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Volcanic ash over Europe during the eruption of Eyjafjallajökull on Iceland, April-May 2010

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Abstract

During the eruption of Eyjafjallajökull on Iceland in April/May 2010, air traffic over Europe was repeatedly interrupted because of volcanic ash in the atmosphere. This completely unusual situation in Europe leads to the demand of improved crisis management, e.g. European wide regulations of volcanic ash thresholds and improved forecasts of theses thresholds. However, the quality of the forecast of fine volcanic ash concentrations in the atmosphere depends to a great extent on a realistic description of the erupted mass flux of fine ash particles, which is rather uncertain. Numerous aerosol measurements (ground based and satellite remote sensing, and in situ measurements) all over Europe have tracked the volcanic ash clouds during the eruption of Eyjafjallajökull offering the possibility for an interdisciplinary effort between volcanologists and aerosol researchers to analyse the release and dispersion of fine volcanic ash in order to better understand the needs for realistic volcanic ash forecasts. In this introductory paper, we provide a general introduction into magma fragmentation processes during explosive volcanic eruptions, describe the evolution of the eruption of Eyjafjallajökull, present the possibilities of ground based in-situ and remote measurements and numerical model studies of volcanic ash and summarise open questions and future directions.

Keywords: Eyjafjallajökull, volcanic activity on Iceland, volcanic ash, dispersion modelling, ground based measurements

1. Introduction

Worldwide, about 60 volcanoes erupt each year (Global Volcanism Program, http://www.volcano.si.edu/world). In 2010, about ten volcanoes produced maximum ash plume heights exceeding 8 km above sea level (http://www.volcano.si.edu/world), including Eyjafjallajökull on Iceland (63.63°N, 19.62°W, 1666 m a.s.l.). Even though the eruption of Eyjafjallajökull was only moderate in intensity, the explosive phase during April/May 2010 triggered the biggest aviation shutdown in history, as north-west wind directions spread fine volcanic ash over Central Europe, Great Britain and Scandinavia forcing the closure of most of the European airspace. The magnitude of the resulting impact was immense. Just during the week of 14-21 April, 25 European countries were affected. The direct loss to airlines is estimated to exceed 1.3 billion Euros with more than 4 million passengers affected and more than 100.000 cancelled flights (Oxford-Economics, 2010).

On Iceland, reconstruction of historic volcanic records has revealed 205 eruptive events at an average of 20–25 eruptions per century. About 150 of these evolved significant explosive activity (Thordarson and Larsen, 2007; Gudmundsson et al., 2008). Therefore the eruption style of Eyjafjallajökull in April/May 2010 **(Fig. 1)** is not unusual in Iceland (Davis et al., 2010), and neither is the duration of the event, e.g. the 1821-23 Eyjafjallajökull eruption lasted 14 months.

However, society’s demands on unaffected mobility have considerably grown in recent decades, and therefore our vulnerability to natural hazards, like volcanic ash eruptions, has increased as well. The probabilities of major disruption are likely to increase even more in the near future because of the constant increase of air traffic. Dependent on circulation patterns, Icelandic volcanic ash may be transported towards Central Europe, in particular when the North Atlantic Oscillation (NAO) is in its negative phase, as during spring 2010 (http://www.maison-jaune.com/blog/wp-content/uploads/2010/09/nao_timeseries.gif).

Another environmental issue is the mobilisation of volcanic ash from the tephra deposits at higher wind speeds, a post-eruptive effect after the Eyjafjallajökull eruption which happens up to now on Iceland and may create health problems for the local population. Different to mineral dust storms, which have been widely investigated concerning the processes affecting mobilisation and climate, volcanic ash storms and their environmental, health and potential climate effects have received little attention until now.

This special issue aims to examine the volcanic eruption of Eyjafjallajökull during April and May 2010, in particular its impact on atmospheric particle concentrations over Europe and on aviation safety, both of which were highly uncertain when the eruption was ongoing. It still remains unclear if the new volcanic ash concentration threshold of 2 mg m^{-3}, above which flights would not be permitted, has sufficient technical and scientific justification and whether it will be officially recognised and adopted by the International Civil Aviation Organisation (ICAO). As air traffic is highly likely to be disrupted by future volcanic eruptions on Iceland or elsewhere worldwide, there is a serious need to be better prepared in order to minimise impacts. The analysis of the Eyjafjallajökull eruption offers a unique and unprecedented opportunity to bring together the knowledge and experience of volcanologists, meteorologists and aerosol scientists to contribute in an interdisciplinary effort to a better understanding and prediction of the possible impacts of volcanic ash. Major topics addressed in this issue by experts of these disciplines are: a) the amount of fine ash released during the eruption, b) in-situ and ground based remote measurements of volcanic ash and c) numerical model studies of the atmospheric dispersion and deposition of volcanic ash. Satellite detection and monitoring of volcanic activity is not in the focus here, because an extra special issue would be necessary to deal with such a wide topic. This introductory paper is arranged as follows: First and because we recognise that readers from the volcanological and atmospheric science communities potentially have rather different backgrounds, we give a general introduction into magma fragmentation processes during explosive volcanic eruptions in section 2 and describe the evolution of the eruption of Eyjafjallajökull (section 3). The possibilities of ground based in-situ and remote measurements and numerical model studies of volcanic ash are outlined in section 4 and 5, respectively. A short summary of the special issue is given in section 6. Finally, open questions and future directions are summarised in the outlook section 7.

2. Magma fragmentation during explosive volcanic eruptions

2.1. Eruption conditions and ash generation

Explosive volcanic eruptions occur when magma containing dissolved volatiles rises in the conduit. Thereby exsolution of volatiles forms gas bubbles that grow by diffusion, decompression and coalescence. The further the magma-gas mixture rises, the more the pressure decreases leading to an acceleration of the mixture against gravitational and friction forces, until a continuous gas stream with clots and clasts of magma (called pyroclasts) leaves the vent explosively (Sparks et al., 1997). The explosive character of a volcanic eruption depends considerably on the viscosity of the magma, where three major types of magma are distinguished from each other (Tab. 1). These types of magma have different melting points, viscosities and typical volatile contents. In general, most efficient fragmentation occurs during explosive eruptions where magmas of rhyolitic composition are involved because of the higher volatile content.

Phreatomagmatic eruptions are triggered by the interaction of external water with magma, for example from a glacier as during the early phase of the Eyjafjallajökull eruption. External water may also be supplied from crater lakes or even the shallow ocean during seamount volcanic eruptions (Colgate and Sigurgeirsson, 1973). The very efficient fragmentation is caused by thermal contraction of magma from chilling on contact with water (Zimanowski et al., 2003). Water initially chills the magma at the interface, which then shatters. The water penetrates the mass of shattered hot glass and is transformed into high-pressure superheated steam by a runaway process of heat transfer and further magma fragmentation, until a violent explosion results. Violent phreatomagmatic eruptions produce especially fine-grained volcanic ash, but because of the abundant water these fine ashes typically aggregate into larger ash-ice particles in the eruption column (Fig. 1c).

Pyroclastic flows occur when the eruption column collapses leading to gas and tephra flows rushing down the flanks of a volcano at high speed thereby also contributing to the fragmentation process. Coignimbrite clouds can arise from pyroclastic flows when the material at the top of a pyroclastic flow gets more buoyant than the surrounding air. These convective clouds can form volcanic plumes as high as the original feeding plume and are a source of substantial amounts of fine volcanic ash as well.

As eruption conditions may be highly variable in time, all fragmentation processes can take place simultaneously producing tephra which is defined as any fragmental material produced by a volcanic eruption regardless of composition and fragment size (Tab. 2), with ϕ units defined as

$$\phi = -\log_2(d/d_0) \qquad \text{(Eq. 1)}$$

with d in mm and d_0= 1mm.

2.2. Plume height and mass eruption rate

From a number of volcanic eruptions the averaged tephra mass eruption rate (total erupted mass divided by the eruption duration) and corresponding averaged plume height are known. Mastin et al. (2009a) plotted plume height (H) against the logarithm of the eruption volume rate (V in m^3/s) with the best fit given by

$$H = 2 \times V^{0.241} \qquad \text{(Eq. 2)}$$

As plume height is typically the easiest parameter to constrain in real time, a first assessment of tephra mass fluxes can be based on empirical relations similar to Eq. 2 (e.g. Sparks et al., 1997) or by using one-dimensional eruption column models. Such models (e.g. Bursik, 2001; Mastin, 2007) determine plume height from the mass flux or vice versa, dependent on the thermal conditions at the vent. Density reduction of the erupted hot gas-pyroclast mixture occurs by dilution and entrainment of ambient air leading to a buoyant mixture rising in the atmosphere until the level of neutral buoyancy is reached which equals to the eruption plume height if overshooting is neglected. Due to the lack of techniques able to measure mass flux in real-time, these two methodologies represent the standard for the determination of this important variable. The tephra flux released during the eruption of Eyjafjallajökull determined using Eq. 2 with reported plume heights from the Volcanic Ash Advisory Centre (VAAC) in London (which are based on radar and pilot observation in Iceland) is presented in **Fig. 2**.

2.3. Mass flux of fine volcanic ash particles

Fine volcanic ash represents a highly variable fraction of the erupted tephra depending on magma composition and eruption conditions as summarised above. A special issue entitled ‘Improved prediction and tracking of volcanic ash clouds’ published in the Journal of Volcanology and Geothermal Research (Volume 186, 2009) gives a recent summary on this topic. According to Rose and Durant (2009) very fine ash particles with diameters less than 30 μm make up only a few percent during basaltic eruptions whereas they can contribute 30–50 % to the total ash content during rhyolitic eruptions. According to Mastin et al. (2009a), the mass fraction of fine debris PM_{63} can vary by nearly two orders of magnitude between small basaltic eruptions and large rhyolitic ones. However, it is the even finer particle size fraction (PM_{10} and $PM_{2.5}$) that may be carried for hundreds of miles before settling onto land or into the ocean. During atmospheric dispersion, such fine ash particles can affect air quality, reduce visibility and endanger aircraft navigation. Information on $PM_{2.5}$ or less has not been in the focus of research of volcanologists so far.

Generally, volcanologists calculate the tephra total grain-size distribution (TGSD) by combining grain-size distributions from fresh samples collected at multiple locations throughout a deposit. TGSDs obtained by this method are not available after each volcanic eruption as volcanoes are often very remote, hardly accessible in particular during an eruption or close to the ocean. Moreover, TGSDs exclude ash that remains in the atmosphere over great distances and therefore may tend to underestimate the mass fraction of fine ash (Mastin et al., 2009a), in particular PM_{10} and less. However, in many cases, this is partly compensated by a premature sedimentation of fine ash caused by the formation of ash-ice aggregates in the volcanic plume or in the ash cloud (Fig. 1c).

During the most explosive phase of the Eyjafjallajökull eruption, the PM_{10} mass fraction made up about 25 % of the ash grains with diameters smaller than 300 µm ($PM_{2.5}$ about 4-5 %) (http://www2.norvol.hi.is/page/ies_EYJO2010_Grain), decreasing to about 5 % by May 3.

3. Evolution of the Eyjafjallajökull eruption

Iceland has been built up over the past 16 million years by basaltic volcanism occurring at the Mid-Atlantic Ridge, caused by spreading of the Eurasian and North American plates and the abundant magma supply by the Iceland Hotspot (Sæmundsson, 1974). The Eyjafjallajökull strato-volcano is located at the western border of the Eastern Volcanic Zone (EVZ) in South Iceland, west of Mýrdalsjökull (Katla). The EVZ is propagating south-westwards into older oceanic crust. Eyjafjallajökull is an elongated, flat cone of 1666 m height. Its summit is covered by a glacier of up to 200m thickness (Sturkell et al., 2010). Only three eruptions have been documented in Eyjafjallajökull before 2010, in 920, 1612 and 1821-1823. Prior to 1991, the volcano was seismically quiet for at least 20 years.

Enhanced seismic activity beneath Eyjafjallajökull, detected in 1991, was followed by persistent micro earthquake activity during the following decade with intense seismic swarms beneath the north-eastern and south-eastern flanks in 1994 and 1999 and a smaller swarm beneath the summit crater in 1996 (e.g. Dahm and Brandsdóttir, 1997, Sturkell et al. 2003), suggestively driven by magma intrusion (Pedersen et al., 2007). Following this decade of unrest, the volcano was relatively quiet until March 2009 when a few earthquakes were recorded beneath the north-eastern flank. Seismic activity increased gradually throughout the year, escalating in an intense swarm in February-March 2010. Simultaneous inflation observed by GPS and InSAR data confirmed magmatic accumulation within the volcano and heralded the subsequent eruptions.

Seismic analysis revealed more than one accumulation zone at shallow (3-5 km) depth (Hensch et al., 2010) and GPS data reflected a temporally and spatially complex intrusion rather than pressure changes in a single magma chamber. First modelling on the geodetic data suggests two pre-eruptive sill intrusions between December 2009 and March 2010 beneath the main earthquake clusters at 4-6 km depth and an eastward ascent of a dike prior to the first eruption onset on 20th of March (Sigmundsson et al., 2010). Lacking deflation during the flank eruption is supposed to be caused by continuous feeding of magma from greater depths. This further inflow of magma, together with previously intruded material (supposedly intrusion events of 1994 and 1999), inevitably led to the main summit eruption on 14th of April, after the eruptive fissure on the flank closed on 12th of April and the volcanic system quickly reached a level of overpressure again.

A detailed chemical analysis of volcanic materials is given at http://www2.norvol.hi.is/page/IES-EY-CEMCOM and in the supplementary material of Sigmundsson et al. (2010). The flank fissure erupted kali-olivine basalts with low SiO_2 content of around 47.7-47.8 % and thus suggesting to be fed from a deep source. The summit eruption produced mainly trachy-andesites with higher acid contents (56.7-59.6%) and could be subdivided into three phases:

a) An explosive phreatomagmatic phase started at the onset of the eruption on 14th April and lasted for 5-7 days. Together with the melt water of the glacier, magma fragmented explosively into large volumes of very fine ash, ejected up to 11 km a.s.l. into the atmosphere (Fig. 1a). Water mixing with magma generally lowers the viscosity threshold for explosive eruptions and the majority of explosive eruptions in Iceland are phreatomagmatic explosive basaltic (lower viscosity) and andesitic eruptions (Gudmundsson et al., 2008), but in case of Eyjafjallajökull the explosivity was also advantaged by the unusually high evolved magma, compared to primitive basalt.

b) From 18th April, explosive activity decreased continuously to a more effusive eruption, causing a lava flow down the northern flank of the volcano starting on 21st of April. With the declining phreatomagmatic character of the eruption, the ash particles got coarser and the ash plume only reached heights of 3-5 km.

c) Around 5th of May, explosive activity increased again. The eruptive behaviour changed to a rather small, but sustained magmatic explosive eruption, producing significant amounts of ash and pumice. Again, the ash plume rose up to 10 km a.s.l. and fine ash was widely dispersed. The continuous eruption ended around the 23rd of May, minor volcanic activity was observed until mid of June 2010. Compared to phase a) washout of fine ash was less efficient in the plume so that a high percentage of fine ash could be dispersed widely.

In summary, the combination of the phreatomagmatic explosive activity due to melt water and above average evolved magma due to resting magma pockets of previous intrusions is supposed to have caused this exceptional amount of fine ash dispersed up to 11 km high into the atmosphere.

4. Ground based measurements of volcanic ash

Besides monitoring volcanic ash clouds by satellite, aircraft measurements (e.g. Schumann et al., 2010; Weber et al., 2010), ground based remote sensing networks for aerosol measurements, e.g. AERONET (Aerosol Robotic Network, http://aeronet.gsfc.nasa.gov/) and EARLINET (European Aerosol Research Lidar Network, http://www.earlinet.org/) and ground based in-situ measurements e.g. coordinated by GAW (Global Atmosphere Watch, http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html) or organised in country-wide networks can provide valuable information on the amount and distribution of volcanic ash in the atmosphere, on the volcanic ash size distribution and on deposition fluxes.

AERONET is a coordinated sunphotometer network (Holben et al., 1998) which has grown to more than 200 stations worldwide. The observations of the aerosol optical depth at several wavelengths in the visible wavelength range are done with standardised instruments. The data is submitted every 24 hours via satellite to the central data centre. A cloud screened version of the data can be accessed through the AERONET homepage already one day after the observations were performed. Although the data has not undergone final quality checks it can be used to estimate the total amount of aerosol mass in the atmosphere. During the eruption of Eyjafjallajökull, a number of AERONET stations observed high aerosol optical depth values caused by volcanic aerosols. Among those are Helgoland, Hamburg, Leipzig, Cabauw, Lille, Palaiseau, Munich and Helsinki. Because cloud free conditions prevailed in Central Europe for several days during the volcanic eruption, a large data set of optical depth values is available. They may be used for comparisons with model results to estimate the aerosol mass concentrations in the atmosphere.

Since 2000, regular observations of the vertical aerosol distribution are performed at the EARLINET stations. Today, about 30 sites participate in EARLINET. The lidar instruments are operated on a regular schedule with typically three observations per week. During special events like Saharan dust outbreaks or volcanic eruptions, they are usually run continuously if the weather conditions (cloud-free sky) allow for it. Lidars give important information about the vertical distribution of an aerosol layer like the volcanic ash plume of the Eyjafjallajökull eruption. The development of the plume can be followed with high temporal resolution at the individual sites and the aerosol extinction can be determined by those systems that are equipped with Raman channels. The Eyjafjallajökull ash plume was first observed by the lidar in Hamburg, followed by the lidars in Leipzig and Munich (Ansmann et al., 2010). Measured aerosol extinction values reached a maximum of 400 Mm^{-1} corresponding to 800 – 1000 $\mu g/m^3$ of volcanic ash at an altitude of approximately 3.5 km. Later during the first explosive phase, the volcanic aerosol was also observed at e.g. Jülich, Barcelona, Potenza, but the extinction values were much lower. Altogether, the EARLINET measurements at different locations in Europe give an overall picture of the development of the volcanic ash plume during April and May 2010, of its vertical extent and of the occurrence of ice clouds induced by volcanic ash particles (Pappalardo et al., 2010).

5. Volcanic ash dispersion modelling

Worldwide, nine VAACs (**Fig. 3**) are responsible for advising international aviation of the location and movement of volcanic ash clouds in the atmosphere. VAACs rely on information of local volcanological agencies, pilot reports, satellite observations and dispersion models to forecast the volcanic ash cloud distribution and issue regular volcanic ash advisories that define the areas predicted as contaminated. The London VAAC, responsible for the Icelandic volcanoes, uses the UK Met Office’s Lagrangian Numerical Atmospheric-dispersion Modelling Environment (NAME) model (Ryall and Maryon, 1998; Jones et al., 2007).

Adjacent Montreal and Toulouse VAACs use the Lagrangian MLDP0 (D'Amours et al., 2010) and the Eulerian MOCAGE (Peuch et al., 1999) models, respectively. Witham et al. (2007) provide an overview of the Lagrangian and Eulerian dispersion models used by the individual VAACs for atmospheric volcanic ash forecast. At the beginning of the Eyjafjallajökull eruption, these VAACs followed the standard procedure of assuming nominal ash emission rates because this was sufficient to discriminate between zones with and without ash contamination as required by the official ICAO guidance of the zero-ash tolerance criteria. However, the set-up of models had to be modified on-the-fly when ash concentration threshold criteria were introduced by the U.K. Civil Aviation Authority (CAA) in early May 2010.

Contemporaneously, various other dispersion models have been applied during the eruption of Eyjafjallajökull to contribute to the forecast of volcanic ash in the atmosphere or to reconstruct ash distributions and estimate mass concentrations. Among these are the models EURAD (Ackermann et al., 1998), FALL3D (Costa et al., 2006, Folch et al., 2009), Flexpart (Stohl et al., 1998), REMOTE (Langmann et al., 2008) and CMAQ (Byun and Ching, 1999, Matthias, 2008). Flexpart is a Lagrangian model that is particularly suitable for transport simulations of gases or particles emitted from a single source. EURAD, FALL3D, REMOTE and CMAQ follow the Eulerian approach but with different horizontal and vertical resolutions and deposition mechanisms. Except FALL3D and the models used by the VAACs, which have been specifically designed for volcanic ash modelling, the other models are usually used for photochemistry and aerosol modelling and therefore do not handle particles larger than about 100 μm in diameter nor do they consider ash aggregation processes.

All these models differ concerning the definition of the source term (eruption rate, column height, vertical distribution of mass), particle size distribution and particle properties (mainly density), atmospheric removal processes (wet and dry deposition, sedimentation velocities, aggregation processes) and meteorological data, typically provided by different numerical weather prediction models. The release rate of fine ash needs to be determined as accurate as possible to realistically simulate the dispersion and concentration of volcanic ash in the atmosphere. As many related quantities are not well constrained, especially in the first hours of an eruption when only few observations are available, preliminary model simulations do typically rely on look-up data tables (e.g. Mastin et al., 2009b). During the Eyjafjallajökull eruption, some modellers adjusted the source strength and variability through a backward estimate by comparing model results with available atmospheric measurements, e.g. from sun photometers (see section 4).

Generally, the different modelling groups confirmed the VAAC forecast of the location and extent of the ash cloud, whereas the modelled mass concentrations and volcanic ash size distributions remain to be evaluated.

6. Summary of the special issue

The special issue includes in-situ and ground based remote sensing measurements of volcanic ash at several locations all over Europe providing information on concentration levels and characterising volcanic ash properties. Complementary, numerical model studies on the atmospheric dispersion of volcanic ash over Europe give an integrated picture on the spatial distribution of volcanic ash. As model predictions were repeatedly criticised during the closures of European airports, the quality of the model results is thoroughly evaluated as well as the uncertainties resulting from the amount of fine volcanic ash released during the eruption. This volcanological issue is also addressed in this special issue. As volcanic ash is largely composed of siliceous material with melting temperature below typical operating temperatures of jet engines, the impact on aircraft operations is addressed as well. Finally, implications for the future are considered, as volcanic activity on Iceland is not at all unusual and can affect Europe when north to north-west wind directions prevail as during the eruption of Eyjafjallajökull in spring 2010.

7. Outlook

To be better prepared for future events of volcanic ash impacts, the shortcomings during the volcanic eruption of Eyjafjallajökull should not only be recognised but should also be improved. An important step in spring 2010 was the suggestion of a volcanic ash concentration threshold of 2 mg m^{-3}, above which flights would not be permitted. Although this value is debatable, it presents a reference value to evaluate the atmospheric volcanic ash burden. Observations from automated or constantly operated systems like satellites, lidars or sun photometers should be made available as quickly as possible, to gain near real-time measurements of volcanic ash mass and particle number concentrations and particle diameters. Appropriate data analysis algorithms need to improved and developed. Even though observation of the time dependency of some source parameters e.g. plume height, onset and cessation of the eruption have been reported in real-time during the eruption of

Eyjafjallajökull, it is in particular important to achieve a robust real-time characterisation of the volcanic source. Reliable measurement techniques need be deployed and developed to more precisely monitor plume height and to supply information of the total mass eruption rate and grain size distribution - also for $PM_{2.5}$ and even smaller particles. Measurement and modelling activities should be combined through optimised strategies to offer real-time evaluation of modelling results, improve model forecasts of the volcanic ash cloud location and mass concentration for aircraft safety but also for optimised observation planning. In principle, models could use as well an effective source term virtually located downwind from the volcanic vent with the initial ash distribution derived from e.g. remote sensing measurements, however, such a model initialisation approach need to be evaluated carefully. Numerical models should be further developed and evaluated to better determine volcanic ash mass and particle number concentration in the atmosphere. Among urgent developments needed are suitable numerical algorithms for volcanic ash particle aggregation processes involving the ice phase and for wet deposition processes, where in particular the choice of appropriate scavenging coefficients needs to be clarified. In this context it should be mentioned that during the eruption of Eyjafjallajökull observations on removal fluxes of volcanic ash particle mass and number concentrations as well as their associated particle diameters after long range transport over Europe are sparse. Even though these removal fluxes can be expected to be rather small over Europe they offer another experimental dataset on volcanic ash dispersion as volcanic ash particles can easily be separated from other aerosol particles and thus deposition fluxes can be quantitatively determined. With the information of deposition fluxes after long-range transport in addition to mass and particle number concentration and particle diameter during atmospheric dispersion and at the source, closure studies are possible for the evaluation of the individual variables. Altogether, an interdisciplinary effort will be necessary to better predict the possible impacts of volcanic ash over Europe. However, there is no need to wait for the next volcanic ash cloud over Europe because yearly about 60 volcanic eruptions occur worldwide so that measurement techniques and numerical model algorithms can be permanently tested and improved.

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Table 1: Major types of magma

Magma Type	SiO_2 [wt%]	T_{melt} [°C]	Viscosity and gas content
Basaltic	45-55	1000-1200	Low
Andesitic	55-65	800-1000	Intermediate
Rhyolitic	65-75	650-1000	High

Table 2: Tephra in different size classes

	Diameter [mm]	ϕ
Bomb, Block	> 64	< -6
Lapilli	< 64	> -6
Coarse Ash	< 2	> -1
Fine Ash	< 0.063	> +5

Figure captions

Fig. 1: Photos of the Eyjafjallajökull eruption taken by Martin Hensch.

a) Ash plume and cloud on April 17th 2010. The picture is taken from the western slope of Katla volcano, approximately 20 km east of the Eyjafjallajökull summit crater. At that time, the ash was ejected in explosive pulses every 0.5-1 min. While smaller particles form an ash cloud drifting away in a more or less stable height, coarser particles are dispersed like a curtain below the cloud. Close to the summit crater, base surges, i.e. turbulent, low-density clouds of rock debris and potentially water or steam, were observed moving over the ground surface.

b) Ash plume and cloud seen from approx. 30 km SW of Eyjafjallajökull during an observation flight on May 19th.The plume height at that time was 5-7 km, where the plume obviously hits a stable layer in the atmosphere: The ash cloud drifts away in long spatially stable waves which were not formed by the eruption pulses, but rather by alternating around an atmospheric boundary.

c) Accretionary lapilly, i.e. rounded balls of tephra and partly ice formed in the eruption plume or cloud, of a diameter of 2-6 mm was dispersed from the ash cloud. The picture is taken on April 22nd, close to the initial eruption site at Fimmvörðuháls, approximately 12 km away from the summit crater.

d) Ash profiles were digged into the Eyjafjallajökull glacier to chronologically sample the ejected material. Occasional snowfall and varying wind directions changing the direction of the ash cloud caused a good separation of the different layers. The photo is taken on April 23rd approximately 1 km west of the Fimmvörðuháls eruption site and 10 km east of the summit crater. The lower thin black layer consists of coarse ash and lapilli from the Fimmvörðuháls eruption in March and April. Both thick layers above are deposits from first week of the summit eruption: The middle layer was formed in the initial phase until April 17th, when the ash cloud moved to the south, the upper layer around April 20th when the ash was again blown eastwards. Different types of deposits are well seen by the colour contrast within the layers.

Fig. 2: Reported plume heights during the Eyjafjallajökull eruptions and resulting tephra flux according to the Eq. 2.

Fig. 3: Area of responsibility of the nine VAAC’s.