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Norsk institutt for luftforskning
Norwegian Institute for Air Research

Measurement of volcanic ash in Norwegian air space

WP 1.4.4 Reduced uncertainty in satellite-based estimates of ash concentrations

Arve Kylling

Scientific report

WP 1.4.4: Reduced uncertainty in satellite-based estimates of ash concentrations

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1 Introduction

Satellite-based measurements give the total amount of volcanic ash per area, typically in units of grams of volcanic ash per square meter (g/m^2). To convert this to concentration (mg/m^3) the vertical thickness of the ash cloud is needed. Often a cloud thickness of 1 km is assumed based on historical data. If the true cloud thickness is less, the real concentration will be larger and vice versa.

The ash cloud thickness is not available from passive remote sensors, e.g. IR-sensors, but may be obtained from ground- and space-based lidars. Dispersion models will also provide information of the ash cloud thickness.

This report gives an overview of volcanic ash cloud thickness as observed by space, aircraft and ground-based lidars. Also, ash cloud thickness as simulated by the Flexpart particle dispersion model is analysed. The impact of varying cloud thickness on the signal measured by IR-sensor in space is investigated. It is chosen to focus on the Eyjafjallajökull 2010 eruption due the wealth of data that are available for that eruption.

2 Observations of ash cloud thickness

The thickness of the ash cloud may be observed from ground, aircraft and satellite-based lidar instruments. During the Eyjafjallajökull eruption all three platforms were utilized.

2.1 Ground-based lidar measurements

In Europe 27 stations with aerosol lidar are organised within the European Aerosol Research Lidar NETwork (EARLINET, `www.earlinet.org`). Throughout the Eyjafjallajökull 2010 eruption EARLINET stations made measurements of the ash cloud. Numerous publications have come from individual stations. A summary with contributions from all stations was provided by Pappalardo et al. (2013). They report altitudes were ash was identified, but do not provide mass concentrations as these are not available from lidar measurements alone.

By combining lidar measurements with other information, e.g. photometer measurements, the ash mass concentrations may be derived. Photometer measurements are made worldwide by the Aerosol Robotic Network (AERONET, `http://aeronet.gsfc.nasa.gov/`, Holben et al. (1998)). Aerosol mass concentration profiles from lidar-photometer measurements for the Eyjafjallajökull eruption have been presented by Ansmann et al. (2010); Gasteiger et al. (2011) and Ansmann et al. (2011). Ash cloud thicknesses of about 0.7 km (Munich, 17 April, 2010), 3 km (Hamburg, 16 April, 2010), 0.5 km (Leipzig, 19 April, 2010) and 2 km (Cabauw, 17 May, 2010), were reported where thickness is defined as altitudes with concentration larger than 0.2 mg/m^3.

Ceilometers are simple automated lidars for measurements of cloud base. They may also be used for aerosol/volcanic ash profiling. A large number of ceilometers are present throughout Europe, see `http://www.dwd.de/ceilomap` and the report for Work Package 1.1, Evaluation of measurement techniques by A. Durant. Ceilometer measurements have been reported for the Eyjafjallajökull eruption by e.g. Flentje et al. (2010) and Wiegner et al. (2012). The ash cloud vertical thickness is similar to those reported above for the relevant EARLINET stations. For example Wiegner et al. (2012) compared ceilometer and a multi-wavelength lidar system for an episode over the Munich area 16-17 April, 2010, and found good agreement between the two instruments. However, generally ceilometers have a smaller signal-to-noise ratio preventing the detection of thin ash layers. Also, separation between dangerous ash and usual continental aerosol neccessitates multi-wavelength Raman information and depolarization. It is noted that careful calibration of the new generation of ceilometers combined with appropriate data analysis allows automated retrieval of aerosol optical depth Wiegner and Geiß (2012).

2.2 Aircraft lidar measurements

Aircraft lidar measurements of the Eyjafjallajökull ash cloud have been presented by Marenco et al. (2011), Schumann et al. (2011) and Chazette et al. (2012). Vertical profiles of ash concentration are provided by Marenco et al. (2011, Fig. 3) based on an elastic backscattering lidar operating at 355 nm. The vertical resolution of the final data are about 45 m with a 7-11 km footprint due to movement of the aircraft. The observation were carried out over Scotland, North and Irish Sea, Orkney and Faeroe Islands and N. England. From their Fig. 3 the ash cloud thickness may be deduced. For situations with low concentrations of ash the vertical thickness was typically around 0.5-1.0 km. For higher concentrations the ash cloud thickness was about 2-2.5 km. See also Fig. 13 of Johnson et al. (2012) which shows ash layer vertical thickness between 500 m and 2 km. It is noted that Marenco et al. (2011) defined the layer thickness as $\sqrt{2}\times$(column load)/(peak concentration). For radiative transfer simulations they found that a uniform layer with a concentration equal to the peak concentration divided by $\sqrt{2}$ and thickness as defined above, works well.

Chazette et al. (2012) presented aerosol extinction coefficient profiles for a case off La Coruna, Spain (12 May) and above UK (16 May). Ash cloud vertical thickness between 1 (filament) and 3 km (plume) was measured. They note that "the ubiquitos cloud cover during the flights makes it difficult to identify ash plumes from space".

2.3 Space-based lidar measurements, CALIOP

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP, `http://www-calipso.larc.nasa.gov/`) is the only lidar in space. In its low-Earth orbit (LEO) it provides vertically resolved profile measurement with a resolution between 30-60 m. While giving excellent vertical resolution, the small footprint, 100 m, of CALIOP gives a revisit time of 16 days.

For the Eyjafjallajökull eruption Winker et al. (2012) presented CALIOP observations for April 2010. However, the CALIOP profiles for April mostly missed the denser parts of the ash cloud. The thinner parts that were observed had average vertical extent ranging from 0.44 to 1 km. Stohl et al. (2011) among others, have compared CALIOP detected ash clouds with dispersion model results. The vertical ash cloud thickness from this study is described below, section 3.

In their Fig. 3, Wiegner et al. (2012) compared the multi-wavelength lidar system (MULIS, EARLINET), a ceilometer, and CALIOP for 17 April, 2010 above Munich, Germany, and found good agreement of vertical location of the ash cloud.

3 Ash cloud thickness from particle dispersion models

An ash dispersion model will give the concentration of ash as a function of particle size, location (x,y,z) and time. Thus, it is possible to calculate the ash cloud thickness from the dispersion model ash concentration. The Numerical Atmospheric-dispersionModeling Environment (NAME) model is used by the London VAAC for predicting volcanic ash (see Webster et al. (2012) and references therein). Stohl et al. (2011) have calculated the ash concentration during the Eyjafjallajökull 2010 eruption using the Flexpart Langrangian particle disperion model (Stohl et al., 2005).

Stohl et al. (2011) presented vertical cross-sections of flexpart ash concentrations and CALIOP total attenuated backscatter for several cases during the Eyjafjallajökull eruption. Kristiansen et al. (2012) compared Flexpart and NAME model results with measurements from the United Kingdom's Facility for Airborne Atmospheric Measurements (FAAM, `http://www.faam.ac.uk`) and the Falcon research aircraft of the Deutsches Zentrum für Luft- und Raumfahrt (Schumann et al., 2011). The comparison between Flexpart (mass concentrations) and CALIOP (total attenuated backscatter) gives qualitative evidence for the ability of the transport model to place the ash cloud in the correct location at a given time. However, no quantitative comparison for the vertical mass concentration is possible. In their Figs. 4, 8 and 12 Kristiansen et al. (2012) compares mass concentrations from the NAME and Flexpart models with FAAM lidar estimates. In general there is good agreement between the models and the measurements. However, the vertical resolution of the input data to the dispersion model will impact the ability of the dispersion model to resolve thin ash layers (compare ECMWF versus GFS input data, Fig. 8 Kristiansen et al. (2012)).

Hervo et al. (2012) compared lidar measurements from Puy de Dôme, France, with Flexpart simulations for two cases, 18 and 19 May 2010 and 18, 19 and 22 April 2010. The measured ash cloud thickness was about 500 m for the first case with Flexpart giving a thickness of about 1 km (Hervo et al., 2012, Fig. 1). For the second case multi-layered ash clouds were present and partially mixed with the planetary boundary layer, making an estimate of the ash cloud thickness difficult.

Having confidence in the dispersion model results, the vertical thickness of the ash cloud during the complete Eyjafjallajökull 2010 eruption is investigated using Flexpart a posteriori results with ECMWF input data (Stohl et al., 2011). Flexpart simulated ash concentrations are available every hour with a vertical resolution of 250 m. Here, six hourly[1] ash concentration fields starting 0600 on 4 April and ending at 1800 17 May, giving a total of 135 ash concentration fields, are used to estimate the ash cloud thickness. The top (bottom) of the ash cloud was taken to be the highest (lowest) voxel with ash concentration larger than 0.2 mg/m^3. The ash cloud thickness was calculated as the difference between the top and bottom altitudes. Voxels void of ash between the top and bottom altitudes were allowed.

The Flexpart ash cloud thickness is shown in Fig. 1 as a function of distance from the vent and time. The vertical thickness is seen to generally decrease with the distance from the vent. But for the first phase of the eruption, the ash cloud was rather thick (about 10 km) up to 1000-1500 km away from the vent. For both the first and second phases the ash cloud extended vertically by over 5 km for distances up to about 2000 km. Beyond 2500 km the vertical thickness is generally less then 1-2 km.

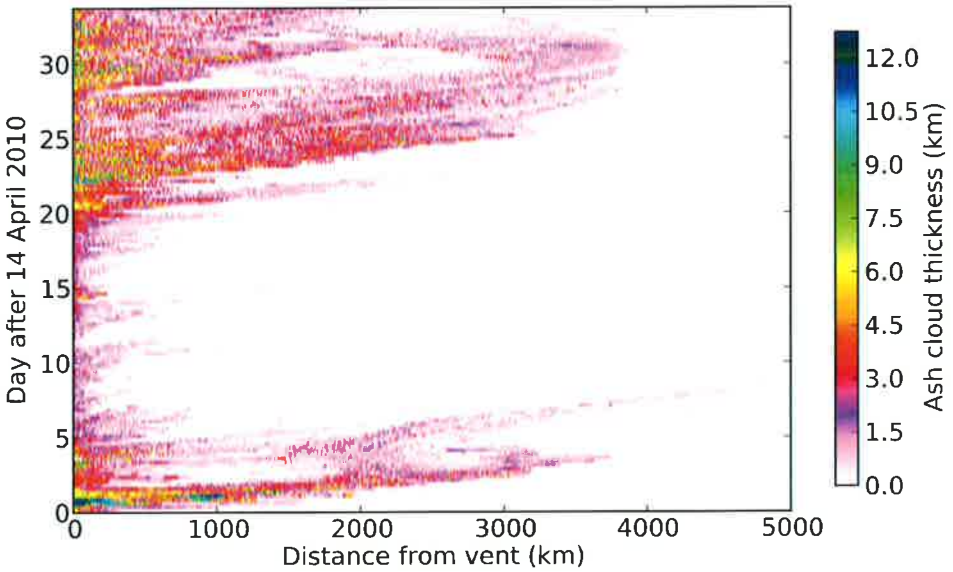

Figure 1: The vertical thickness of the ash cloud as simulated by Flexpart as a function of distance from the vent and time.

The vertical extent of the Eyjafjallajökull ash cloud simulated by Flexpart has been compared with surface and satellite mounted lidars in several investigations. Stohl et al. (2011) compared Flexpart simulations with CALIOP observations and found that the Flexpart largely reproduced the measured ash layers. For example, on 12 May at 0400 UTC CALIOP captured a dense part of the ash cloud (Stohl et al., 2011, Fig. A4). At around 50°N south of Iceland the ash cloud had a thickness of about 4-5 km. The thickness simulated by Flexpart was similar.

The vertical thickness of the ash cloud is plotted against the logarithm mass loading in Fig. 2. There appears to be a weak correspondence between the logarithm of the mass loading and the ash cloud thickness.

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[1] Flexpart output is available every hour. For other reports in the project information about water and ice clouds from ECMWF are utilizied. Water and ice cloud information is available every six hours from ECMWF. To keep the data sets in the various reports the same, a time step of six hours is used. Flexpart data are not averaged in time, rather the ash field for every six hour is used.

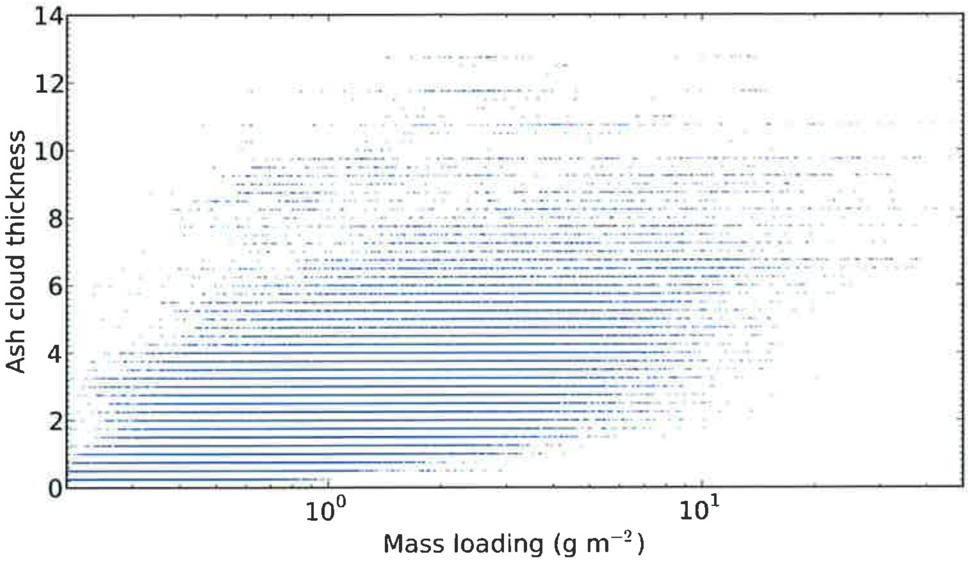


Figure 2: Scatter plot of the vertical thickness of the ash cloud as simulated by Flexpart versus the mass loading. Note logarithmic scale on the x-axis. Also note that due to the large number of points, the points merge into horizontal lines for some thinknesses. The vertical stratification is due to the vertical sampling for this Flexpart simulation (250 m).

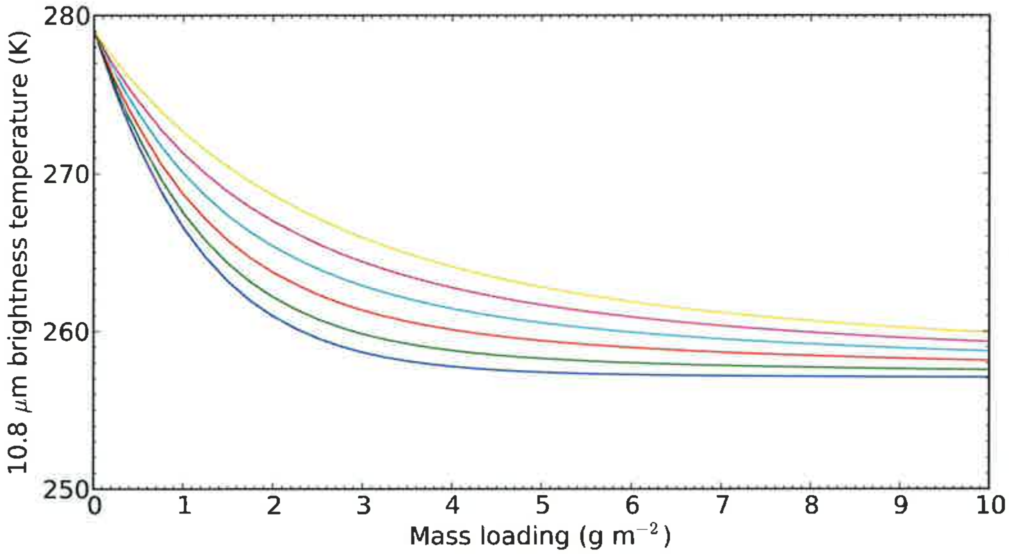
4 The effect of ash cloud thickness.

To investigate the impact of ash cloud thickness on the brightness temperature measured by e.g. SEVIRI, radiative transfer simulations for the 10.8 and 12.0 μm SEVIRI channels were performed. The uvspec radiative transfer model from the libRadtran software package (Mayer and Kylling, 2005) was used together with Mie calculations of the ash particle optical properties. The ash cloud was assumed to be vertically homogeneous with top heights at 5 and 10 km. The ash cloud thickness was set to 0.25, 1, 2, 3, 4, and 5 km. For simplicity monodispersed ash particles with radius of 2 μm were used. The temperature profile was taken from the sub-arctic summer atmosphere of Anderson et al. (1986). The surface temperture was set to 280 K.

In Fig. 3 the 10.8 μm brightness temperature is shown as a function of ash mass loading for an ash cloud with top at 5 km (upper row) and 10 km (lower row). For a mass loading of 2 g/m^2 the brightness temperature increases by about 8 K when the ash cloud thickness increases from 0.25 to 5 km. With the ash cloud top fixed, the ash particles are distributed to lower and warmer layers of the atmosphere when the thickness increases. Thus, the brightness temperature increases as the cloud thickness increases.

The brightness temperature may be used to estimate the mass loading (Wen and Rose, 1994; Prata and Prata, 2012) for a given brightness temperature difference. The green curve represents the "standard" ash cloud thickness of 1 km used in most retrievals. Given a brightness temperature of 265 K and a cloud top height of 5 km, the mass loading is 1.2, 1.4, or 1.6 g/m^2 depending if the vertical thickness of the cloud is 2, 1 or 0.5 km respectively. The sensitivity of the brightness temperature to ash cloud thickness changes with the mass loading and has a maximum around a mass loading of 2.6 g/m^2 (2.2) for a cloud top at 5 km (10). The behaviour is similar for the cloud top at 10 km.

The 10.8-12.0 μm brightness temperature difference is shown as a function of ash mass loading for an ash cloud with top at 5 km (upper row) and 10 km (lower row) in Fig. 4. The sensitivity of the brightness temperature difference to ash cloud thickness also depends on the mass loading as is evident from Fig. 4. The brightness temperature difference is used to detect ash clouds. Vertically shallow clouds have a larger negative brightness



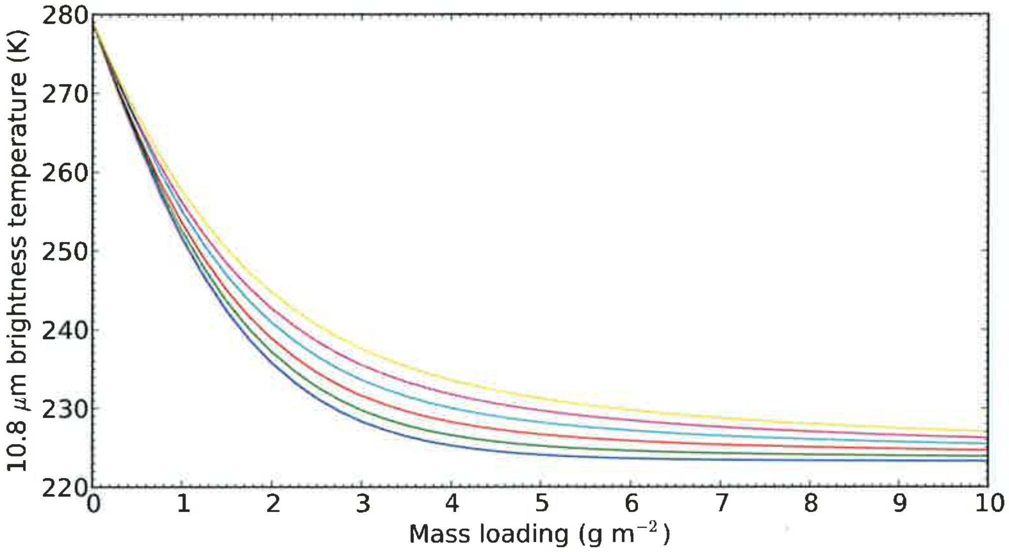


Figure 3: The 10.8 μm brightness temperature as a function of ash mass loading for an ash cloud with top at 5 km (upper row) and 10 km (lower row). The blue curve is for an ash cloud thickness of 0.25 km, green: 1.0, red: 2.0, cyan: 3.0, purple: 4.0 and yellow: 5.0 km. Note different scale on y-axis in upper and lower rows.

temperature difference than thicker clouds for ash mass loadings less then about 3.5 g/m^2 (4.5) for an ash cloud with top at 5 km (10.0). For larger ash mass loading the behaviour is opposite. It is noted that the sensitivity may change if the simplification of monodispersed particles is lifted.

Corradini et al. (2008) found that decreasing the ash cloud thickness from 1 to 0.5 km gave an uncertainty of about 10% in the retrieved total mass for a MODIS scene of ash from Mt. Etna, Sicily, Italy. Their ash cloud top was at 5 km.

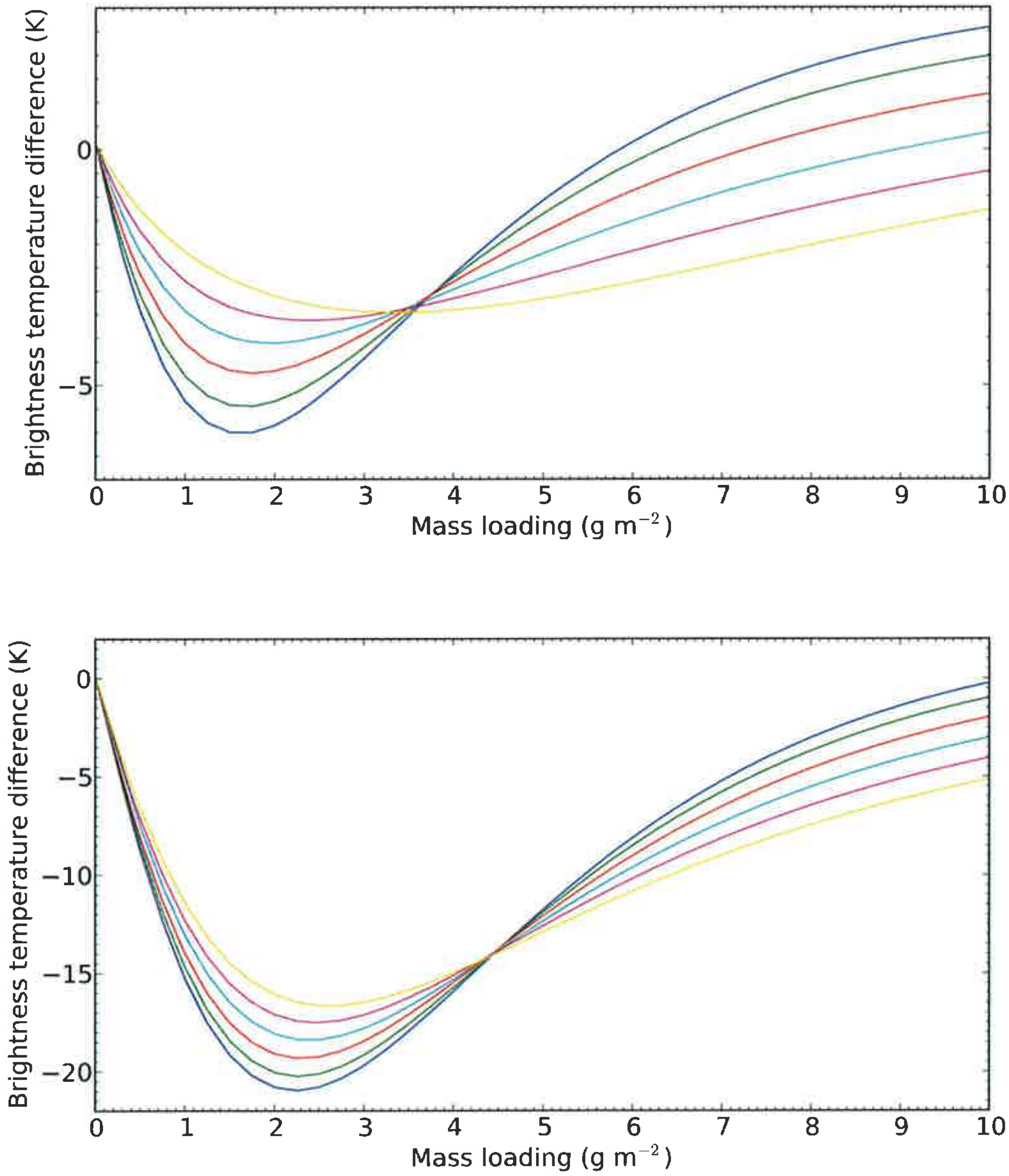


Figure 4: The brightness temperature difference (10.8-12.0 μm) as a function of ash mass loading for an ash cloud with top at 5 km (upper row) and 10 km (lower row). The blue curve is for an ash cloud thickness of 0.25 km, green: 1.0, red: 2.0, cyan: 3.0, purple: 4.0 and yellow: 5.0 km. Note different scale on y-axis in upper and lower rows.

5 Conclusions

Lidar provides the optimal tool for vertical profiling of ash mass concentrations together with appropriate ancillary instrumentation. During the Eyjafjallajökull 2010 eruption the ash cloud vertical extent varied between 0.25 to 10 km depending on location and time. The dependence of vertical extent on ash mass loading appears to be weak.

Lack of knowledge about the vertical extent of the ash cloud gives uncertainties in the retrieved ash mass concentration. In an operational setting the present approach of using a fixed vertical thickness for all ash situations is sensible. The uncertainty in the retrieved mass loading should, however, include the uncertainty due to the lack of knowledge about the vertical distribution of the ash cloud.

For the future one might envisage a system where retrievals are performed in an iterative fashion. The first iteration used standard 1 km ash clouds. These ash cloud mass loadings are the input to Flexpart inversion modelling. The ash cloud from the a posteriori Flexpart run is next used to provide ash profile input to an improved and extended ash retrieval algorithm that may account for the vertical ash cloud thickness. See also report for WP 1.4.3.

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ABSTRACT
Satellite-based measurements of volcanic ash give the total amount of volcanic ash per area, typically in units of grams of volcanic ash per square meter. To convert this to concentration the vertical thickness of the ash cloud is needed.
The ash cloud thickness is not available from passive remote sensors, e.g. IR-sensors, but may be obtained from ground- and space-based lidars. Dispersion models will also provide information of the ash cloud thickness.
This report gives an overview of volcanic ash cloud thickness as observed by space, aircraft and ground-based lidars. Also, ash cloud thickness as simulated by the Flexpart particle dispersion model is analysed. The impact of varying cloud thickness on the signal measured by IR-sensor in space is investigated. Focus is on the Eyjafjallajokull 2010 eruption for which a unique wealth of data are available.

NORWEGIAN TITLE
Målinger av vulkanaske i norsk luftrom. WP 1.1.4 Redusert usikkerhet i satellittbasert bestemmelse av askekonsentrasjoner

KEYWORDS

Volcanic ash	Remote sensing	Radiative transfer

ABSTRACT (in Norwegian)
Satellittmålinger av vulkansk aske gir mengde aske per flateareal, typisk i gram per kvadratmeter. For å konvertere askemengde per areal til konsentrasjon kreves kjennskap til askeskyenes vertikale utstrekning.
Askeskyers vertikale utstrekning er ikke tilgjengelig fra passive måleinstrument, f.eks. IR-sensorer. Den kan måles med lidar enten fra bakke, fly eller satellitt. Partikkeldispersjonsmodeller kan også gi innsikt i askeskyer vertikale tykkelse.
Rapporten gir en oversikt over vulkanske askeskyers vertikale utbredelse observert fra satellitt-, fly- og bakkebaserte lidarer. Askeskyer simulert med dispersjonsmodellen Flexpart er også analysert. Betydningen av askeskyers vertikale utbredelse på IR-stråling målt av satellitt er undersøkt. Fokus er på utbruddet av Eyjafjallajökull 2010 pga. den unike mengden med data som er tilgjengelig for dette utbruddet.

** Classification*	*A*	*Unclassified (can be ordered from NILU)*
	B	*Restricted distribution*
	C	*Classified (not to be distributed)*

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