A short meteorological overview of the Eyjafjallajökull eruption 14 April–23 May 2010

Weather – August 2010, Vol. 65, No. 8

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Introduction

Eyjafjallajökull is an ice-capped stratovolcano with maximum height of about 1660 metres above sea level located on the south-central coast of Iceland (Figure 1). It had been dormant for nearly 200 years when, following about a year of seismic unrest, an eruption began on the evening of 20 March 2010. The eruption fissure was initially about 0.5km long, located on the northern side of Fimmvörðuháls, east of the Eyjafjallajökull ice cap. The eruption was small-scale with negligible ash production. The eruption site is rather easily reached which meant that both scientists and the general public could monitor the situation closely. As well as following the eruption on live web cameras, many drove or hiked towards the eruption site to get a closer look at the spectacular scene of lava-splatters and flowing lava. The eruption ceased on 12 April but only two days later, on 14 April, an explosive subglacial eruption started in the caldera beneath the Eyjafjallajökull ice cap.

From the first day it was clear that this was a significant eruption. During the next few days, the eruption produced profuse quantities of fine-grained silicic ash, and the strong northwesterly winds over Iceland at that time carried this southeastwards into the crowded airspace of the UK and continental Europe. This caused major disruption to air traffic in northern Europe during the first week of the eruption; later, airports located as far south as Spain and Morocco had some short closures due to ash also being advected into their air spaces. This was the biggest aerial shutdown in Europe since World War II and affected at least ten million passengers worldwide.

The production of lava and ash ceased around the end of May as tremor activity declined. It is, though, too soon to be sure that the volcano is now dormant again – bearing in mind that its last eruption in 1821 lasted, intermittently, for over a year. The purpose of this article is to provide a meteorological and pictorial overview of the forty days of volcanic activity.

Volcanic eruptions in Iceland and weather patterns

Volcanic eruptions are not uncommon in Iceland. During the last 20 years there have been six: Hekla (1991 and 2000), Gjálp in Vatnajökull (1996), Grímsvötn in Vatnajökull (1998 and 2004) and now Eyjafjallajökull (2010). Usually eruptions peak during the first few days and then the activity decreases and eventually ceases. The current eruption has shown different characteristics, however, with decreasing and then increasing explosive activity. Estimates of the production of ash and volcanic aerosols are never easy to calculate, but the variations in the eruption strength added to the complexity. Furthermore, with every change in volcanic activity, new estimates needed to be fed into the dispersion model run by the London VAAC (Volcanic Ash Advisory Centre) in order for the predictions of the ash advection to be reliable.

Another factor that is crucial for the advection of ash and volcanic aerosols from an eruption site is, of course, the weather situation. As Iceland is located in the middle of the North Atlantic, the weather is highly dependent on cyclonic activity along the North Atlantic storm tracks. Although depressions are more frequent and deeper in the winter they still have an impact on Icelandic weather in other seasons, often with frequent changes in wind speed and direction.

This, however, was not the case during the first few days of the Eyjafjallajökull eruption. Instead, during the first week there was, most of the time, an anticyclone south of Iceland both at the surface and at higher levels. Figure 2 shows analysed mean sea-level pressure and 500mbar geopotential height on 15, 18, 24 April and 7 May 2010, all at 1200 UTC. The analyses for 15 and 18 April are characteristic of the situation during the first week.

Figure 1. Eyjafjallajökull and Mýrdalsjökull on the southcentral coast of Iceland. The two eruption sites are shown: on Fimmvörðuháls 20 March–12 April 2010 and in the caldera of Eyjafjallajökull starting on 14 April 2010.

14–17 April

The eruption peaked during the first few days. Radar measurement showed the plume reaching a height of 9.5km on the first day, but later 5–7km; there was frequent lightning. The magma melted ice from the ice cap and, as the magma came in contact with water, explosions sent ash and volcanic aerosols into the atmosphere. The production of ash and tephra is

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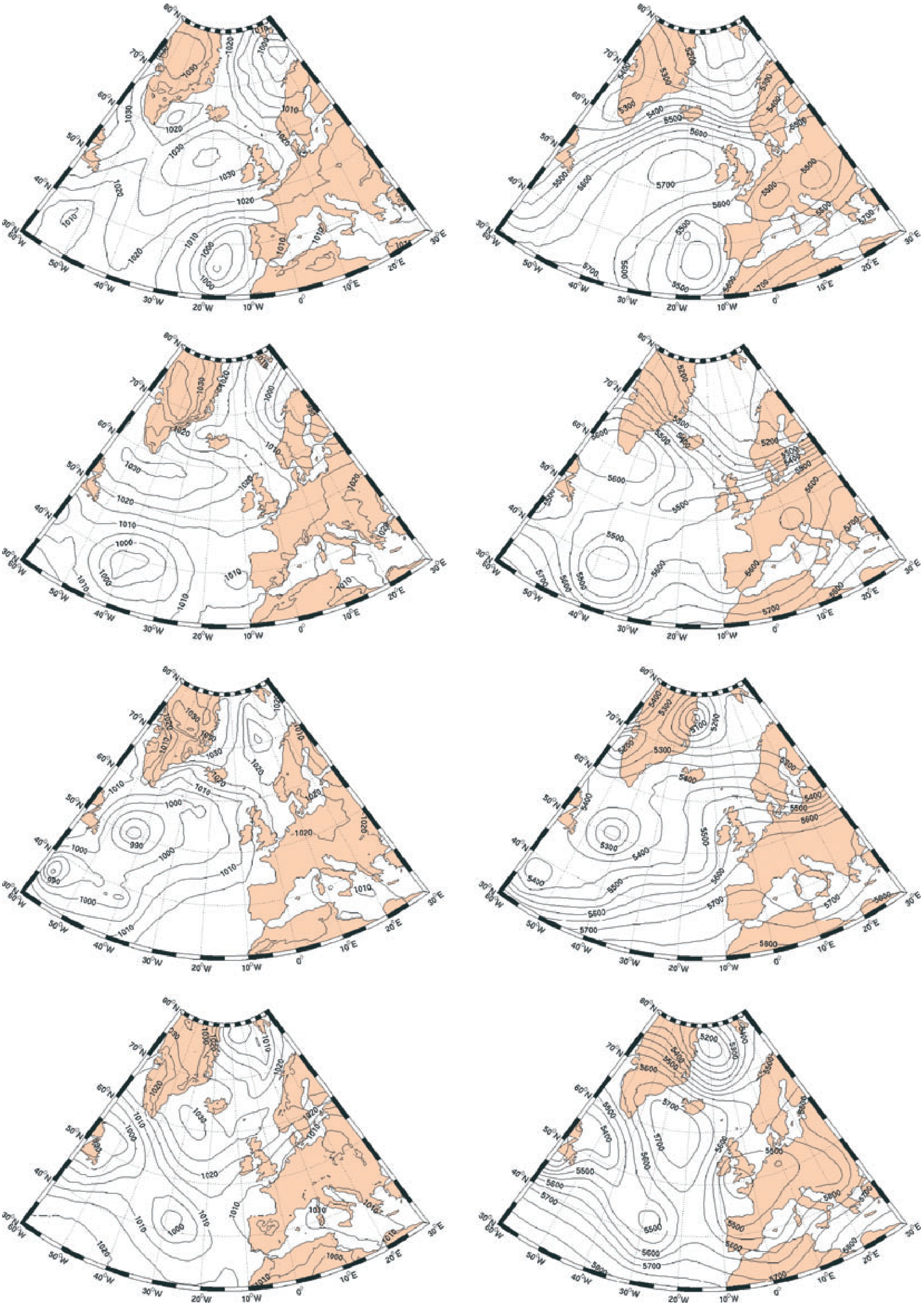

Figure 2. ECMWF operational analysis. Left column: mean sea-level pressure (mbar) and right column 500mbar geopotential height (m). Top row: 1200 UTC on15 April, second row: 1200 UTC on 18 April, third row: 1200 UTC on 24 April and bottom row: 1200 UTC on 7 May. Contour intervals are 5mbar and 50m respectively.

estimated to have been around 75 × 10^4 kgs^{-1} in the initial and most explosive phase. Tephra was sampled on Mýrdalssandur, about 50km east of the volcano, by the Institue of Earth Sciences, University of Iceland. The analysis shows that the fallout was very fine-grained. About 24% of the sample was smaller than 10µm which is in the range of aerosols and about 33% in the range 10–50µm (pers. comm., Ármann Höskuldsson and Þröstur Þorsteinsson).

During these first few days, at upper levels there were strong westerly to northwesterly winds over Iceland, as Figure 2 indicates. On 15/16 April, the observed winds over Keflavík airport at 700mbar (~3km) were westerly 18–29ms^{-1} and westerly 32–44ms^{-1} at 500mbar (~5km). It is likely that these strong winds kept the plume height lower during this period than would have been the case with lighter winds (Figure 3).

The ash was advected rapidly from the volcano, first towards northern Norway where airspace was closed for safety reasons on the evening of 14 April. On 15 April, the ash spread to a much larger area, with airspace being closed in Norway, Sweden, Great Britain and Northern Ireland.

Satellite products, such as dust microphysics RGB images, have been vital tools in monitoring advection of ash from the volcano. The dust microphysics composite was originally developed to detect sand storms but ash particles can also be detected with the same composite. In such images, volcanic ash particles, as well as other dust particles, are coloured orange or red. On 15 April, at 1200 UTC, an ash cloud could be detected extending in an east-southeast direction from the southern tip of Iceland towards the Faroe Islands and then eastward towards western Norway (Figure 4).

For the local population, the worst ash fall by far happened on 17 April. During that day the rural community to the south of the volcano was covered in ash cloud about 1km thick, which flowed continuously from the volcano. The photograph on the cover of this issue shows a close-up of the eruption site on 17 April. The eruption plume was very active with explosions and lightning, and rose with a southerly tilt. There was heavy ash at the surface of the ice cap which, due to its mass, never left the surface, but instead flowed down the slope towards the south coast. Figure 5 shows the ash cloud that covered the low lands. The MODIS true-colour satellite composite in Figure 6 also shows this cloud. While the upper-level ash cloud was directed almost straight southward from the eruption site – advected by the upper level northerly winds – at low levels there were northerly or northnortheasterly 5–10ms^{-1} winds and ash fall over a wider area south of both Eyjafjallajökull and Mýrdalsjökull. Measurements of the ash thickness in the rural community taken by the Institute of Earth Sciences, University of Iceland, show ash fall as thick as 5cm (pers. comm., Guðrún Larsen and Ármann Höskuldsson).

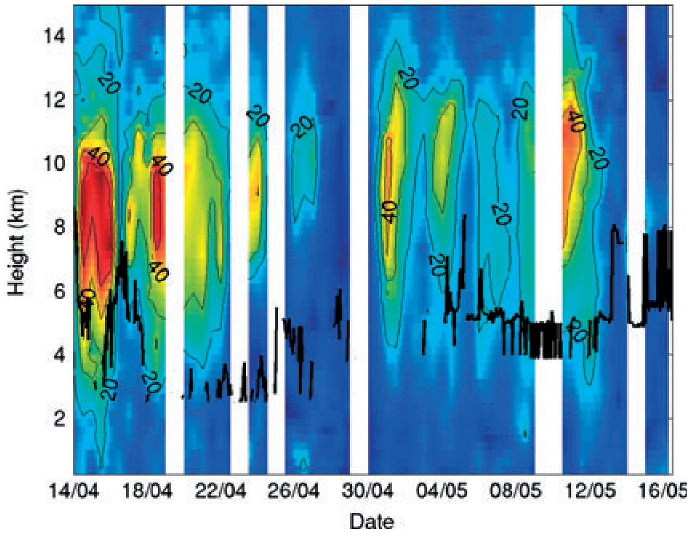

Figure 3. Observed wind speed (ms^{-1}) at Keflavík international airport as a function of altitude and time and the height of the plume (km) according to radar measurements.

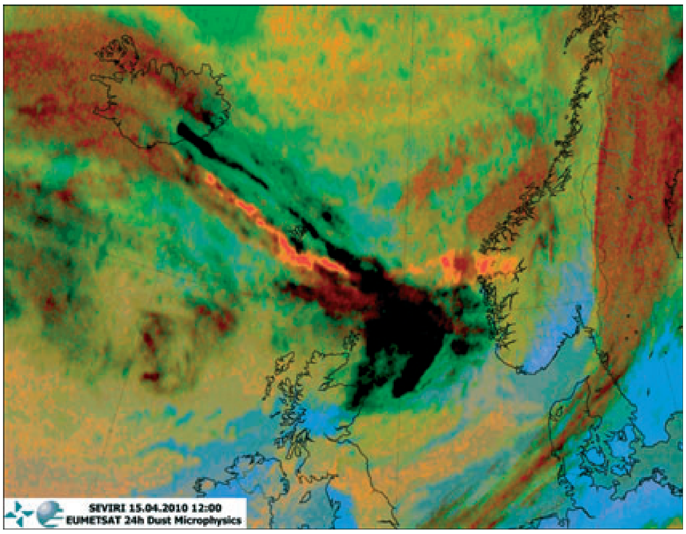

Figure 4. A SEVIRI dust microphysics RGB image at 1200 UTC on 15 April. An ash cloud from Eyjafjallajökull extends southeastward towards the Faroe Islands and then eastward into western Norway.

Figure 5. A view of the low-level ash cloud at 2000 UTC on 17 April 2010. The cloud was about 1km thick, visibility was very poor and the depth of the ash fall was up to 5cm. (© Sigmar Jónsson.)

18–30 April

There was a significant change in the activity on the 18/19 April with less ash production and no lightning activity. The plume height

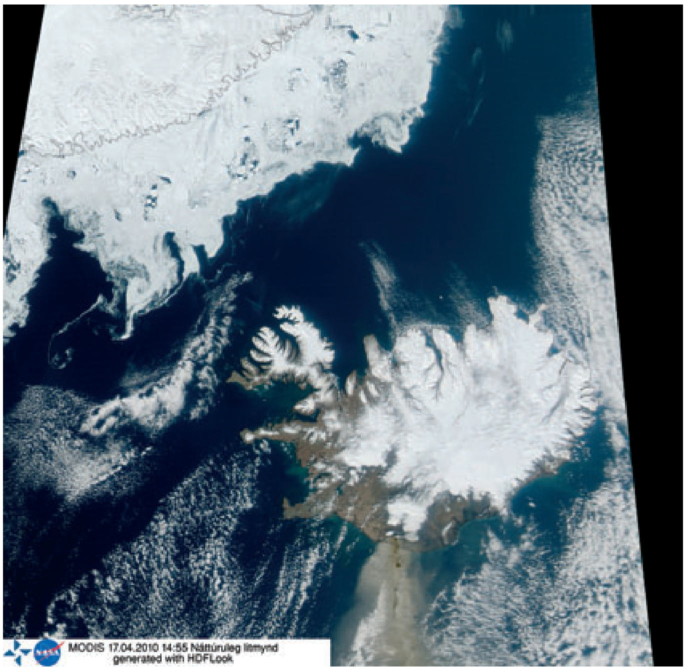

Figure 6. A MODIS true-colour image at 1320 UTC on 17 April 2010. The upper-level ash cloud was rather narrow while the lower-level ash cloud spread out perpendicular to the upper-level winds. The heaviest ash fall was in the region south of Eyjafjallajökull but there was also ash fall south of Mýrdalsjökull.

Figure 7. The eruption plume at 1542 UTC on 23 April 2010, during the less active phase. At the altitude of the plume there were light northerly winds. Two ash layers can be detected, at about 2.3km and 2.6km in altitude. Downwind (to the right) the layers seem to combine into one layer. The plume rises through the ash layers with a negligible tilt and overshoots slightly. (© Magnús Tumi Guðmundsson.)

dropped to 3–5km in altitude and was often not seen on the radar located at Keflavik. This is because the radar is located at Keflavík international airport about 150km from the eruption site. Because of this distance and mountain ranges located between it and the eruption site the radar cannot detect a low-level plume. It is estimated that the intensity of the eruption dropped by one to two orders of magnitude, to perhaps less than 10^4 kgs^{-1} and simultaneously there was a drop in the production of very fine ash with less than 5% of the tephra with grain size smaller than 50μm (pers. comm., Ármann Höskuldsson and Þröstur Þorsteinsson). On 21 April, lava started to flow northward beneath the outlet glacier Gígjökull.

With the plume having a less explosive character and the winds being mainly light, layering of ash in the atmosphere was now visible, even immediately above the volcano. Figure 7 shows a photograph taken on 23 April. The plume height was estimated at about 3.5km; a few ash layers can clearly be detected. Over the summit there were at least two layers, one at about 2.3km in altitude and another one at about 2.6km. The plume rose with a negligible tilt with height and overshot through the top ash layer. Due to the weak winds at that time, the horizontal spread of ash was not only downwind of the eruption site but also to some extent in other directions. There were no measurements of the vertical profile of the atmosphere in the area but it seems likely that weak inversions along with the buoyancy of the particles may have played a role in creating these ash layers. Further downstream, the ash layers seemed to join together in a single layer that was advected far afield. Just downwind of the eruption site (to the right in Figure 7) the heaviest ash particles can be seen falling out. The 'mist' covering the slopes of the mountain is actually drifting ash.

Although during this period it is estimated that the ash produced was confined to lower levels, i.e. below 6km, air traffic was still disrupted. For example, on 24 April low-level winds over Iceland were easterly and, for the first time during the eruption, ash was advected over Reykjavík and Keflavik international airport closed temporarily. Ash fall was detected in the Reykjavík area but measurements of airborne particles and sulphuric dioxide showed concentrations no higher than measured on a day with heavy traffic.

1–4 May

During the first few days of May the plume was darker; ash and tephra production was estimated as slightly increased at perhaps $1–5 \times 10^4$ kgs^{-1}. On 4 May, lava production seemed to come to a halt and the eruption became quite explosive again.

5–23 May

With little or no lava production, the eruption turned explosive with periods of enhanced activity. On 5 May, a strong sulphuric dioxide signal was detected by satellites and the day after the plume height rose to over 8km in altitude and the production of ash and volcanic aerosols increased temporarily. The upper-level winds were northerly, spreading the ash mainly southwards over the North Atlantic and then around an upper low into the westernmost regions of Europe a few days later (Figure 2). As a result, airports in the Canary Islands, Spain and Morocco were closed temporarily. Furthermore, because of the increased plume height, ash was predicted to reach transatlantic flight levels; as a result, the air space was also closed over parts of the North Atlantic. This resulted in transatlantic air traffic being rerouted northward into Icelandic airspace. On 8 May, 758 aircraft came through the area, where on average about 260 aircraft fly through in a day. This record was broken daily during the next four days with the new record standing at 1012 aircraft in a day on 11 May.

After the initial rise the plume height decreased again to 6–7km in altitude and ash production decreased slightly. The eruption activity was stable with periods of more explosions and thus higher plume altitude. From 19 April until 10 May no lightning activity was detected by the ADT system of the UK Met Office but lightning was again detected every day from 11 May until 20 May, peaking at over 20 lightning strokes during 16 May.

Due to light easterly winds on 18 May ash drifted westward; high aerosol concentration, although below health limits, was measured in Reykjavík.

From 18 May, the magma flow and explosive activity decreased slowly and so did the plume's altitude. During a reconnaissance flight on 23 May, it was noted that although steam exited the eruption site, there was no magma inflow and the plume was only steam. However, the geophysical tremor was still higher than before the onset of the eruption and small tremor pulses were detected. This meant that even though there was very little activity it was still not possible to determine if the eruption had ceased. Given how uncharacteristic this eruption has been in comparison to other Icelandic eruptions in historical times, the eruption site will continue to be monitored closely.

Local ash fall

The direction of local ash fall is highly dependent on low-level wind direction and as most of the ash falls out rather quickly, the rural community in the vicinity of Eyjafjallajökull experienced substantial ash fall during the eruption. The worst ash fall south of the volcano occurred on 17 April but there were numerous days with ash fall in the area. For example, on 19 April due to persistent northerly winds, about $10ms^{-1}$, the rural community experienced not only ash fall but also drifting ash. In places, the ash fall was a few centimetres. Figure 8 shows a photo of ash accumulated on a tin roof in the region. Communities to the east experienced significant ash fall on 6 and 7 May with concentrations of airborne particles in Vík measured at 418µg per cubic metre on 6 May. This is far above health limits and health authorities advised the public to stay inside. During the next few days blowing ash was also a considerable problem.

Although this has been the largest explosive eruption in Iceland since Katla erupted in 1918, a relatively small area of Iceland has been badly affected. This is because the winds were mainly northerly and northwesterly and therefore carried the ash only a short distance overland. Although ash fall has been widely reported, it is estimated that only about $300km^2$, or about 3% of the total area of Iceland, experienced significant ash fall. The manned synoptic weather stations all report ash fall when appropriate and the Icelandic Met Office set up an online registration form that the public could use to report ash fall, timing, location, amount and other important information as well as upload photographs. The form has been widely used and the information is an important record of the local spread of ash.

Figure 8. Ash deposited on a tin roof in the area south of Eyjafjallajökul, 16 May 2010. (© Ari Tryggvason.)

Concluding remarks

The eruption in Eyjafjallajökull in April and May 2010 was a medium-size eruption with significant local ash fall in only a small part of Iceland; the eruption plume seldom rose above the tropopause. However, as the upper-level winds advected ash over the UK and continental Europe, as well as into the transatlantic flight routes, the eruption caused the largest disruption of air traffic since World War II.

This has raised many questions regarding estimates of ash and volcanic aerosol production in medium-size explosive eruptions and the impact of upper-level winds on the dispersion downwind. Also, due to the unstable characteristics of the eruption, it has become quite clear how important monitoring the productivity of the volcano is as well as constantly re-evaluating eruption strength and tephra and ash production. Such information is vital to dispersion models predicting the far-field advection. The stability of the ambient atmosphere is important for the entrainment rate and strong upper-level winds decrease plume height. In order to get better predictions of ash advection in the far field, it is clear that better observations of the plume and the ambient atmosphere are necessary.

It is also clear that drifting ash may become a problem in the region for the next few years. It will be important to monitor and predict when drifting ash may be a health problem for both humans and livestock. High resolution modelling and an increased observational network may therefore be necessary.

Acknowledgments

The monitoring of the eruption in Eyjafjallajökull was carried out by the Icelandic Met Office and the Institute of Earth Sciences, University of Iceland. Thanks to Inga Dagmar Karlsdóttir for supplying Figure 1 and Hróbjartur Þorsteinsson for supplying Figure 4.

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DOI: 10.1002/wea.634