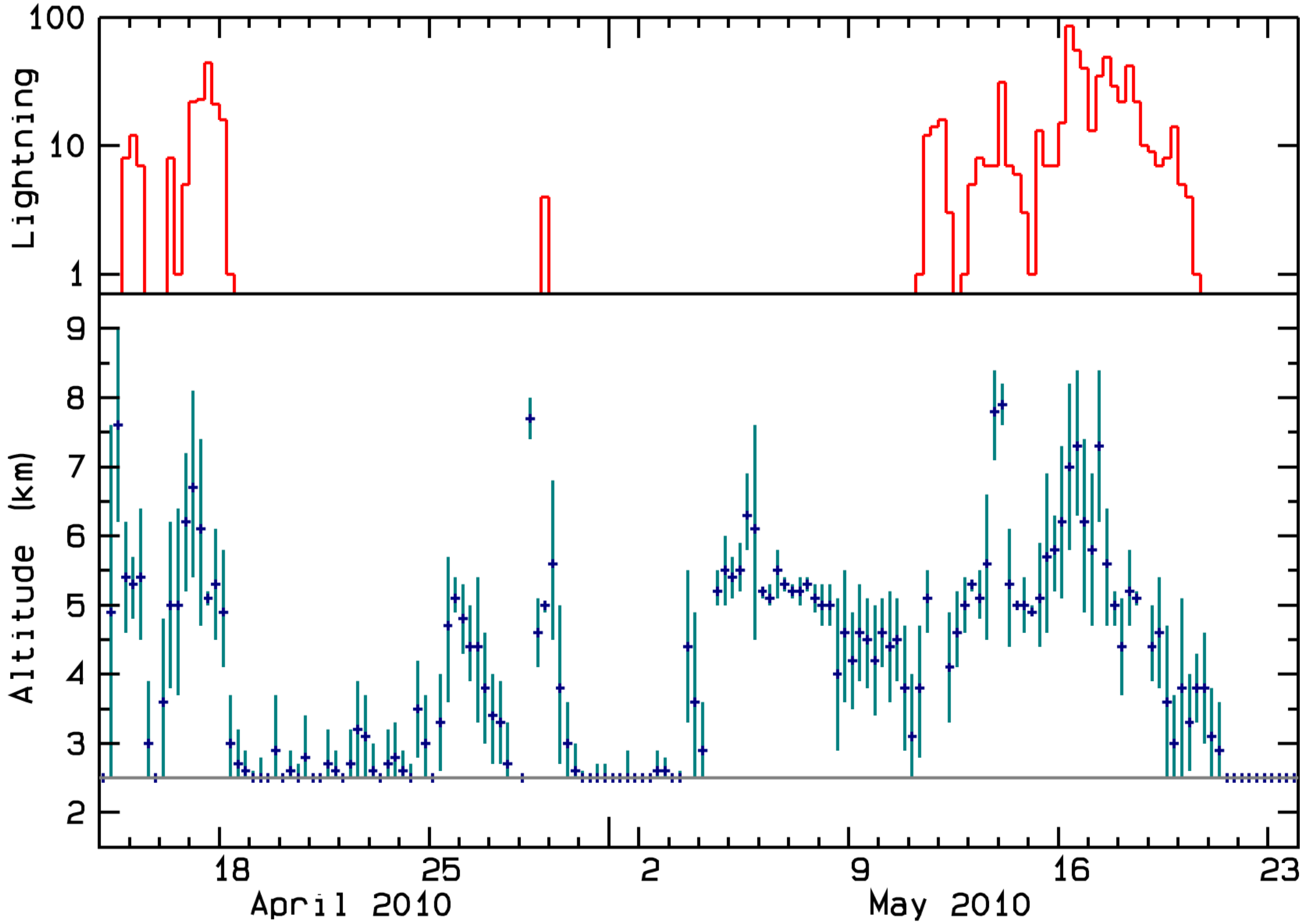
Icelandic Met Office



Arason, P., A. J. Bennett & L. E. Burgin (2011), Charge mechanism of volcanic lightning revealed during the 2010 eruption of Eyjafjallajökull, *Journal of Geophysical Research*, **116**, B00C03, doi:10.1029/2011JB008651

Lightning (6hr) & plume-top altitude

Icelandic Met Office

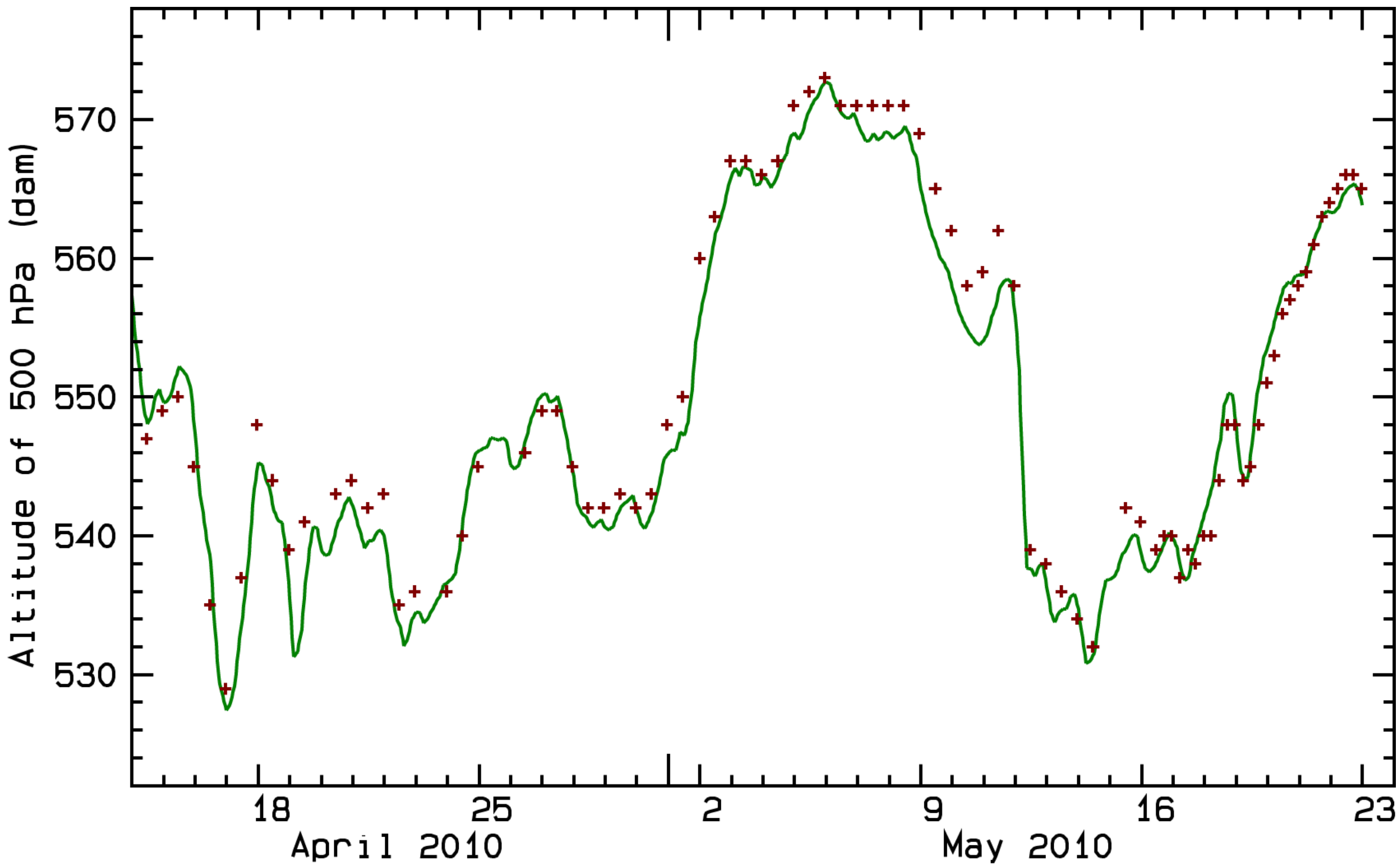


Arason, Bennett & Burgin (2011), *J. Geophys. Res.*, (Fig. 7)

Altitude of the 500 hPa level

Proxy of "mean" temperature 0-6 km

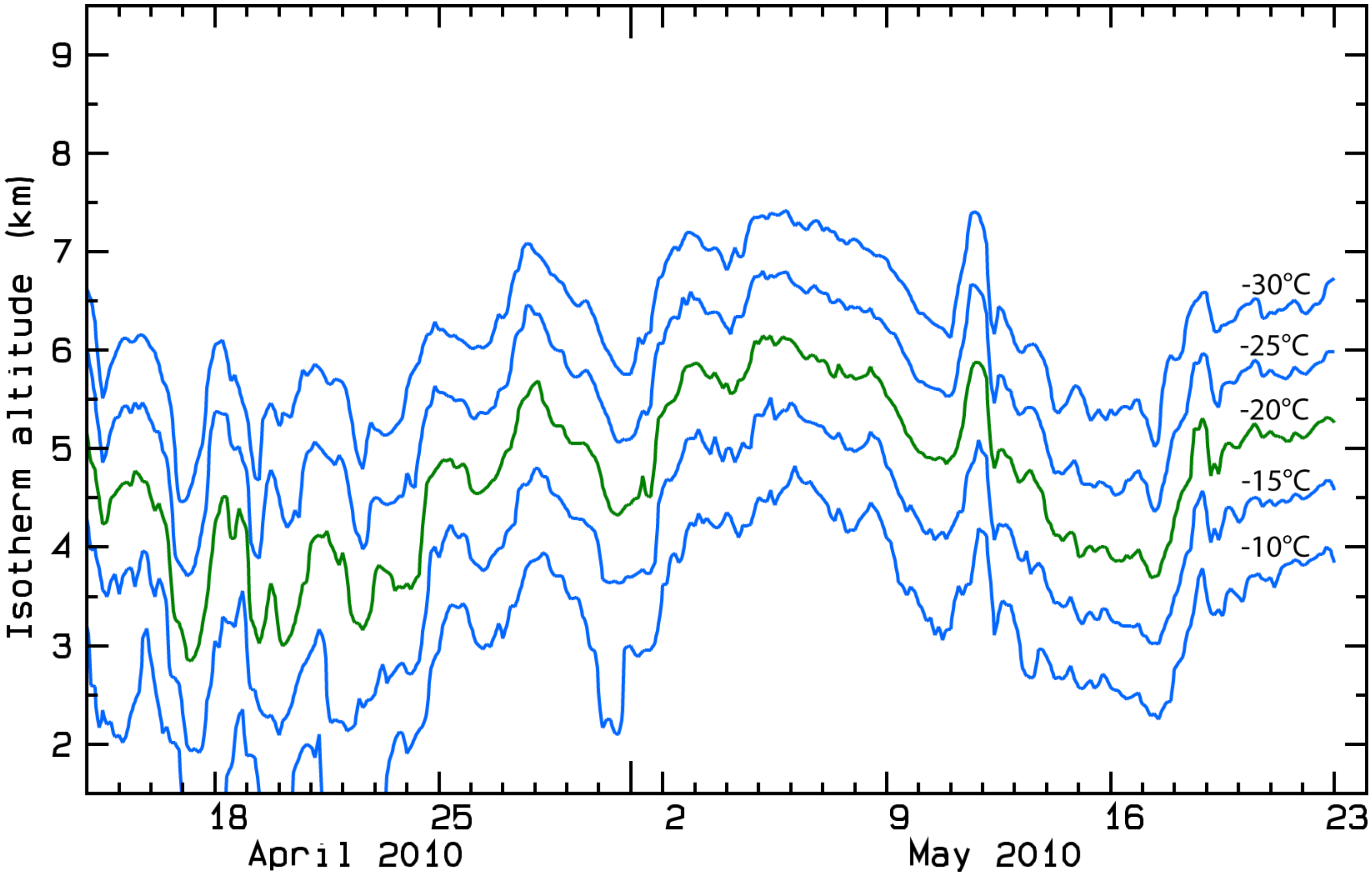
Icelandic Met Office



Arason, Bennett & Burgin (2011), *J. Geophys. Res.*, (Fig. 9)

Altitude of isotherms above the volcano from UK Met Office Unified Model

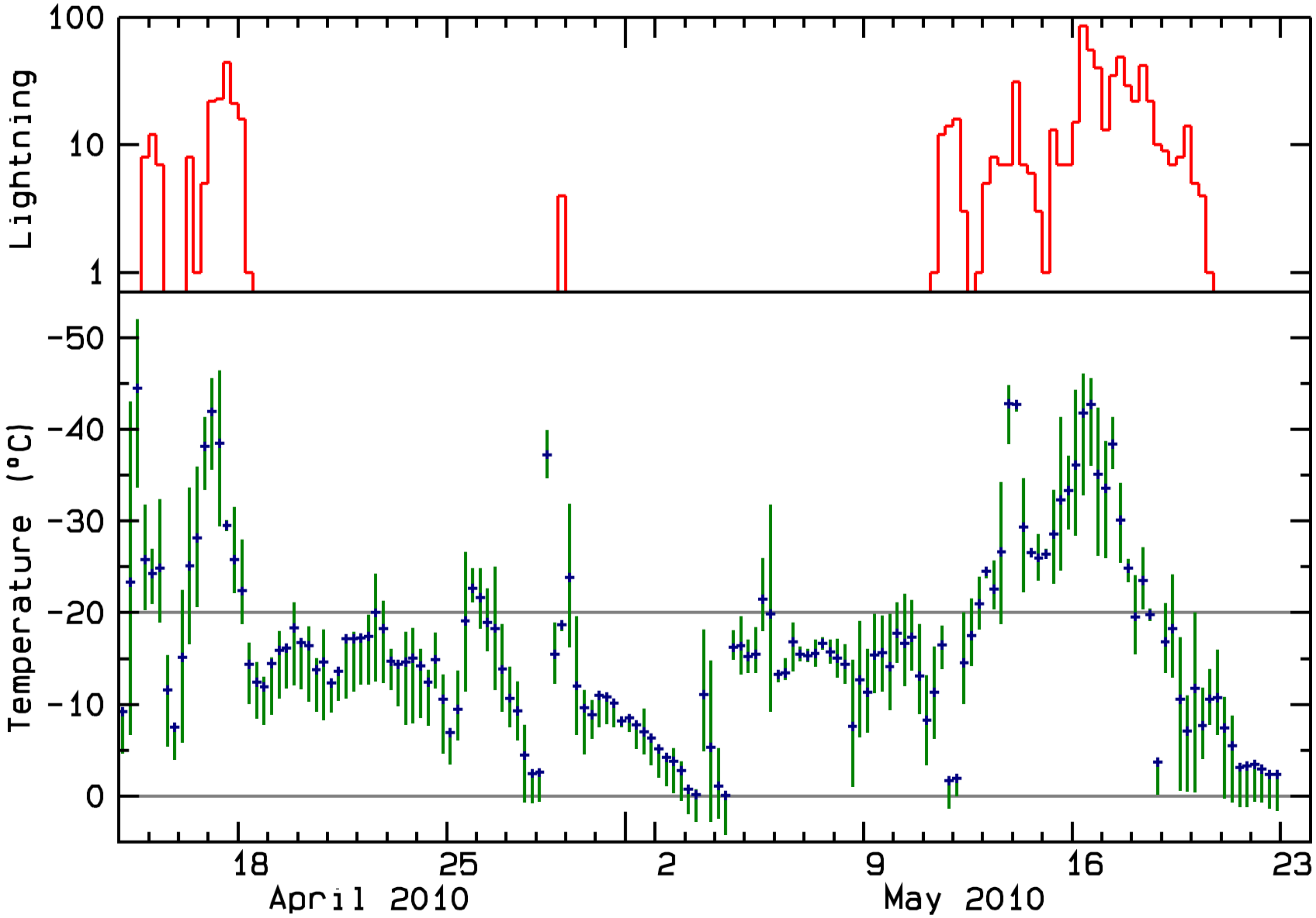
Icelandic Met Office



Arason, Bennett & Burgin (2011), *J. Geophys. Res.*, (Fig. 11)

Lightning & plume-top temperature

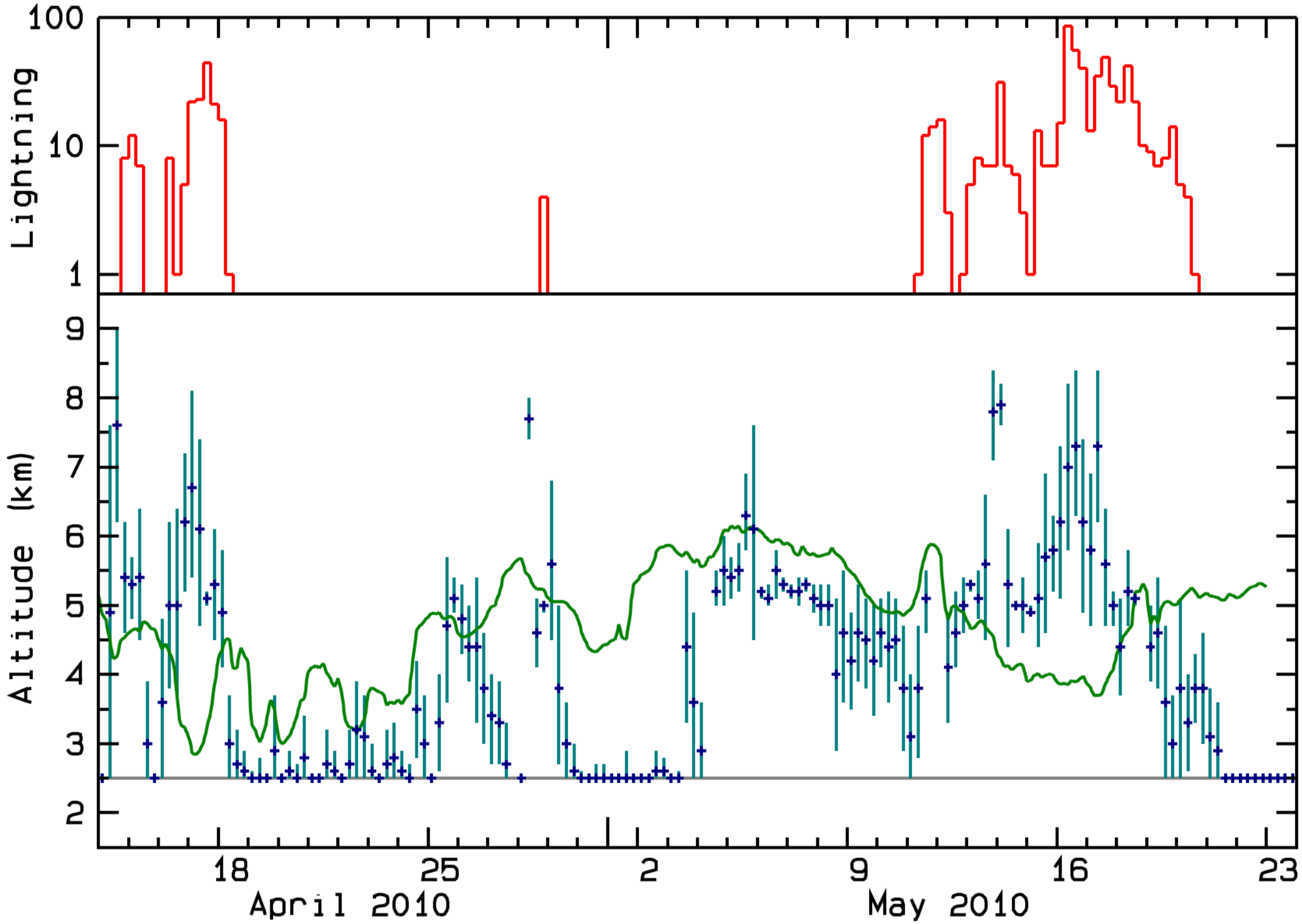
Icelandic Met Office



Arason, Bennett & Burgin (2011), *J. Geophys. Res.*, (Fig. 13)

Lightning, plume-top altitude and the −20 °C isotherm

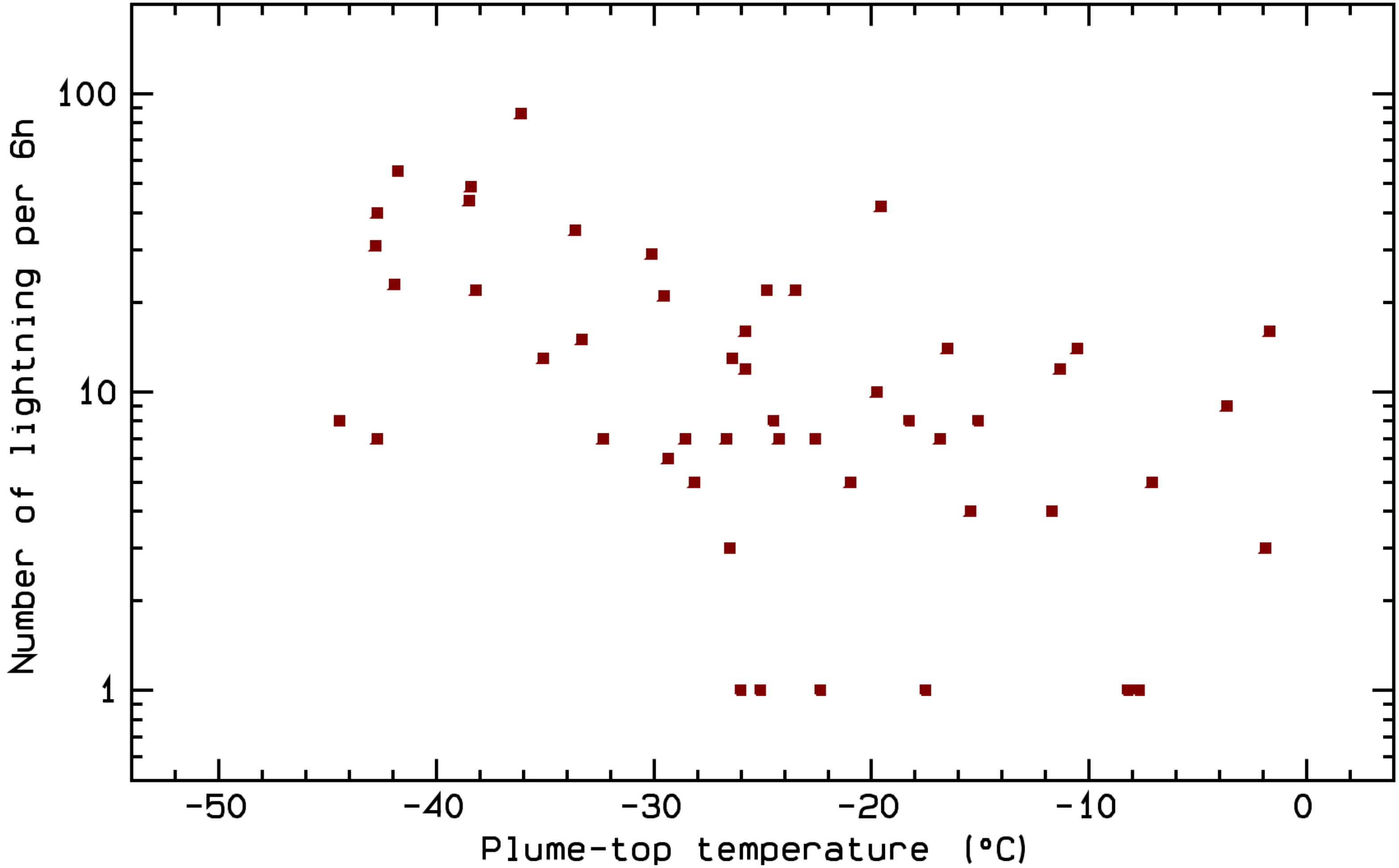
Icelandic Met Office



Arason, Bennett & Burgin (2011), *J. Geophys. Res.*, (Fig. 12)

Lightning rate vs. plume-top temperature

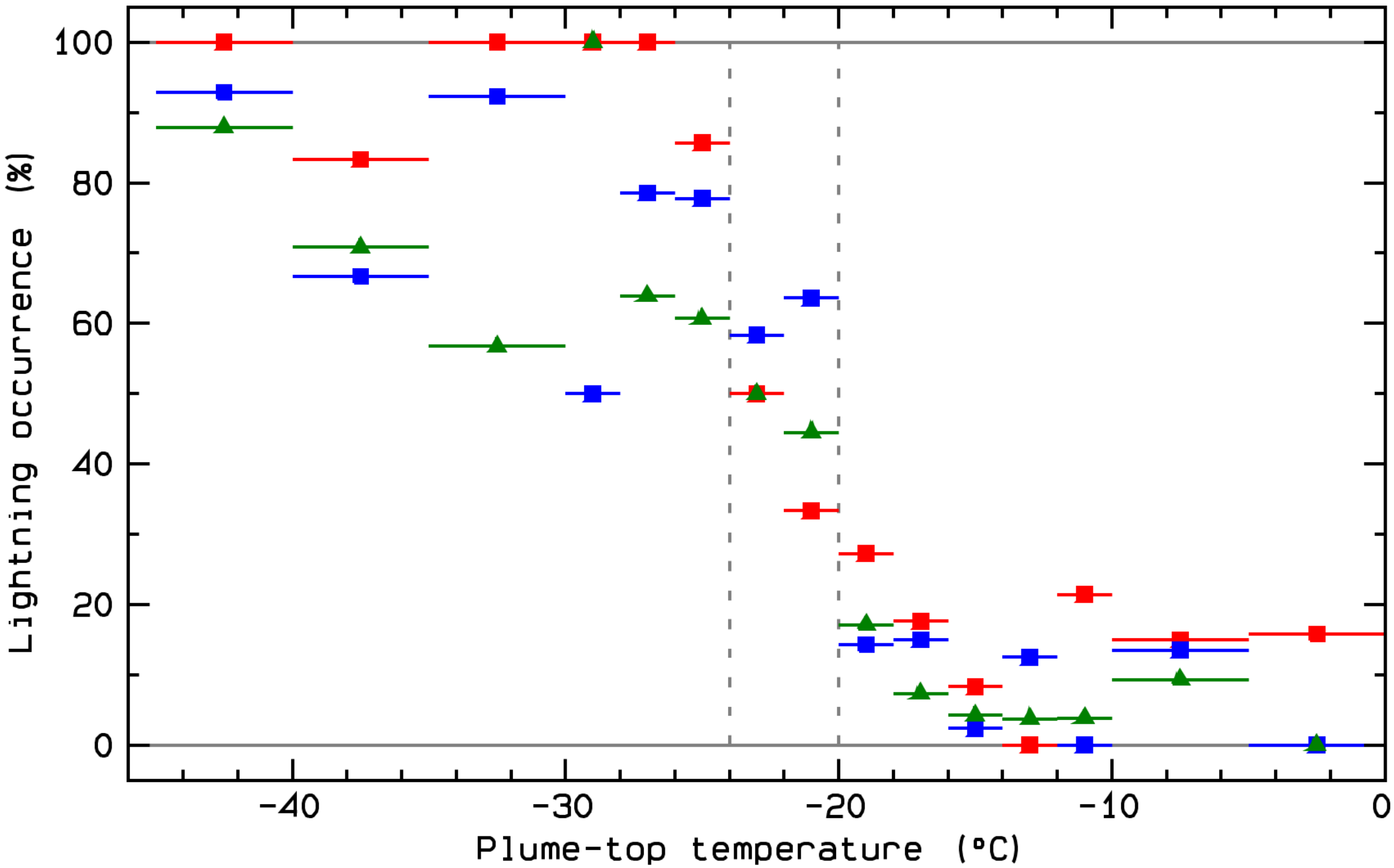
Icelandic Met Office



Arason, Bennett & Burgin (2011), *J. Geophys. Res.*, (Fig. 15)

Critical temperature: −20 °C to −24 °C

Icelandic Met Office



Bins
1 hr
3 hr
6 hr

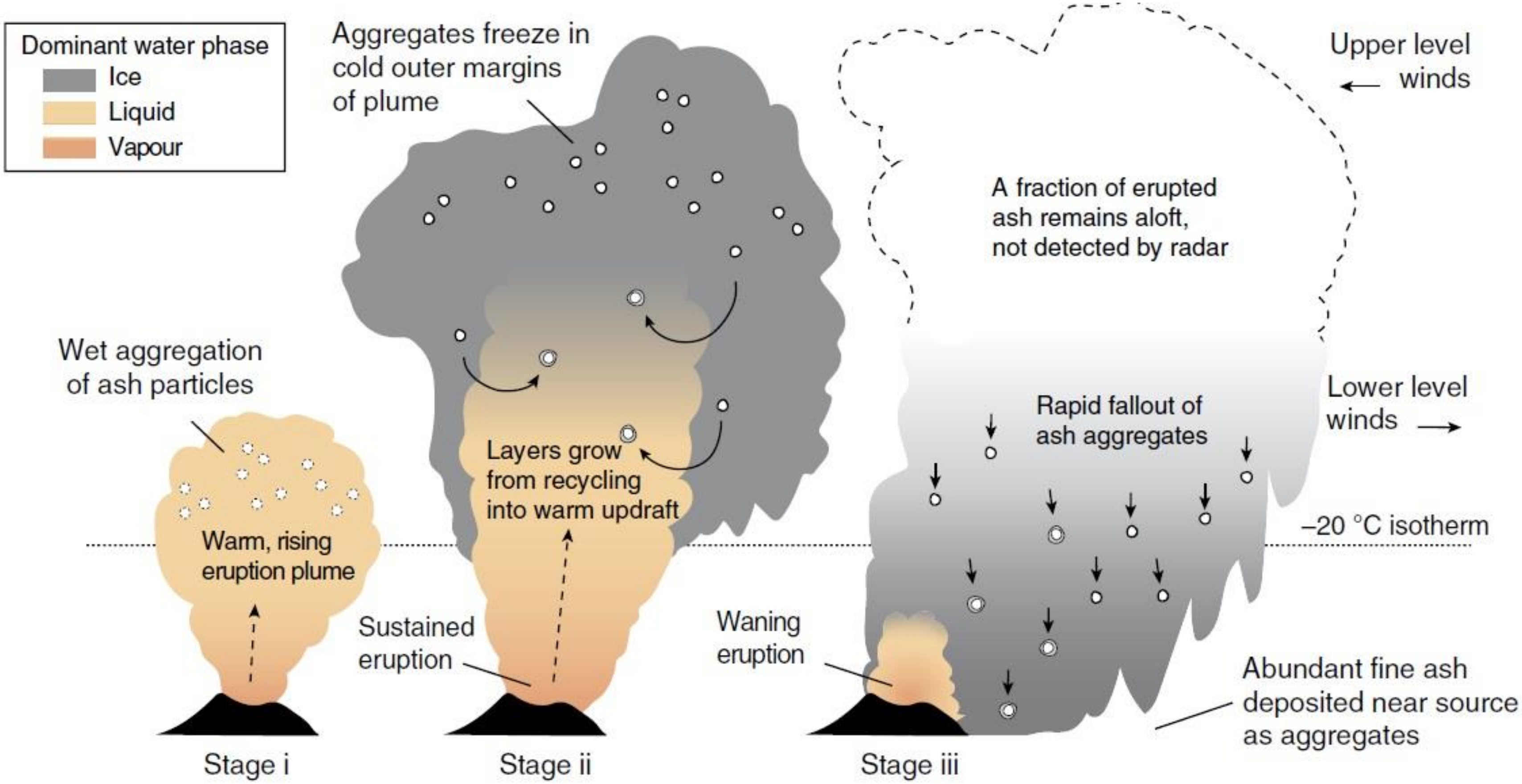
Arason, Bennett & Burgin (2011), *J. Geophys. Res.*, (Fig. 16)

Eyjafjallajökull eruption
April 2010

Plume lightning seen from a distance of 72 km
Notice the characteristic fibrous anvil shape of the plume top

Photo Þórður Arason 17 April 2010 at 04:47:09

Scrubbing of fine ash



Van Eaton, A. R., L. G. Mastin, M. Herzog, H. F. Schwaiger, D. J. Schneider, K. L. Wallace & A. B. Clarke (2015), Hail formation triggers rapid ash aggregation in volcanic plumes, *Nature Communications*, **6**, Article no. 7860, doi:10.1038/ncomms8860.

Ash-infused hail – Eyjafjallajökull 22 April 2010

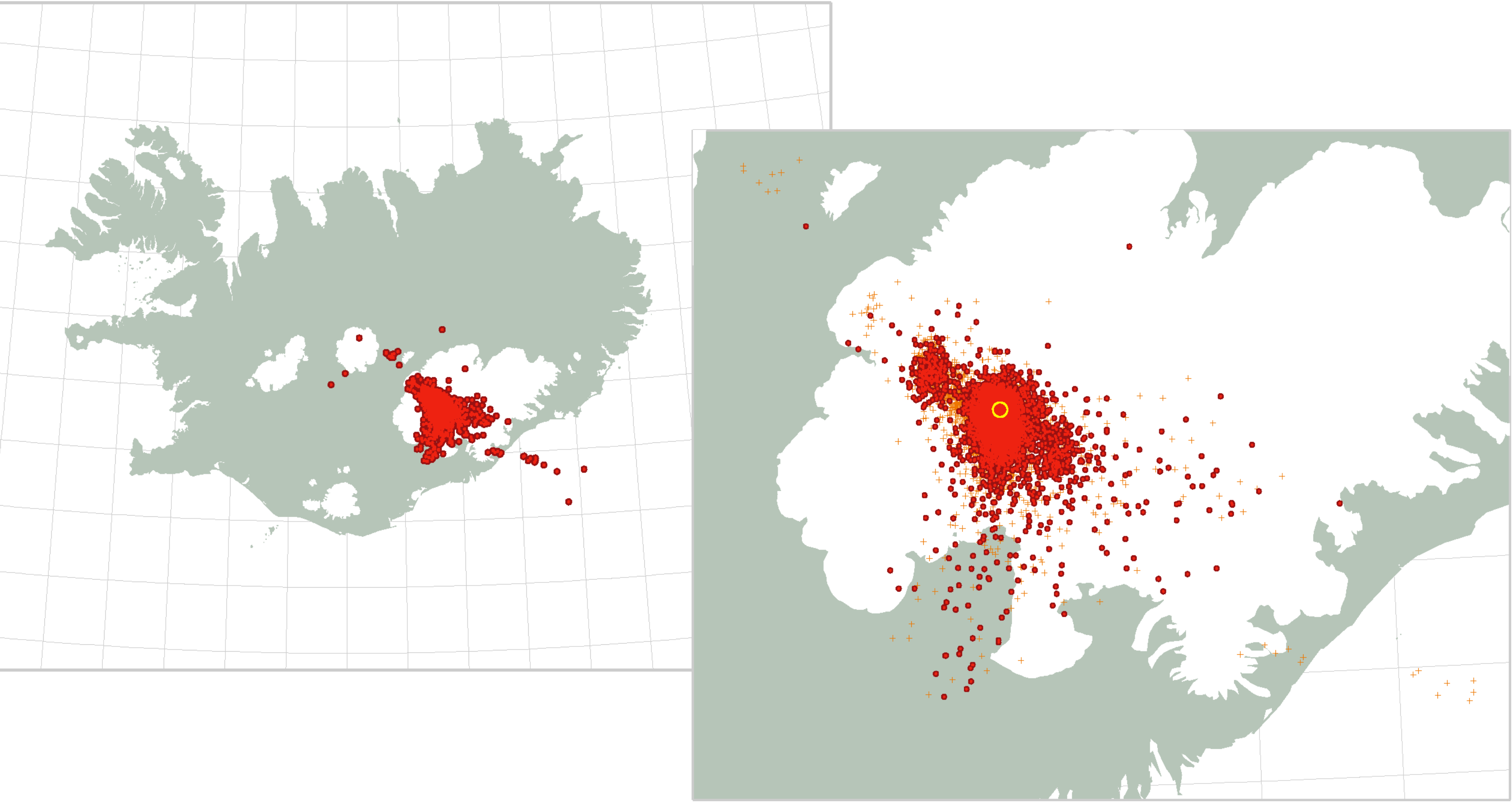
Ash-infused hail on the glacier about 5 km east of the Eyjafjallajökull crater

Photo Thor Thordarson 22 April 2010


Grímsvötn eruption
May 2011
15 km
10 km
Tr
5 km
Gr
Photo Bolli Valgarðsson 21 May 2011 at 19:20

Located lightning 21-28 May 2011

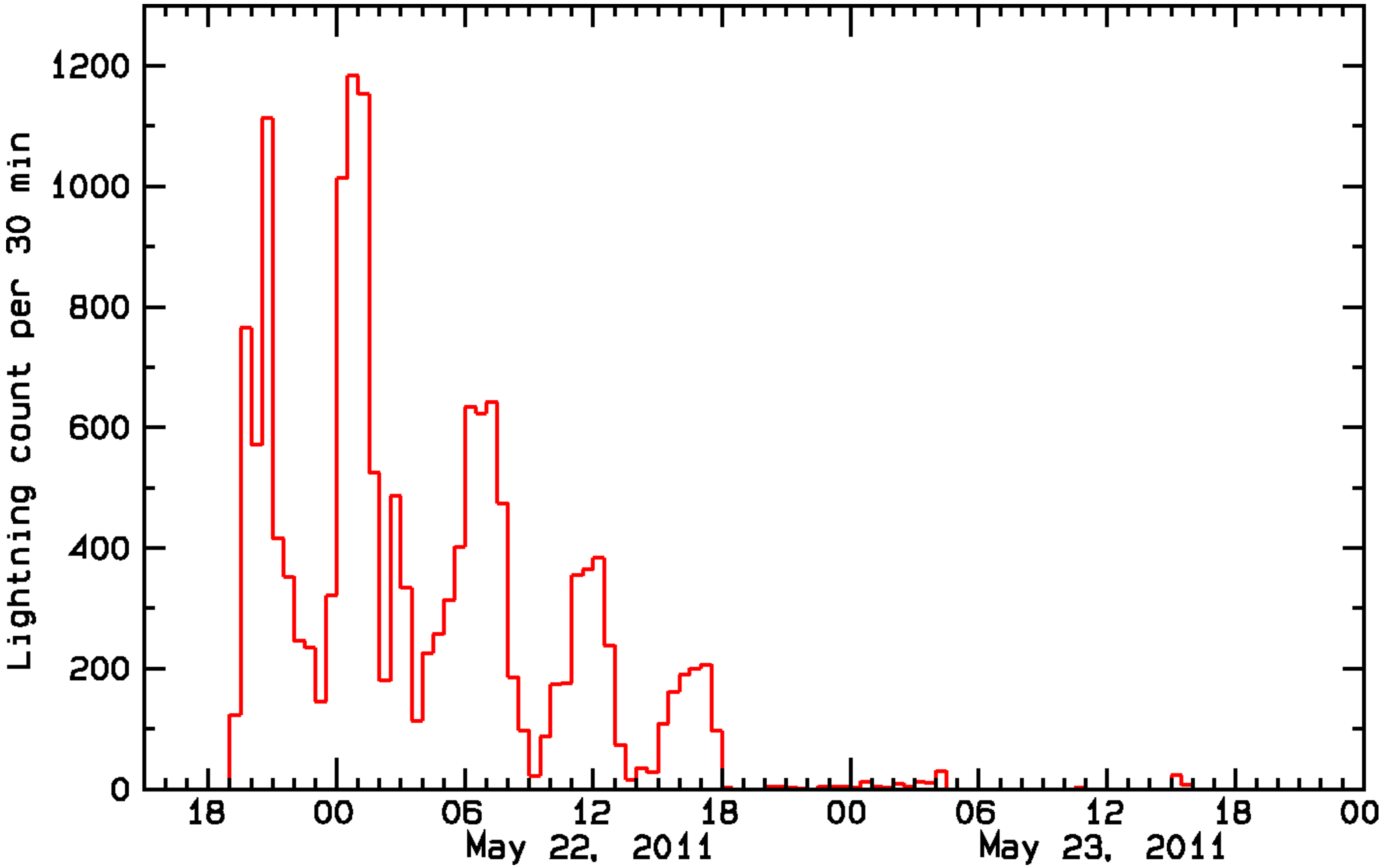
Icelandic Met Office



Lightning rate

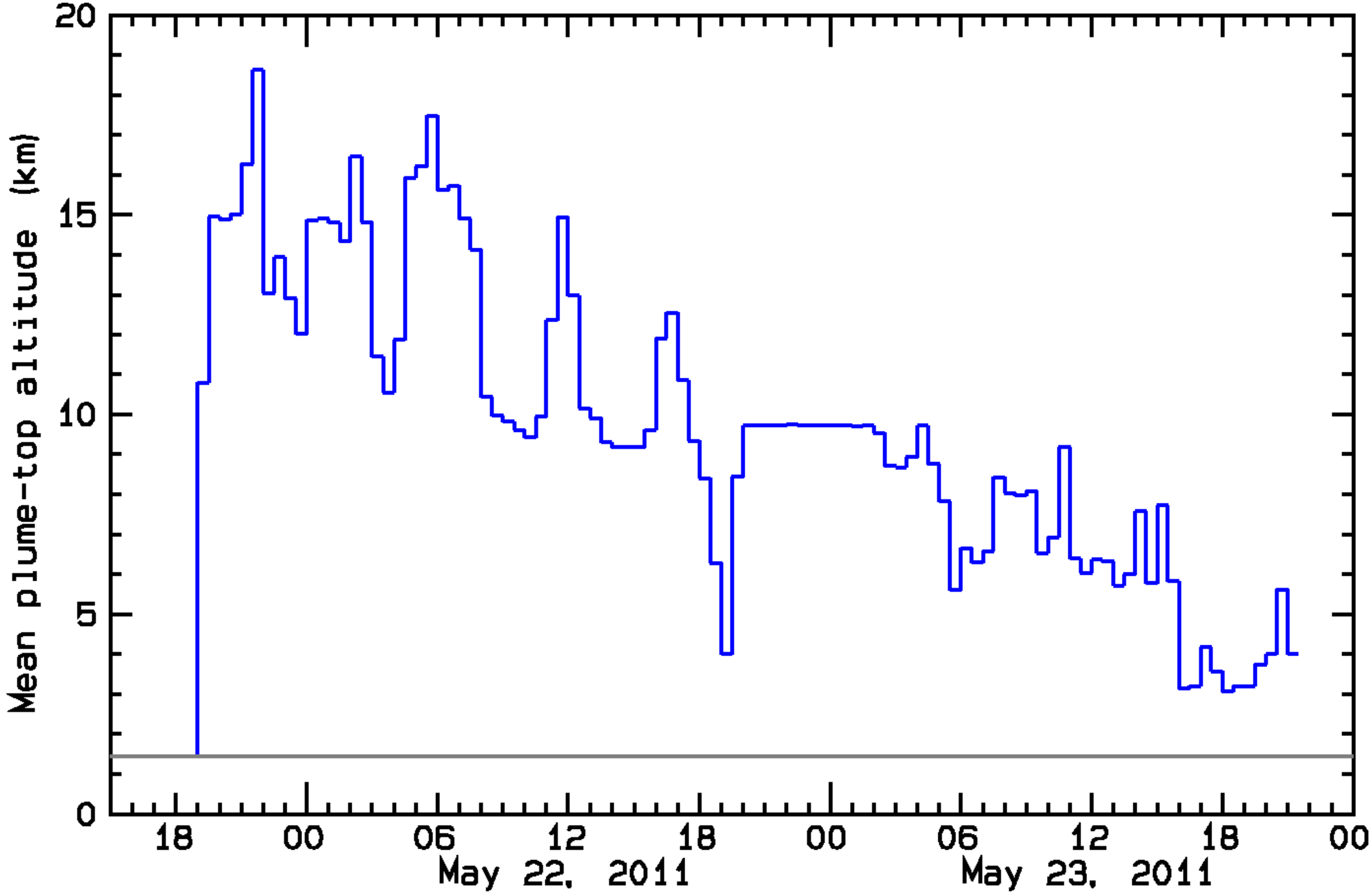
Oscillations became evident during real-time monitoring

Icelandic Met Office



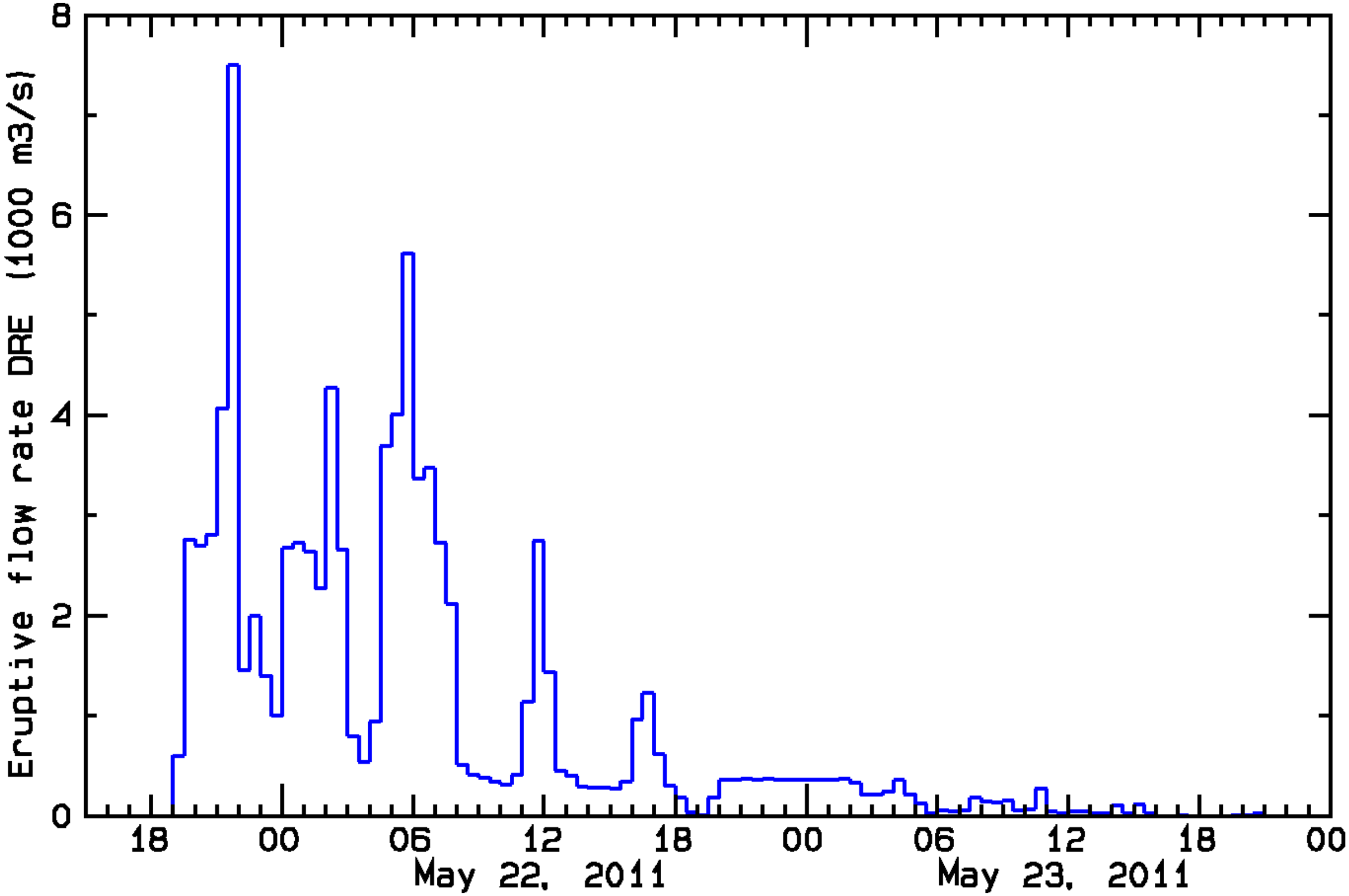
Plume-top altitude
30 minute mean values

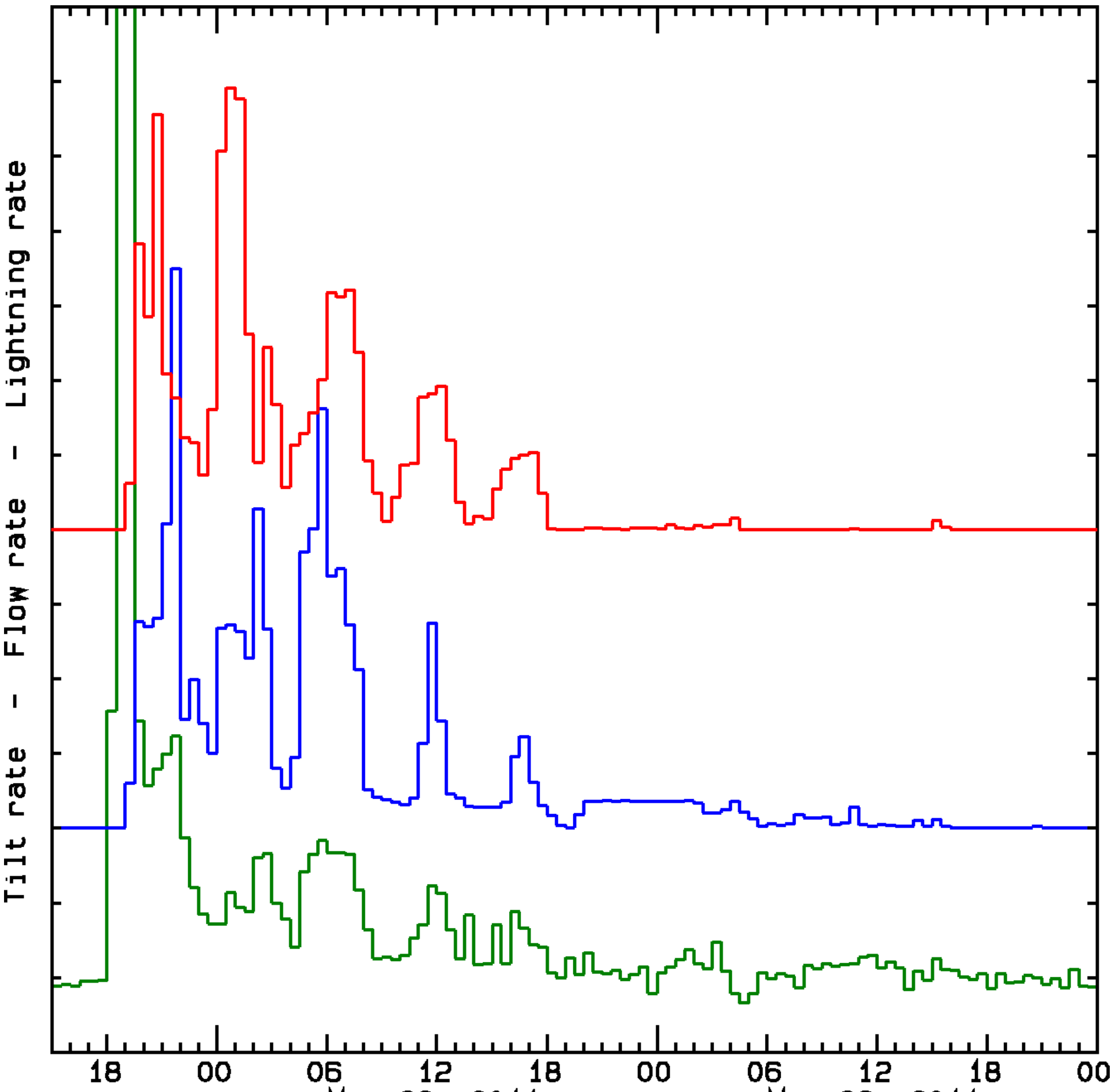
Icelandic Met Office



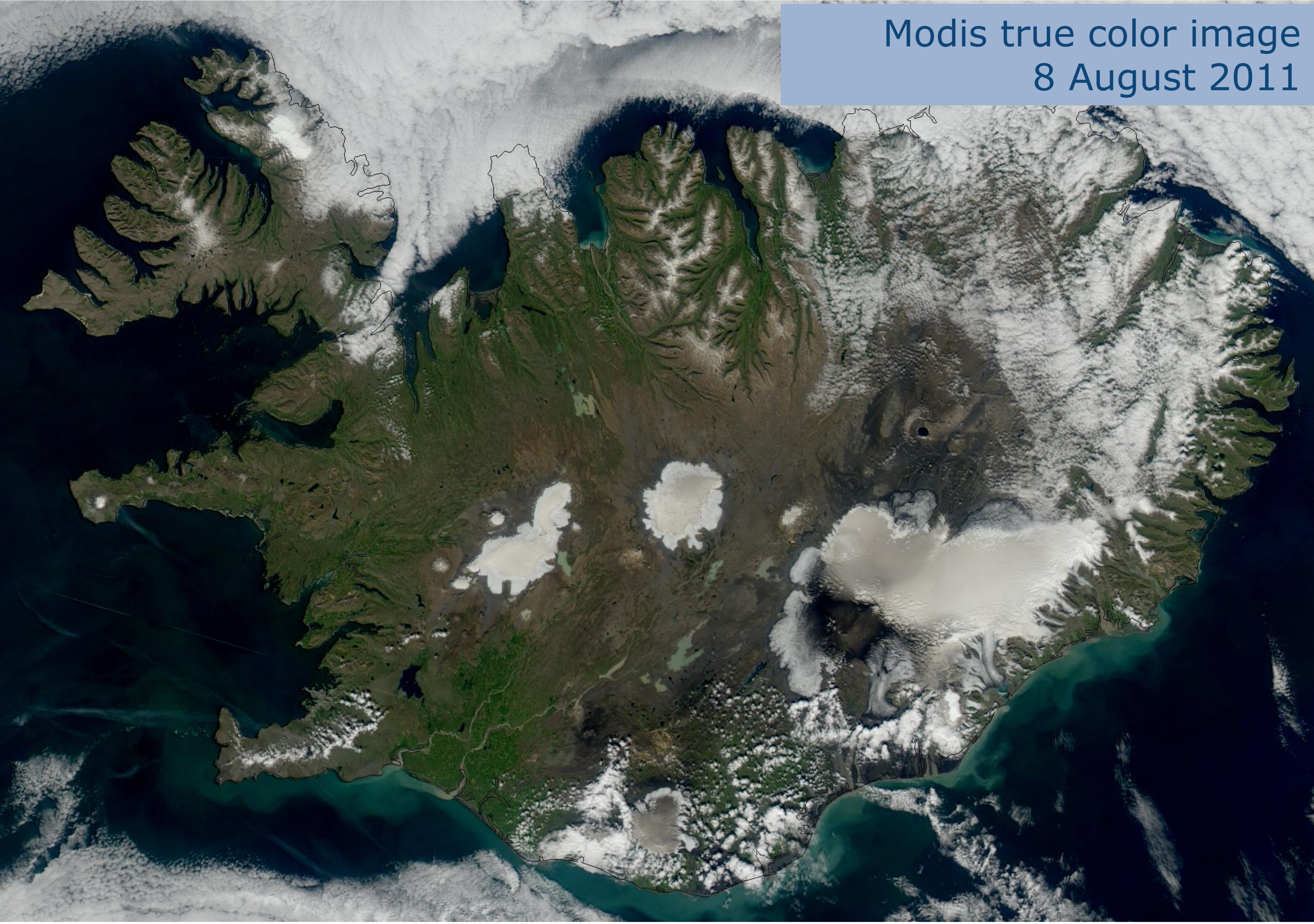
Flow rate

Calculated using Mastin et al. (2009)




Tilt rate - Flow rate - Lightning rate
18
00
06
12
18
00
06
12
18
00
May 22, 2011
May 23, 2011

Modis true color image 8 August 2011



3 km from Grímsvötn crater

Hagl-01: Grímsvötn 2011 ash section 3 km from the crater

Photo Þórður Arason 11 June 2011

Total mass	1262 g
ice	49%
ash (<1.68mm)	46%
gravel	5%

Hagl-02: Chunk of ash-infused hail, 6.2 km from crater

Photo Þórður Arason 11 June 2011

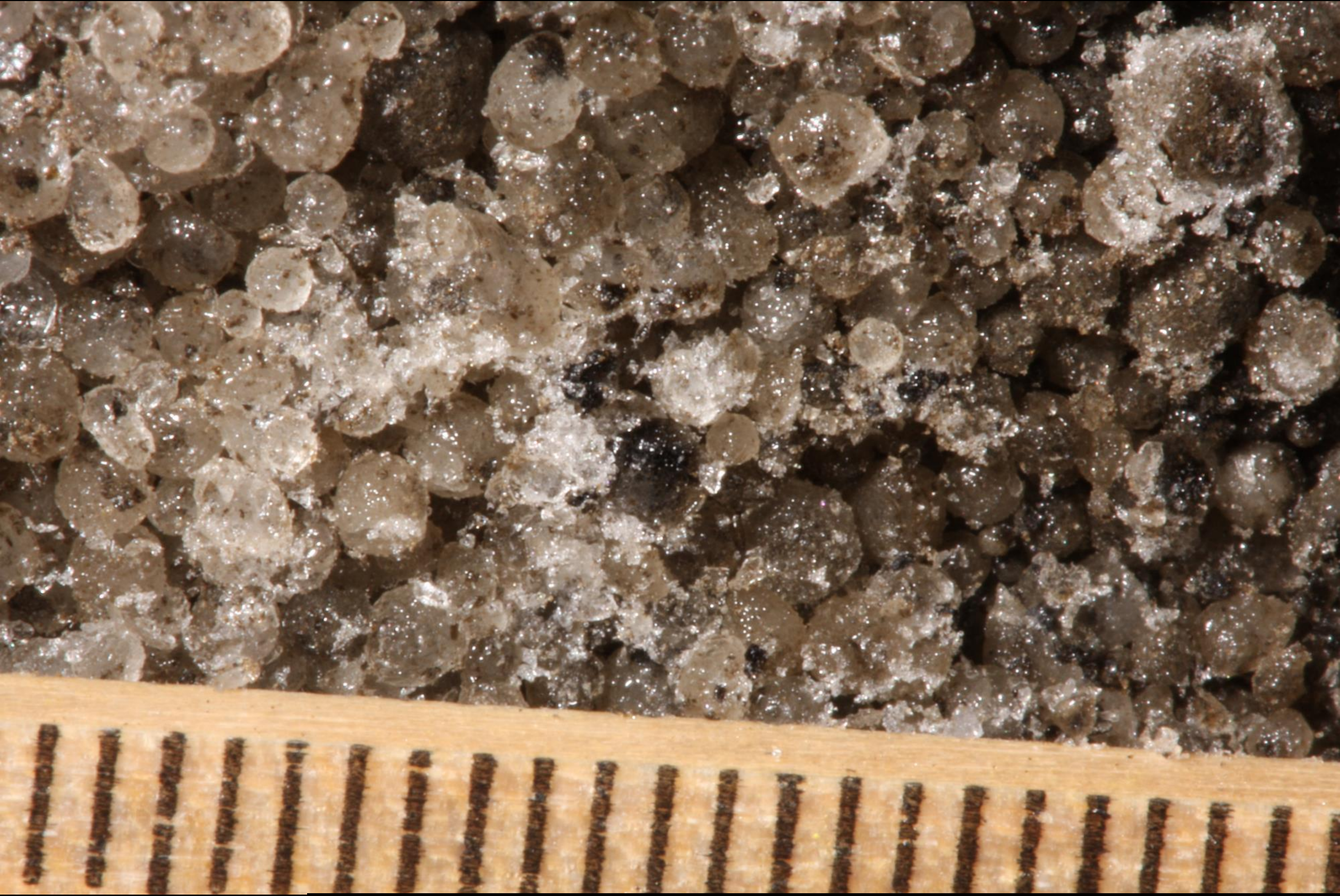
Occurrence of ash-infused hail at five sites

Icelandic Met Office

Site	Distance/dir. from crater (km)	Section thickness (cm)	Hail (%)	Mixed ash/hail (%)
Hagl-01	3.0 / SSW	>300 (190)	34	23
Hagl-02	6.2 / S	109	27	13
Hagl-03	4.2 / WSW	80	0	0
Hagl-04	1.8 / SSW	? (90)	48	0
Hagl-05	1.9 / SSE	45	7	36

Grímsvötn 2011 – Hagl-02

Macro-photo Þórður Arason 11 June 2011



Grímsvötn 2011 – Hagl-02

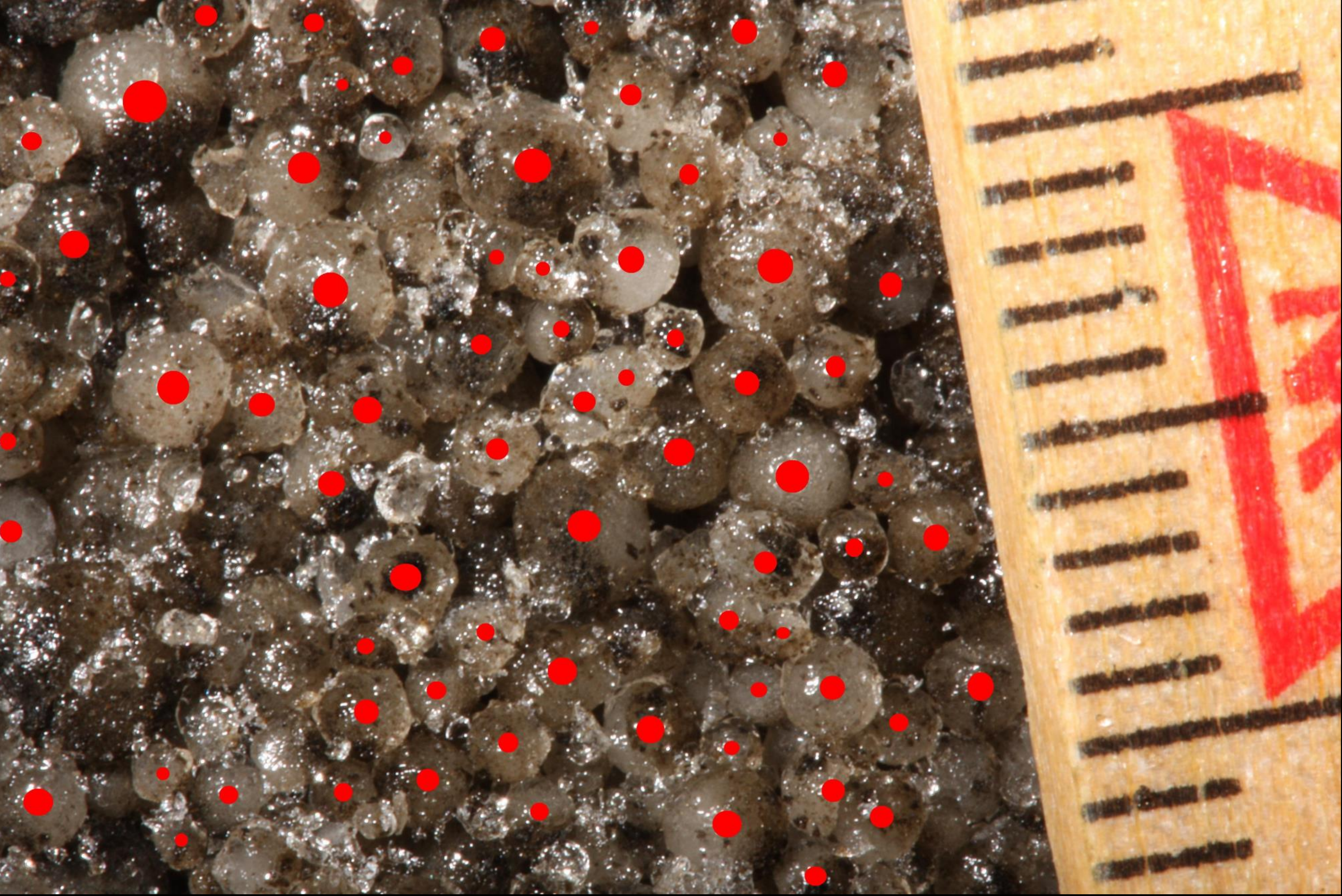
Macro-photo Þórður Arason 11 June 2011

Grímsvötn 2011 – Hagl-02

Macro-photo Þórður Arason 11 June 2011

Grímsvötn 2011 – Hagl-01

Macro-photo Þórður Arason 11 June 2011

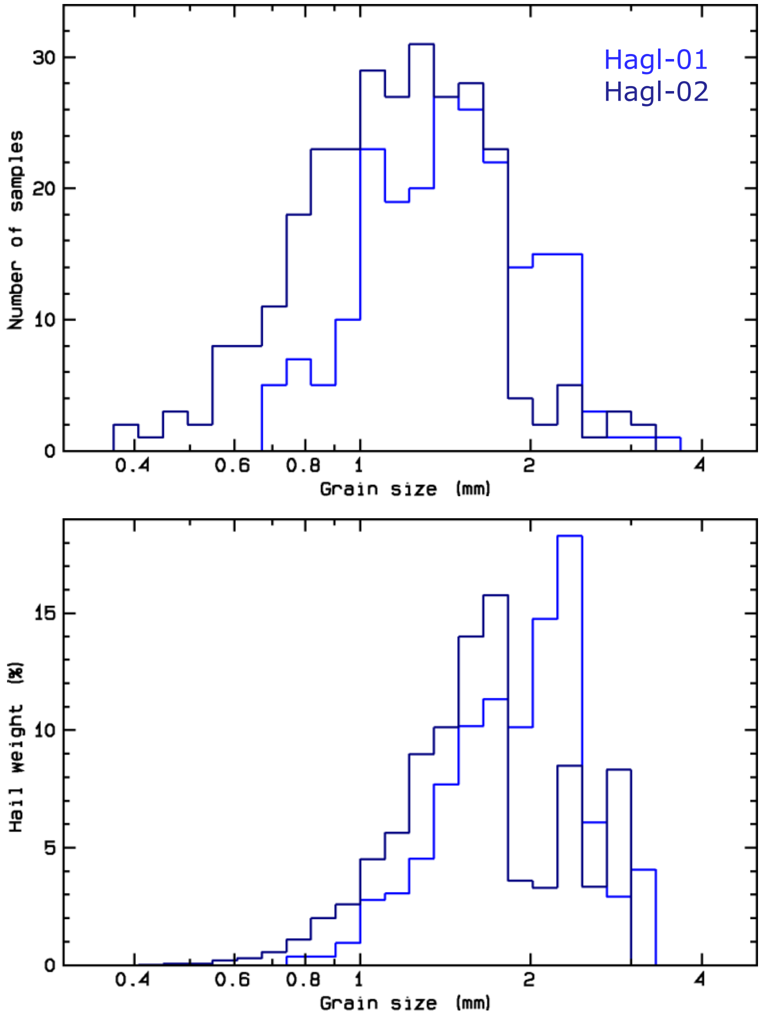


Grímsvötn 2011 – Hagl-02

Macro-photo Þórður Arason 11 June 2011

Hail size distributions

Icelandic Met Office



Hail sizes were estimated from several photos of layers of in-situ hail

Most had diameter of 1-2 mm

Utilization of volcanic lightning

Icelandic Met Office

Long-range lightning location systems (mainly useful at high latitudes where meteorological thunderstorms are infrequent)

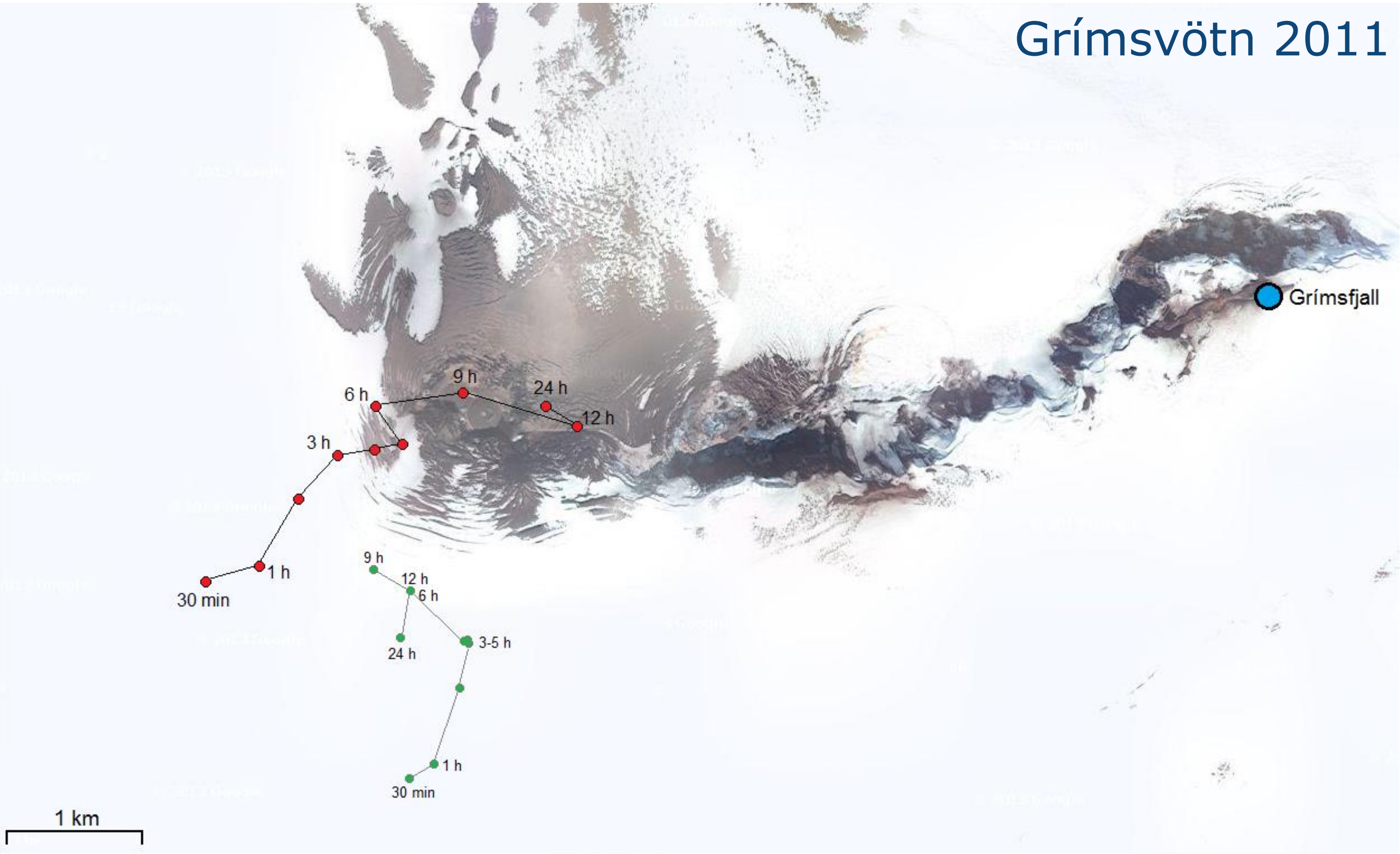
1. Verification of the onset of an eruption
2. Location of vent within volcanic complex

High T-P chemical factory

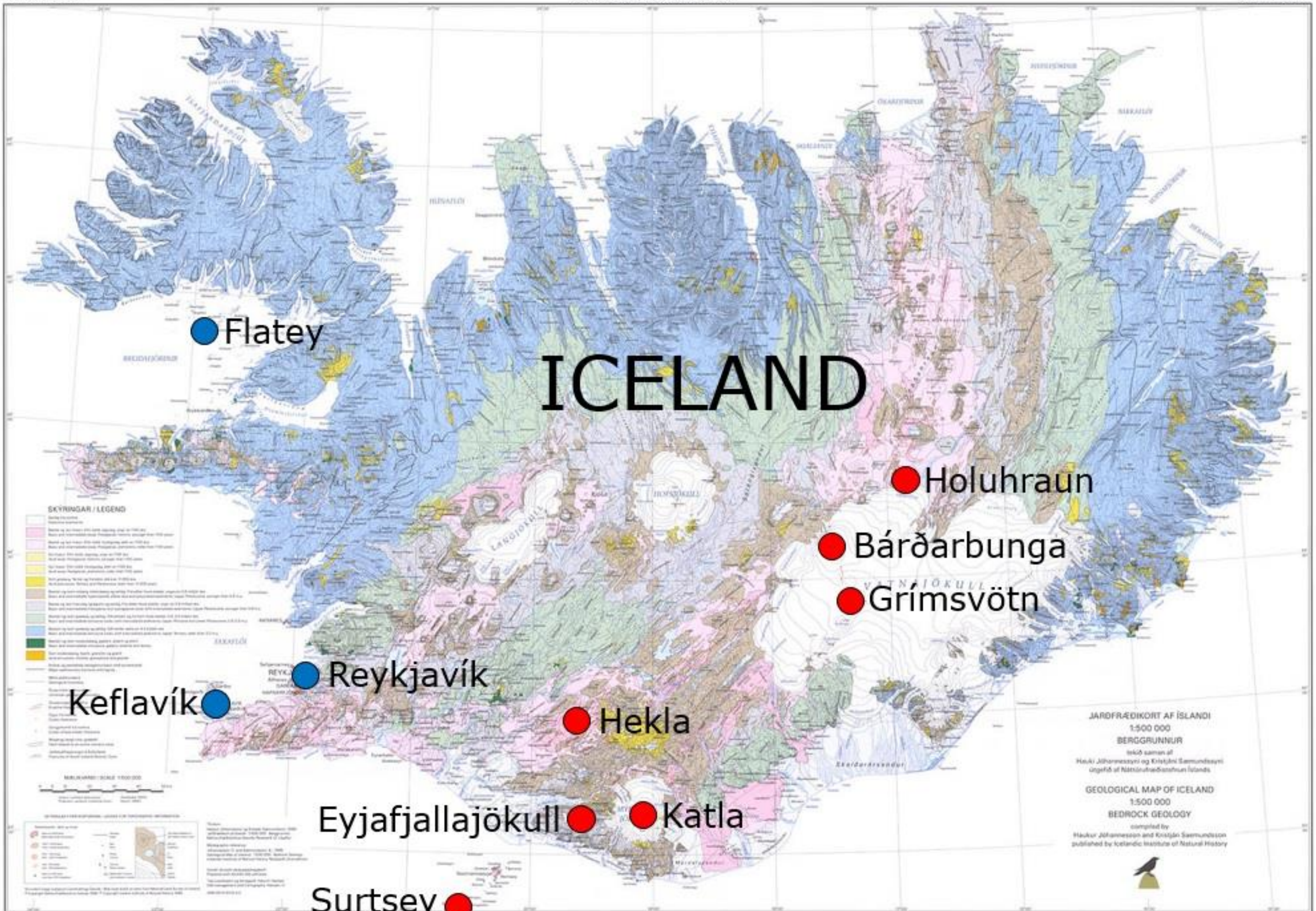
1. Mix air, water and ash (all the chemical elements)
2. High temperature and pressure for a brief time: Temperature of 30,000 K and pressure of 1 MPa (10 atm)
3. Each lightning channel ~100 m^3
4. May produce useful molecules for life on Earth

Estimation of eruption site location using volcanic lightning

Icelandic Met Office



Þórður Arason, Guðrún Nína Petersen & Halldór Björnsson (2013), Estimation of eruption site location using volcanic lightning, Report VÍ 2013-006, Veðurstofa Íslands, Reykjavík, 15 pp. (www.hergilsey.is/arason/rit)


ICELAND
Flatey
Reykjavík
Keflavík
Holuhraun
Bárðarbunga
Grímsvötn
Hekla
Eyjafjallajökull
Katla
Surtsey
SKÝRINGAR / LEGEND
JARÐFRÆÐIKORT AF ÍSLANDI
1:500 000
BERGGRUNNUR
GEOLOGICAL MAP OF ICELAND
1:500 000
BEDROCK GEOLOGY
compiled by
Haukur Jóhannesson and Kristján Sæmundsson
published by Icelandic Institute of Natural History

Arctic Tern (Kría) in Flatey island. Photo Þórður Arason, August 2016.

Abstract

Icelandic Met Office

Þórður Arason (2016), *Earth, Water, Wind and Fire – On the Charge Generation of Volcanic Lightning*, Presentation at the USGS Cascades Volcano Observatory, Vancouver, Washington, 7 December 2016.

A few different processes that have been proposed as the cause for electric charge generation in volcanic plumes will be discussed. Observations during the Eyjafjallajökull 2010 eruption in Iceland suggest that the charge generation for large whole-plume thunderbolts may have been analogous to the one in meteorological thunderstorms, where hail plays a significant role in both the generation and separation of charges within the cloud. At the top of plumes where ambient temperatures may reach –20° to –50°C, fine ash particles may provide ample nuclei for condensation and ice growth. The occurrence and properties of hail in preserved deposits will be shown for the Eyjafjallajökull 2010 and Grímsvötn 2011 eruptions. In addition to charge generation, ash-infused hail may supply a vessel for fine grained ash to be scrubbed prematurely from plumes and deposited close to the volcano.