Abstract

The eruption of Grímsvötn volcano in Iceland in 2011 lasted for a week, 21–28 May. The eruption was explosive and peaked during the first hours, with the eruption plume reaching 20–25 km altitude. The height of the plume was monitored every 5 min with a C-band weather radar located at Keflavík International Airport and a mobile X-band radar, 257 km and 75 km distance from the volcano respectively. In addition, photographs taken during the first half-hour of the eruption give information regarding the initial rise. Time series of the plume-top altitude were constructed from the radar observations. This paper presents the two independent radar time series. The series have been cross validated and there is a good agreement between them. The echo top radar series of the altitude of the volcanic plume are publicly available from the Pangaea Data Publisher (http://doi.pangaea.de/10.1594/PANGAEA.778390).
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Two weather radar time series of the altitude of the volcanic plume during the May 2011 eruption of Grímsvötn, Iceland

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1 Introduction

An explosive subglacial volcanic eruption started in the Grímsvötn caldera in southern Iceland at, or a few minutes before, 19 UTC on 21 May 2011. The volcanic plume from the eruption was monitored using a C-band and an X-band weather radar, located at different distances from the volcano. In addition there were visual observations from the ground and air as well as a number of photographs of the plume. The strength of the eruption decreased rapidly and the plume was at or below 10 km altitude after 24 hours. The eruption was officially declared over on 28 May at 07 UTC.

Grímsvötn is Iceland's most active volcano. Previously it has erupted twice in the last 15 years, in December 1998 and November 2004 (Vogfjörd et al., 2005), and has during the past centuries had a frequency close to one eruption per decade. As the volcano is located beneath Vatnajökull icecap the eruptions are always explosive, with ash and other volcanic material being ejected into the atmosphere. The eruption in May 2011 was of short duration but caused some disruption to aviation in the region. The winds advecting the ash from the crater were mainly northerly and northeasterly. There were short-time closures of the Keflavík International Airport in Iceland and airports in northern UK and northern Germany were also affected.

The purpose of this article is to present and describe time series of the altitude of the volcanic plume, as measured by the two weather radars operating during the eruption. While the time series from the C-band radar is continuous from 21–25 May, at a 5 min time resolution, the time series from the X-band radar is fragmented due to operational difficulties. In addition, a cross validation of the time series is presented. Series of photographs taken during the first half-hour of the eruption give further information of the initial rise of the volcanic plume.

The structure of this paper is as follows: In Sect. 2 we describe the weather radars, their specifications and limitations. There is a short description of the photographs used to describe the rise in the first hour of the eruption in Sect. 3. The time series are presented in Sect. 4 and cross-validated in Sect. 5. Finally, concluding remarks follow in Sect. 6.

2 The weather radars: specifications and limitations

2.1 The Keflavík Radar

The weather radar at Keflavík International Airport in southwest Iceland was the only fixed-position operational weather radar in Iceland during the eruption. It is owned and operated by the Icelandic Meteorological Office (IMO). Its specifications are described in detail in Arason et al. (2011), see Table 1 of that paper, but here specifications pertinent to data from the Grímsvötn 2011 eruption are briefly summarised. The radar is an Ericsson C-band doppler radar located about 3 km north of the airport and 257 km from the Grímsvötn volcano (Fig. 1). Its main purpose is weather monitoring and the radar detects precipitation and precipitating clouds within a maximum range of 480 km, but the operational strategy is to make 240 km reflectivity scans and 120 km doppler scans. Each scan is made four times an hour. Previously, the radar has been successfully used for monitoring six volcanic eruptions in Iceland (Larsen et al., 1992; Lacasse et al., 2004; Vogfjörd et al., 2005; Oddsson, 2007; Arason et al., 2011; Petersen et al., 2012). Radars have also been used to monitor eruptions in the US and Italy (Harris and Rose, 1983; Rose et al., 1995; Gouhier and Donnadieu, 2008). See also Bull and Buumann (2012) and references therein. In case of a volcanic eruption in Iceland within a radius of 240–480 km from the radar the strategy is to make 480 km reflectivity scans every five minutes. During the Grímsvötn 2011 eruption the first 480 km reflectivity scan was made at 19:48 UTC on 21 May. No doppler scans were made during the eruption period.

The half-power beam width is 0.9° and during scans the beam circles from an initial angle of 0.5°, increasing the elevation angle at the end of each circle to a maximum angle of 40° (Arason et al., 2011). This means that over Grímsvötn the beam width is 5.8 km and the altitude of the lowest beam is 6.2 km a.s.l. The partial beam blockage of the lowest elevation angle (0.5°) in the direction of Grímsvötn has been estimated to be below 20%, using a 1 km digital elevation model (Crochet, 2009). The radar has therefore a fairly clear view of the eruption plume, as can be seen in figure 2(a) which shows the seven lowest elevation angles of the current scanning strategy and their height above sea level for a distance of up to 300 km. The half-power beam width of 0.9° results in an overlapping of the beams for the three lowest elevation angles, 0.5°, 0.9° and 1.3°.

2.2 The Mobile Radar

During the eruption a mobile X-band radar was operated in S-Iceland. X-band radars operate at a shorter wavelength than C-band radars and are therefore more sensitive to smaller particles. Higher resolution volume data could potentially give information about the concentration and size distribution of particles, which is important for down-stream dispersion analysis and forecasts. Further research on the volume reflectivity data is ongoing but is outside of the scope of this paper. Furthermore X-band radars are small, can be portable and run on diesel engine power. The X-band radar operating in Iceland in 2011 is a Meteor 50DX radar (Selex Systems Integration GmbH) on loan from the Italian Civil Protection until IMO had its own mobile radar up and running in spring 2012. The radar is a compact weather radar on a trailer with a total weight of 2800 kg which makes it easy to move to favourable locations in case of an eruption. Table 1 contains specifications of the radar for operations during the eruption of Grímsvötn in 2011. The mobile radar was up and running in Kirkjubæjarklaustur, S-Iceland (Fig. 1), at 03:27 UTC 22 May or about 8.5 hours after the eruption started. It was moved 500 m eastward, and 200 m closer to the volcano, between 17 and 18 UTC on 24 May to a location where it could be connected to mains power.

Kirkjubæjarklaustur is located south of the volcano, in a region that experienced heavy ash fall. This resulted in extremely challenging environment for operating the radar. There were intermittent power generation problems during the first two days, while powered with a diesel engine, and difficult working conditions. Figure 3 shows a photograph of the mobile radar, taken in the field on 22 May at about 09 UTC when ash fall obscured all daylight. The problems with discontinuous power generation meant that the radar needed to be restarted a few times and this resulted unintentionally in slightly different scanning strategy on 22 May than from 23 May and onward, see Tables 1 and 2. However, as the strength of the eruption decreased rapidly, elevation angles 6.3–13.3° detected the plume-top on May 22 but elevation angles 1.6–6.1° from 23 May. Also, the altitude difference over Grímsvötn between the two sets of elevation angles is 300 m or less. Given the beam half-power width of 1.3°, or 1.7 km over Grímsvötn, we do not expect this difference to affect the results.

The view of the eruption site from Kirkjubæjarklaustur is obscured by Þórðarhyrna mountain (1668 m a.s.l.). As a result the lowest elevation angle beam (0.5° from 23 May) is orographically blocked and the second lowest angle beam (1.6°) is estimated to be 40% blocked.

Figure 2(b) shows the 11 lowest elevation angles of the scanning strategy during the eruption and their height above sea level for a distance of up to 90 km. Note that due to the half-power beam width of 1.3° the three lowest elevation angles, 0.5°, 1.6° and 2.9°, overlap.

2.3 A comparison of the vertical detection limitations of the two radars

Table 2 shows a comparison of the altitudes of the lowest elevation angles of both radars. The volcanic plume rose to about 25 km in the initial phase of the eruption but the maximum observed height after the mobile radar started operating was 20 km a.s.l. As described previously the lowest angle (0.5°) of the mobile radar was orographically blocked, but the next eight elevation angles spanned the range of plume altitudes from 2.5 km to 21.1 km a.s.l. and were sufficient to monitor the progress of the eruption. In contrast, due to the distance from the C-band radar to Grímsvötn the lowest level that the Keflavík radar could detect the plume was at 6.2 km and the six lowest elevation angles were sufficient to cover the range of plume altitudes observed during the eruption.

3 Photographs

The sky was clear over Grímsvötn when the eruption started in the early evening of 21 May. Several photographs were taken during the first half-hour of the eruption. Of particular interest are a series of photographs taken from Skeiðarársandur, 50 km south of Grímsvötn, for which we have been able to estimate a height scale. The first photo of the plume at 19:09 UTC shows the plume reaching about 6 km in altitude. From that and the subsequent photos the rise speed of the plume head is estimated as 10–25 $\mathrm{m\,s^{-1}}$.

Figure 4 shows one of these photos, taken by Bolli Valgarðsson at 19:20 UTC, when the plume had reached over 14 km a.s.l. That evening the tropopause was observed at 8.9 km altitude at Keflavík airport, and Fig. 4 shows clearly how the plume spread horizontally when it entered the very stable air of the stratosphere.

4 The time series

Two time series have been constructed, from the detected echo tops of each radar. The echo top height is defined from the highest altitude where the threshold reflectivity is exceeded. A linear interpolation of the reflectivity value of the highest beam exceeding the threshold and the reflectivity value of the beam above are used to estimate the echo top height (see Arason et al. (2011) for details).

The threshold reflectivity applied for both radars was set to -20 dBZ. The minimum detectable signal (MDS) of the C-band and the X-band radars is -109 dBm and -113 dBm, corresponding to a signal at the volcano of +2 dBZ and -10 dBZ, respectively. With hindsight the threshold value is too low. However, we have verified that this choice of -20 dBZ does not affect the estimates of the echo top heights generated by the radar software.

Figure 5 shows the two radar time series during the first 53 hours of the eruption as well as the initial rise of the plume estimated from photographs. The Keflavík radar was set to scan within 480 km radius from 19:48 UTC and the first detection of the eruption plume is therefore after the initial rise with echo top height of 14.9 km a.s.l. The mobile radar became operational at 03:27 UTC on 22 May detecting the echo top at 11.7 km. As can be seen from Fig. 5 the availability of the data from the Keflavík radar is much higher than from the mobile radar, due to previously mentioned challenging operations of the mobile radar.

Due to the semi-discrete stepping of the radar detection of the plume top altitude, it can be difficult to get a clear picture of the height variations of the plume from the raw data. Figure 5 also shows a 30-min average of the plume-top altitude based on the echo top heights from both radars as well as estimates of the initial rise from photographs. The figure shows more clearly that the plume-top height had large variations in time, often decreasing/increasing by several km over a short time period. In fact, the variation in altitude had an oscillation time of about 5 hours. This oscillation is also evident in lightning activity and tiltmeter data and is therefore due to eruption variations.

5 Cross-validation

To cross-validate the plume-top altitude data series from the two radars, synchronous observations were compared. The Keflavík and the mobile radar series include 587 and 168 values of altitude estimates, respectively. For all the 168 scans of the mobile radar, there exists a corresponding radar scan by the Keflavík radar within at least 2 minutes. For this comparison 2 minutes are considered synchronous. During 66 of these Keflavík scans, the plume was below minimum detection height. The remaining 102 cases of synchronous independent plume-top altitude estimates were used for comparison.

The comparison of these 102 plume-top altitude estimates is summarized in Table 3 and in Fig. 6. As can be seen in the figure the estimates are concentrated to the semi-discrete altitudes that arise as a result of the discrete elevation angles of the radars. In Table 3 the data are categorized by the elevation angles of the Keflavík radar; 0.5°, 0.9°, 1.3° and 2.4°. For each of these four elevation angles the number of cases, range and mean values are shown for both radars. Furthermore, the mean difference between the altitude estimates is shown along with a standard error. The overall plume-top altitude mean difference between the two radar estimates is not significantly different from zero. The mean difference is about 80 m with an uncertainity of ±240 m.

A least squares line through the origin gives $y = 1.026x$, with a coefficient of determination $R^2 = 0.67$, when x and y are the plume-top altitude estimates from the Keflavík and the mobile radar, respectively. The slope is not significantly different from unity, and using $y = 1x$ also results in $R^2 = 0.67$.

The two radars, that are of different type and operating at different wavelength, were located at very different distances from the volcano and with different sets of elevation angles resulting in different vertical resolution of the plume. Despite this the estimated plume-top altitudes are on average not significantly different.

6 Conclusions

Although the eruption of Grímsvötn in May 2011 was of short duration it still caused some disruptions of air traffic in northern Europe and emphasised the importance of improving monitoring of explosive volcanic plumes as well as of transport and dispersion of ash and other volcanic material in the atmosphere. In fact, a large European project, FUTUREVOLC, starting in autumn 2012 has as one of its goals to develop a monitoring system integrating ground-based and remote sensing observations.

The paper describes two independent time series of the altitude of the volcanic plume during the eruption as observed with a C-band weather radar and an X-band mobile radar located 257 km and 75 km from the volcano, respectively. The two time series compare favourably, the C-band series is more complete while the X-band series has slightly higher vertical resolution.

There are gaps in the data from the mobile radar, mainly due to the very difficult operating conditions. Clearly when applying mobile radars for eruption monitoring it is beneficial to have pre-designated observational locations with the needed infrastructure in place for quick initiation of operation. Locating the radar outside of the thickest ash cloud would ease operations although that may not always be possible. The difficulties related to the operations of the mobile radar emphasise the need for auxiliary operational systems outside of the affected area, such as the Keflavík radar. Although the vertical resolution of the data is coarser than from a mobile system located closer to the erupting volcano, the operation is stable and the data provide vital information on the eruption. Another C-band radar was installed in E-Iceland in spring 2012 and all active volcanoes in Iceland are now within a 240 km distance from a C-band radar. However, it is obvious that for a minor explosive eruption the C-band radars may not be able to detect the volcanic plume due to the distance from the radars, orographic blocking and/or the operating wavelength. Therefore mobile X-band radars at carefully chosen locations are important. Selection of such sites with regards to all active volcanoes is ongoing in Iceland.

This was the first time a mobile radar was available for volcanic eruption plume monitoring in Iceland and the eruption was therefore the first real test of its usefulness for this purpose. The data from the radar was very useful, however it is clear that for future eruptions changing the scanning strategy to increase the vertical resolution may yield improved information on the structure of the plume. Figures 2 and 5 show that though the mobile radar used eight elevation angles to detect the eruption plume, that results in only a small addition to the vertical resolution given by the Keflavík radar, using six elevation angles for monitoring of the plume. While the main purpose of the Keflavík radar is weather monitoring and therefore the scanning strategy is rather strict, the purpose of the mobile radar is solely volcanic plume monitoring and the scanning strategy is therefore more flexible. Adding elevation angles to the mobile radar scans and subsequently decreasing the time resolution would improve volcanic plume monitoring. In such a scenario the fixed radar would give an estimate of the height of the volcanic plume 12 times an hour (every 5 min), with an uncertainty of 2–3 km, for eruption of the size and location of the Grímsvötn 2011 eruption, while the mobile radar would 4–6 times an hour supply higher spatial resolution data of the eruption plume. This would result in not only better estimates of the plume altitude but would also give higher resolution volume data.

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Table 1. Specifications of the mobile weather radar during the eruption of Grímsvötn in 2011.

Type	X-band Meteor 50DX (9.4 GHz)
Duration of operation	22 May 04 UTC – 25 May 14 UTC
Location	Kirkjubæjarklaustur, 63°46′30″N, 17°57′49″W
Antenna type	XDP15, parabolic, prime focus reflector
Reflector diameter	1.8 m
Height of antenna	47 m a.s.l.
Peak transmitted power	75 kW
Pulse duration	2 μs, but 0.45 μs on 23 May 02:23–12:45 UTC
Wavelength	3.2 cm
Pulse repetition frequency	550 Hz, but 1200 Hz on 23 May 02:23–12:45 UTC
Operational range	120 km
Range step	0.2 km
Minimum gain of antenna	42.5 dB
Minimum detectable signal	-113 dBm
Duration of reflectivity scans	20 s per elevation angle, but 15 s on 23 May 02:23–12:45 UTC
Duration of beam raising	5 s per elevation angle
Half-power beam width	1.3°
Polarization	Horizontal and vertical
Angle position accuracy	$\pm 0.1°$
Scanning speed	3 rpm, but 4 rpm on 23 May 02:23–12:45 UTC
Elevation angles reflectivity scans, on 22 May	0.7°, 1.8°, 3.1°, 4.6°, 6.3°, 8.3°, 10.6°, 13.2°, 16.2°, 19.7°, 23.8°, 28.4°, 33.8° and 40.0°
Elevation angles reflectivity scans, from 23 May	0.5°, 1.6°, 2.9°, 4.4°, 6.1°, 8.1°, 10.4°, 13.1°, 16.1°, 19.6°, 23.7°, 28.4°, 33.8° and 40.0°
Reflectivity threshold (echo top)	-20 dBZ
Data managing software	Rainbow®5

Table 2. Elevation angles and altitudes (km a.s.l.) of the radar-beam midpoints at the lowest levels over Grímsvötn volcano.

Keflavík radar										
Elevation angles (°)				0.5	0.9	1.3	2.4		3.5	4.5
Altitude (km)				6.2	8.0	9.9	14.9		19.9	24.4
Mobile radar	22 May 2011									
Elevation angles (°)	0.7*	1.8	3.1	4.6	6.3	8.3	10.6	13.2	16.2	19.7
Altitude (km)	1.3	2.7	4.4	6.4	8.6	11.2	14.2	17.5	21.3	25.6
Mobile radar	23–25 May 2011									
Elevation angles (°)	0.5*	1.6	2.9	4.4	6.1	8.1	10.4	13.1	16.1	19.6
Altitude (km)	1.0	2.5	4.2	6.1	8.3	10.9	13.9	17.3	21.1	25.4

* Note that the lowest elevation angle of the mobile radar was orographically blocked in the direction of Grímsvötn volcano.

Table 3. Comparison of synchronous estimates of the plume-top altitude by the two radars. Range and mean values are in km a.s.l.

Keflavík clusters		N	Keflavík radar		Mobile radar		Mean difference
Angle	Range		Range	Mean	Range	Mean	±std. error
0.5°	<7	12	5.7-6.5	6.15	2.5-10.3	6.15	0.00±0.52
0.9°	7-8.5	6	7.2-7.9	7.70	2.5-7.7	5.53	-2.17±0.69
1.3°	8.5-12	60	9.1-10.7	9.91	6.3-14.1	9.64	-0.28±0.23
2.4°	12-17	24	14.4-15.1	14.81	9.4-19.7	16.38	+1.56±0.70
>2.4°	>17	0	-	-	-	-	-
All data		102	5.7-15.1	10.49	2.5-19.7	10.57	+0.08±0.24

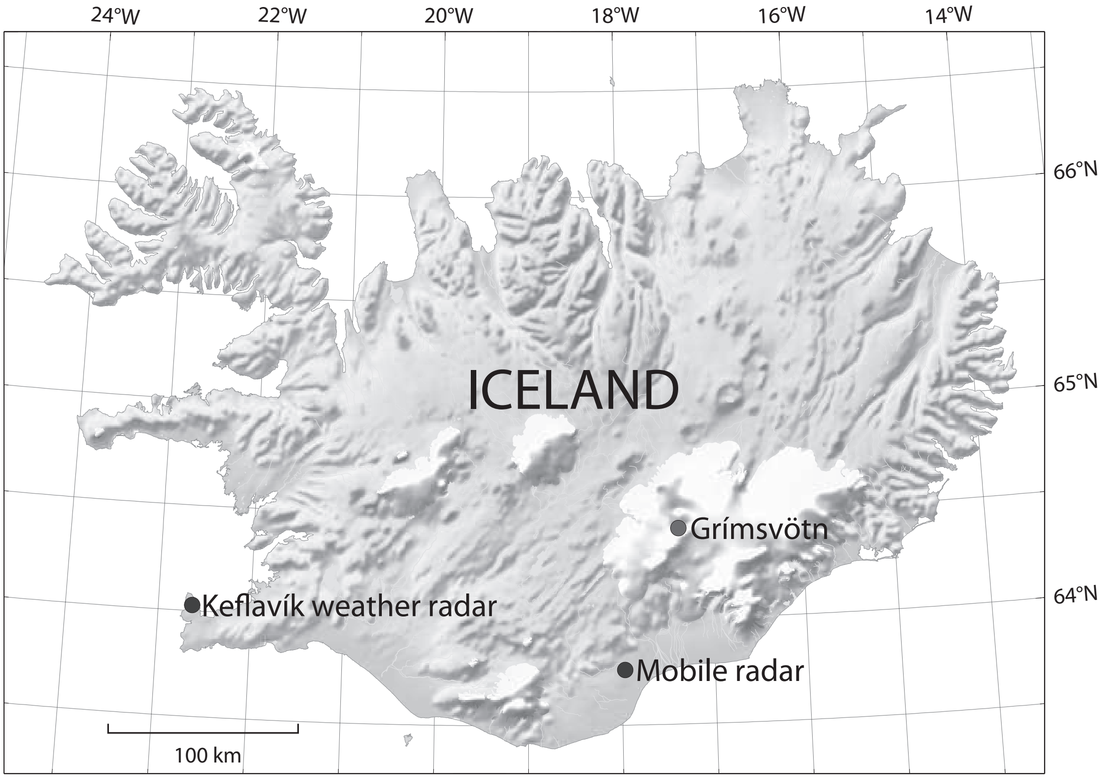

Fig. 1. A map of Iceland and the location of the stationary weather radar at Keflavík airport and the mobile weather radar in Kirkjubæjarklaustur. The radars were 257 and 75 km from Grímsvötn volcano, respectively.

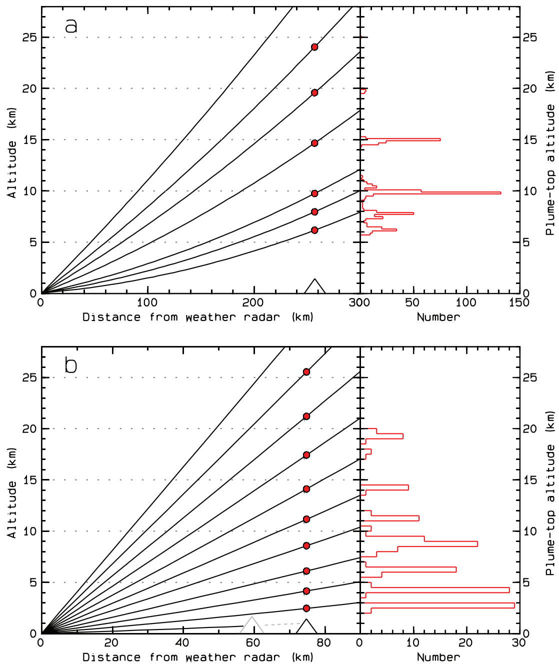

Fig. 2. Left: A range-height diagram of the altitude (km a.s.l.) as a function of distance from the weather radars (km), for the lowest elevation angles of the scanning strategy during the eruption. Right: A histogram of the plume-top altitudes (km a.s.l.) observed by the radars. The location of Grímsvötn is marked with a black triangle. (a) Range-height diagram and histogram of altitude estimates from the C-band Keflavík weather radar. The seven lowest elevation angles (0.5°-6.0°) are shown. (b) Range-height diagram and histogram of altitude estimates from the X-band mobile weather radar located close to Kirkjubæjarklaustur. The eleven lowest elevation angles (0.5°-23.8°) are shown. Note that the lowest elevation angle is blocked by the Þórðarhyrna mountain, marked by a gray triangle.

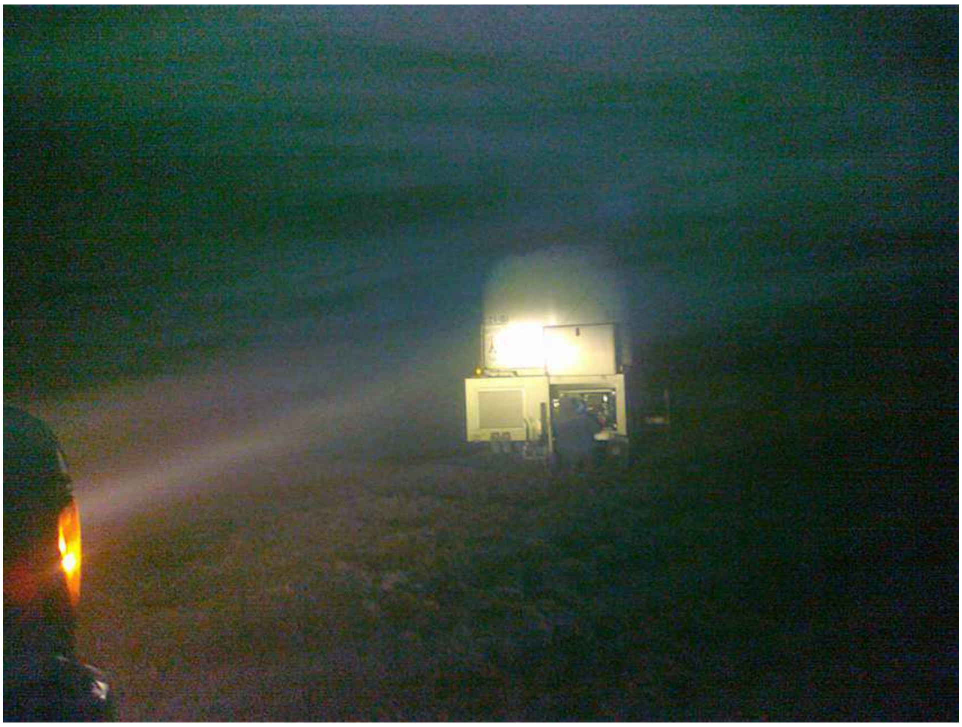

Fig. 3. The X-band mobile radar during very difficult operating conditions. Intense ash-fall caused very low visibility and darkness. Photo Geirfinnur S. Sigurðsson, 22 May 2011 at 09 UTC.

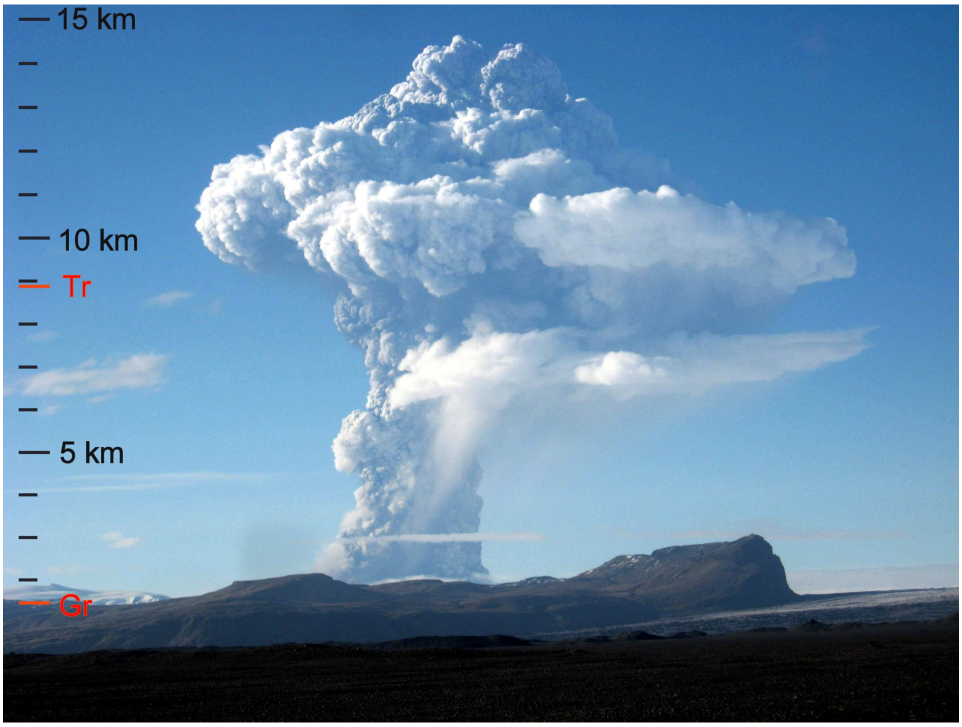

Fig. 4. The initial Grímsvötn eruption plume seen from Skeiðarársandur, 50 km south of the volcano. Approximate altitude scale at the distance of Grímsvötn (Gr) on the left, and the tropopause (Tr) at this time was at about 8.9 km. Photo Bolli Valgarðsson, 21 May 2011 at 19:20 UTC.

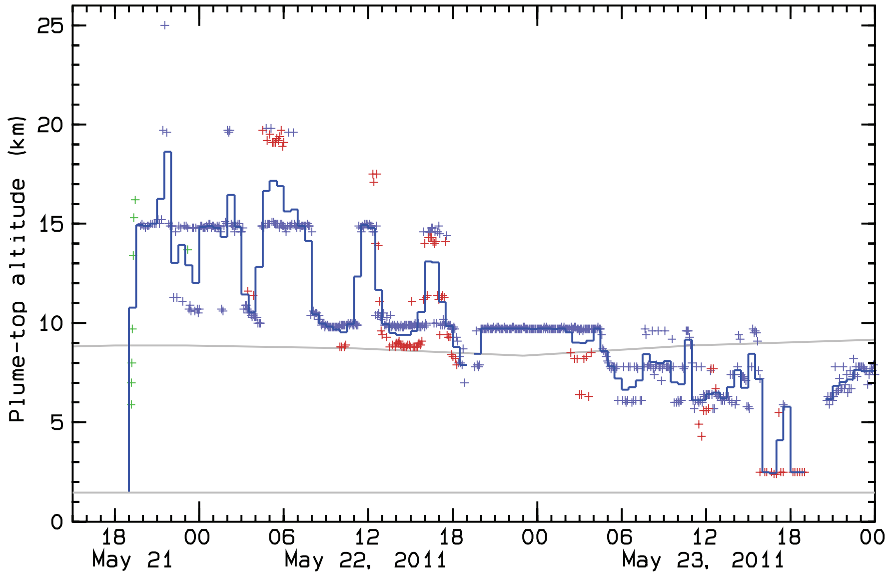

Fig. 5. The time series of the 5-min detected plume-top altitude (km a.s.l.) during the first 53 hours of the eruption. Altitude estimates are from the C-band weather radar (blue) and the X-band mobile radar (red), as well as the initial rise of the plume estimated from photographs (green). The altitude of the tropopause, observed by Keflavík radiosondes is shown at about 9 km a.s.l. (gray). The lower gray line represents the altitude of the Grímsvötn caldera. A 30-minute average plume-top altitude of all the estimates is shown by the blue curve.

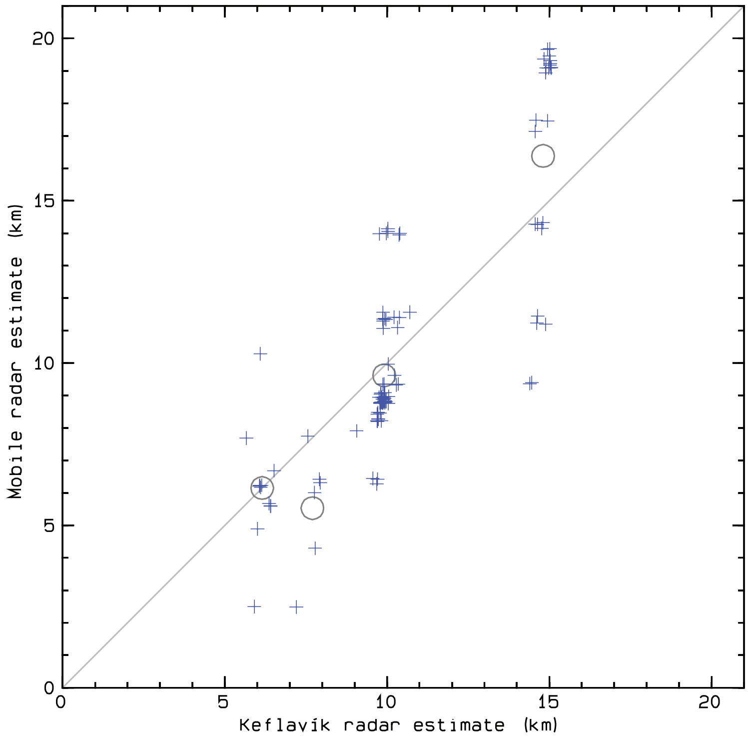

Fig. 6. Comparison of synchronous plume-top altitude estimates by the two radars. The circles show mean values of clusters for the Keflavík radar elevation angles, see Table 3.