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Properties of ash-infused hail during the Grímsvötn 2011 eruption and implications for radar detection of volcanic columns

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Eyjafjallajökull eruption
April 2010

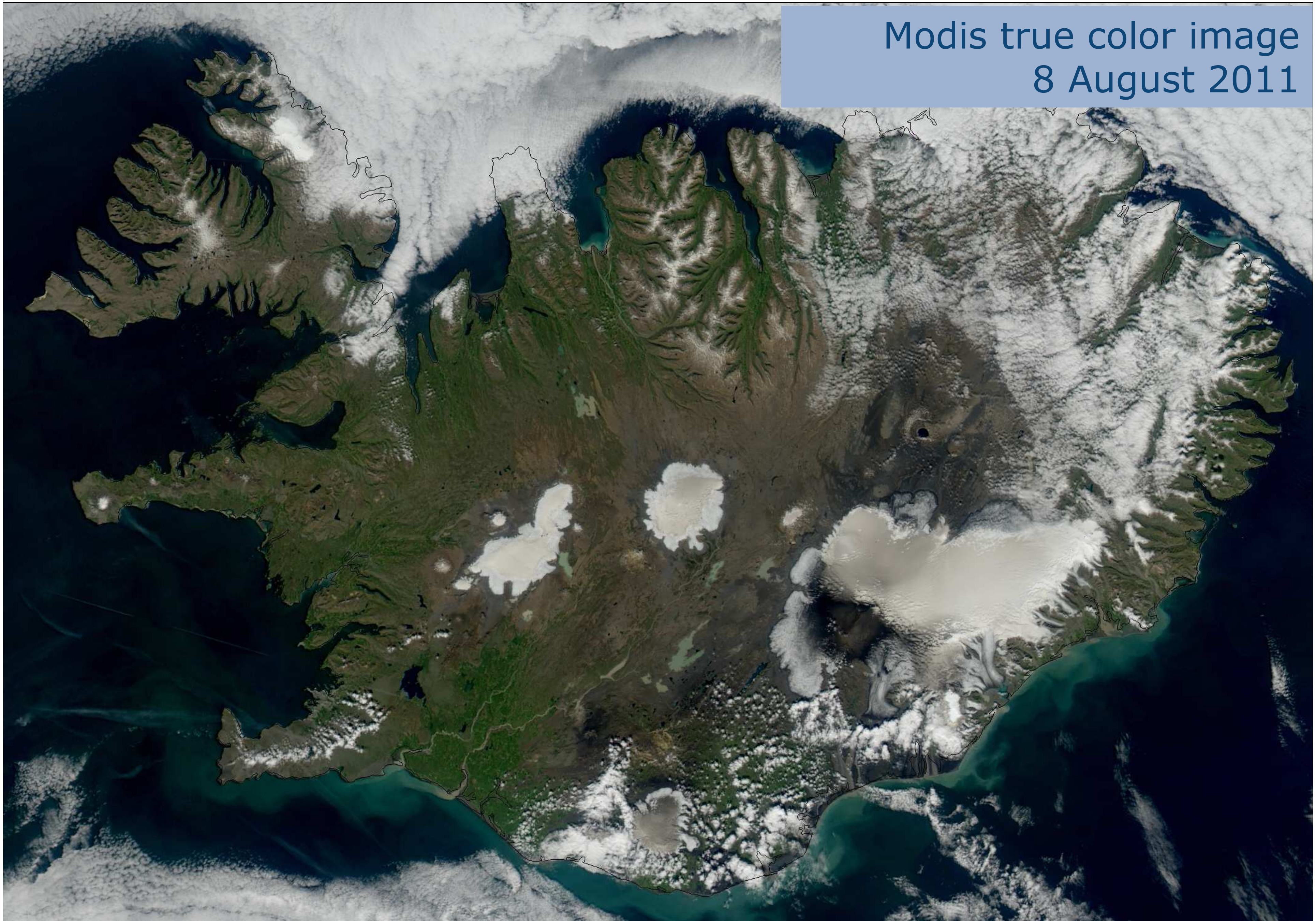
Plume lightning seen from a distance of 72 km
Notice the characteristic fibrous anvil shape of the plume top

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

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


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


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

Occurrence of ash-infused hail at five sites

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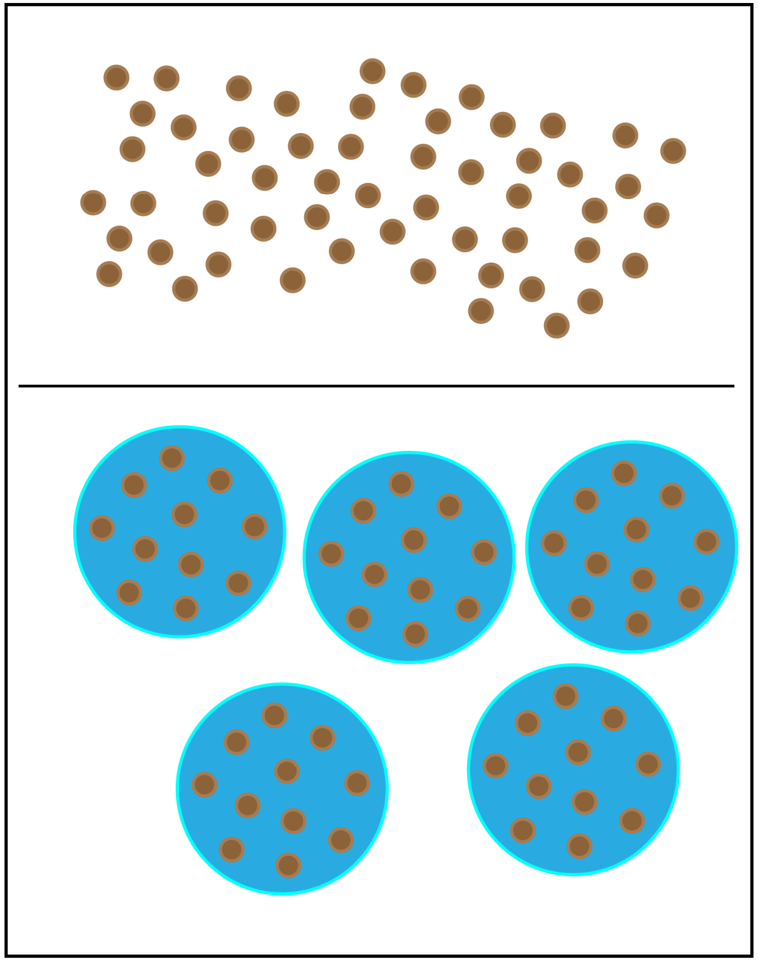
Site	Distance/dir. from crater (km)	Section thickness (cm)	Hail (%)	Mixed ash/hail (%)
Hagl-01	3.0 / SSW	>300 (190)	34	23
Hagl-02	6.2 / S	109	27	13
Hagl-03	4.2 / WSW	80	0	0
Hagl-04	1.8 / SSW	? (90)	48	0
Hagl-05	1.9 / SSE	45	7	36

Radar detection of ash vs. ash-infused hail



What difference does it make to radar detection if the ash grains are embedded into larger hail-grains?

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

Bulk properties of ash-infused hail samples

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Sample	Mass (g)	Mass ash (%)	Mass gravel (%)	Mass water (%)	Ice (% vol.)	Hail density (kg/m^3)
Hagl-01-a	416	34	3	63	84	1.16
Hagl-01-b	593	31	3	67	86	1.13
Hagl-02-a	519	54	4	42	69	1.40
Hagl-02-b	1262	46	5	49	75	1.30
Hagl-04	445	58	10	32	61	1.53
Hagl-05	920	48	12	40	69	1.39

Ash grain size distribution

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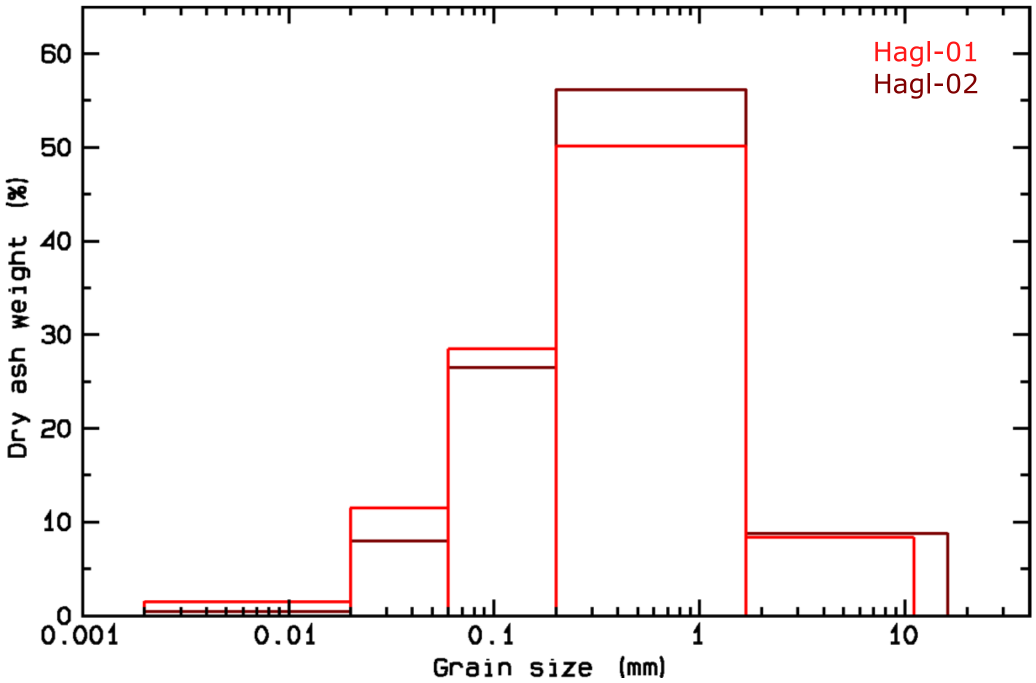
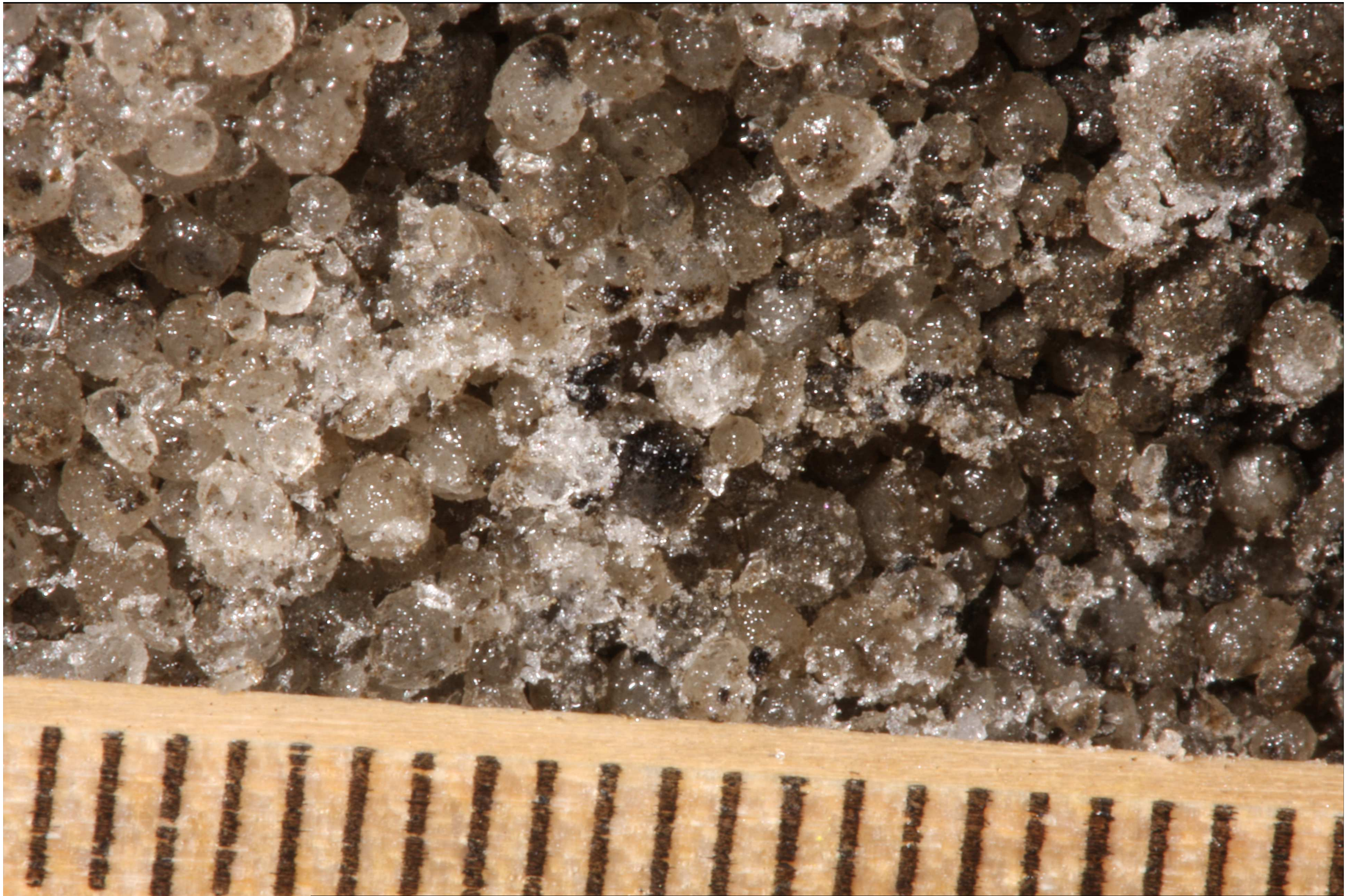


Ash grain size distribution was estimated from melted bulk samples of ash-infused hail

Grímsvötn 2011 – Hagl-02

Macro-photo Þórður Arason 11 June 2011



Grímsvötn 2011 – Hagl-02

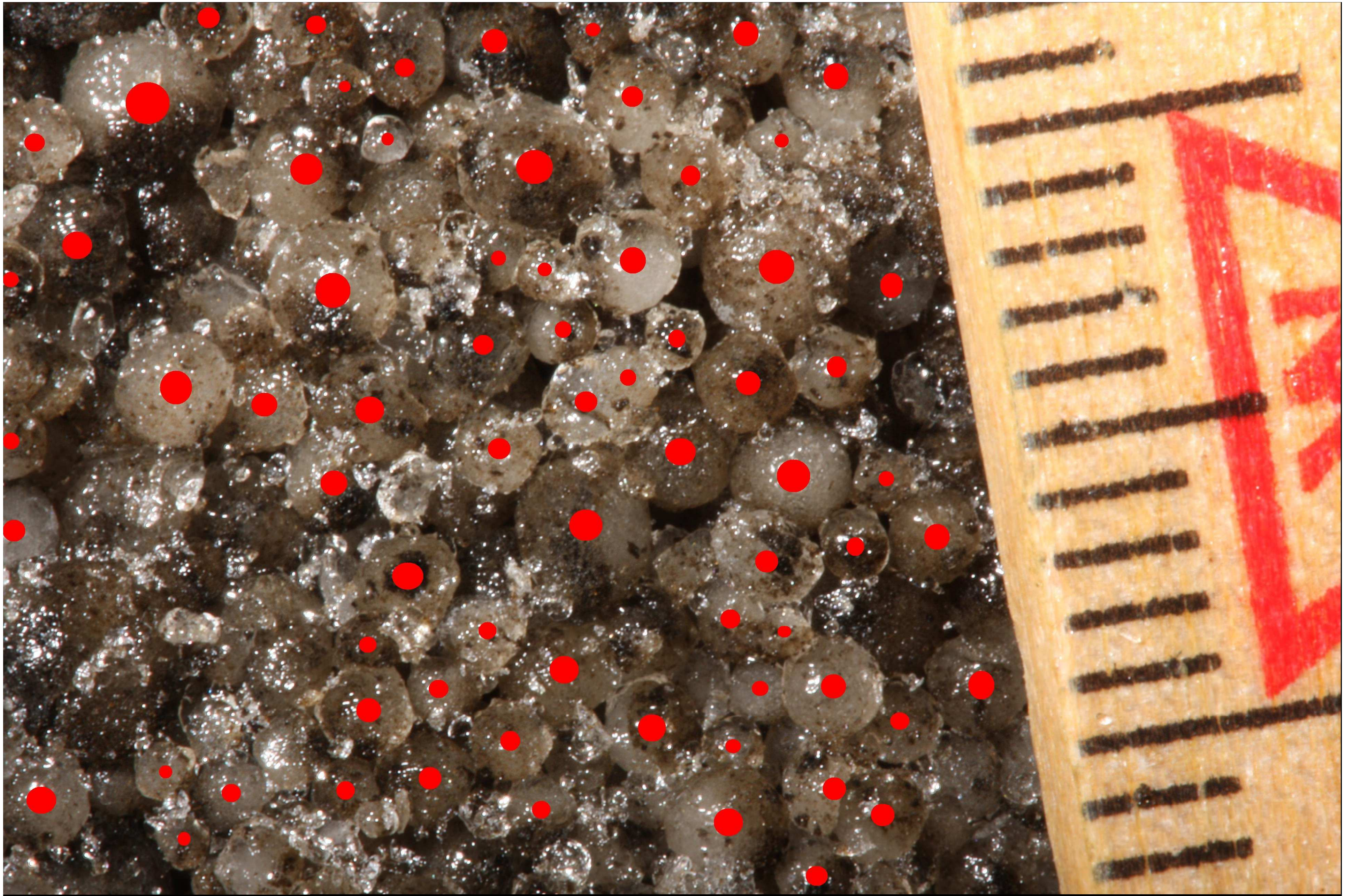
Macro-photo Þórður Arason 11 June 2011

Grímsvötn 2011 – Hagl-02

Macro-photo Þórður Arason 11 June 2011

Grímsvötn 2011 – Hagl-01

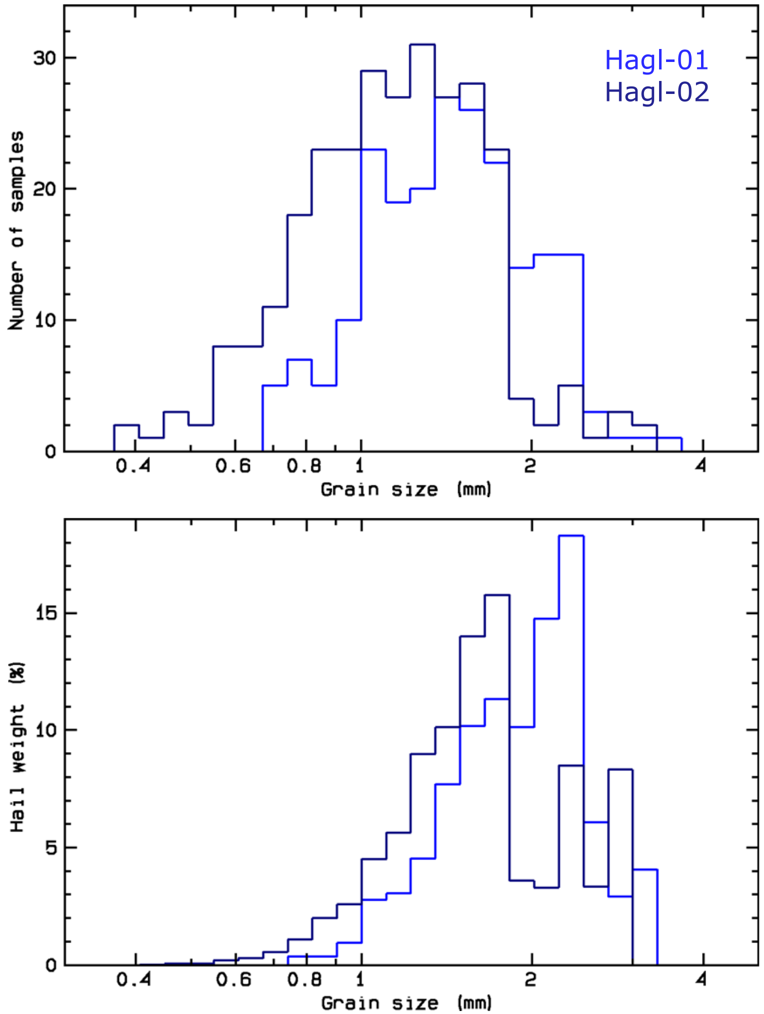
Macro-photo Þórður Arason 11 June 2011



Grímsvötn 2011 – Hagl-02

Macro-photo Þórður Arason 11 June 2011

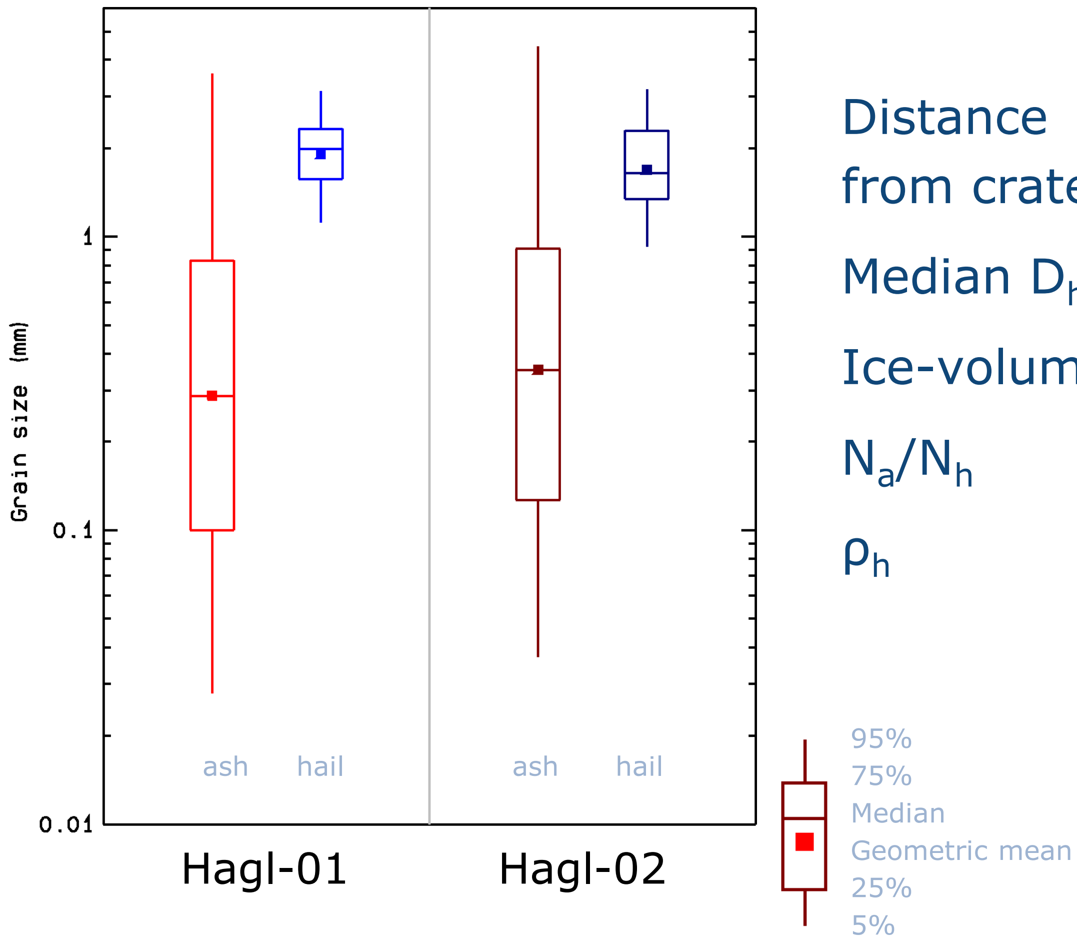
Hail size distributions



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

Most had diameter of 1-2 mm

Grain size distribution at two sites



	Hagl-01	Hagl-02
Distance from crater	3.0 km	6.2 km
Median D_h/D_a	6.9	4.7
Ice-volume	85%	73%
N_a/N_h	50	28
ρ_h	1.14	1.33

The Radar Equation

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$$\frac{P_r}{P_t} = \left\{\frac{\pi^3 c\, \tau\, G^2 \varphi\, \theta}{1024\ \ln 2\ \lambda^2 r^2}\right\} |k|^2 N\, D^6$$

$$|k|^2_{ice} = 0.197, \quad |k|^2_{ash} = 0.39$$

By assuming (wrongly) that a plume consists of individual fine grained ash particles, when in fact the ash is embedded in larger hail grains, leads to overestimation of ash mass concentration of (C):

Hagl-01: $C_{calc}/C_{real} = 380$

Hagl-02: $C_{calc}/C_{real} = 120$

Precipitation from the plume

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Stokes law:

$$v_s = \frac{(\rho_p - \rho_f)}{18\,\mu}\, g\, D^2$$

$$\rho_{air} \ll \rho_h\,,\, \rho_a : \quad \frac{v_h}{v_a} = \frac{\rho_h}{\rho_a}\frac{D_h^2}{D_a^2}$$

By assuming (wrongly) that plume consists of individual fine grained ash particles, when in fact the ash is embedded in larger hail grains, leads to underestimation of ash precipitation rate (R):

Hagl-01: $\mathbf{R_{calc}/R_{real} = 1/22}$

Hagl-02: $\mathbf{R_{calc}/R_{real} = 1/13}$

Mass flux

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By assuming (wrongly) that plume consists of individual fine grained ash particles, when in fact the ash is embedded in larger hail grains, leads to

- **overestimation of mass concentration and**
- **underestimation of precipitation rate**

These effects oppose each other when mass flux is estimated:

Hagl-01: $M_{calc}/M_{real} = 17$

Hagl-02: $M_{calc}/M_{real} = 9$

Conclusions

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- **Thick layers of ash-infused hail were observed surrounding the crater of the Grímsvötn May 2011 volcanic eruption**
- **Analysis of hail-samples indicate that ash grain size was considerably smaller than hail grain size**
- **Ice content of the hail varied between 60-85% (by vol.)**
- **Radar reflectivity of ash in a plume depends strongly on whether the grains are separate or concentrated into hail**
- **If large proportions of ash grains are embedded into hail, then calculations of plume mass concentration and mass flux can be wrong by orders of magnitude**