Volcanic ash layers over Europe - Airborne observations with the DLR-Falcon research aircraft in April/May 2010


+ many more partners (IPA, FB, CNRS/LaMP, TU Darmstadt, IfT Leipzig, LMU München, NILU, Uni. Iceland, DWD, VAAC, DFS, LBA, KNMI, etc.)
Eyjafjallajökull .... pronounced ['ɛɪ ɛɪ ɛɪ ɛɪ ja,fjatlɄa,jœkylɄ]

Eruption occurred (below ice) on early morning of 14 April 2010

- April 2009: first seismic activities
- February - March 2010: large number of earth quakes
- 20 March 2010: first eruption, 4 – 7 km altitude
- 14 – 18 April: volcanic ash clouds reach up to 8 km heigth, flooding, ash layers
- 18 April – 1 May: Weaker eruptionen, 3 - 5 km.
- 6 - 21 May 2010 new strong eruption, up to 9 km altitude.

Distribution of ash
(composite map of first 10 days)

http://en.wikipedia.org/wiki/Air_travel_disruption_after_the_2010_Eyjafjallajökull_eruption
Hazards for aviation

1) **Sand-blast effect**: cockpit windows, wing aerodynamic, large particles only.

2) **Jet engines**, documented from 300 up to 1000 distance from source:
   - Silicate melts already at < 1000 °C,
   - Erosion at engine fans,
   - Closure of ventilation holes (overheating),
   - Lack of oxygen in the engine (blow out).

3) **Sensor**: altimeter and airspeed indicator can get clogged.

   **Problem**: real hazard depends on ash concentration, engine type, flight attitude, ...!

   **April 2010**: No threshold values for safe airtraffic available.
Lidar measurements performed by the Univ. of Munich

(LMU-MIM, at Munich-Maisach; **plume age: ~28 h**)

0-7 km altitude above sea level

The measurements shown start on April 16 (18 MESZ) and end on April 17 (24 MESZ).

(V. Freudenthaler, S. Groß, M. Wiegner, B. Mayer)
19 April, 13:00 UTC - Mid-European airspace closed

DLR-Falcon started at 14:11 UTC

http://www.radarvirtuel.com/

taken from BBC: Iceland volcano in maps
Objectives: Operational & scientific

- Closure of airspace justified or exaggerated?
- Quality of forecasts?
- Comparable to Saharan dust?
- Engine ash load thresholds?
- How to improve the ICAO-VAAC-DWD-DFS-BMVBS decision processes

- What do the lidar and satellite instruments see?
- Volcanic source (mass, particle sizes, chemistry)
- Particle numbers and sizes, and mass concentration
- Chemical plume composition
Falcon 20E D-CMET, DLR Oberpfaffenhofen (seit 1976)

- Aerosol & trace gas inlet:
  - Total & non-vol. aerosol, 3-λ B_{ap}, particle comp. & shape (4 nm - 2.5 µm)
  - CO (UV fluoresc.), O_{3} (UV photom.), SO_{2} (fluoresc.), H_{2}O (τ-point, Ly-α)

- Meteorological measurements:

- DLR Falcon 20-E5:
  - Max. altitude: 42,000 ft
  - Max. endurance: 4 h

- GPaC (particle collector): TU Darmstadt

- 2-µm-Wind-Lidar (heterodyne)

- FSSP-300 & 2-DC (0.3 - 800 µm)
  - DLR & LaMP

- PCASP-100X (dry accumulation mode concentration)
Weekend April 16-18, 2010: integration of the instruments
Map with flight tracks of all DLR Falcon flights

- April 19
- April 22 (a)
- April 22 (b)
- April 23
- April 29 (a)
- April 29 (b)
- May 1
- May 2
- May 3
- May 9
- May 13 (a)
- May 13 (b)
- May 16 (a)
- May 16 (b)
- May 17 (a)
- May 17 (b)
- May 18
April 19, 2010 - lidar results

Oliver Reitebuch, Stephan Rahm, Martin Wirth (DLR)

Vulcanic ash layer
Convective planetary boundary layer
Planetary boundary layer

Leipzig
Munich
Stuttgart
Cirrus Cloud
Hamburg
Cabauw
Vulcanic ash layer over Leipzig, April 19, 2010, 15:00 UTC
19 April 2010: vertical profile measurements over Leipzig

Leipzig lidar

DLR-Falcon, 14:50 - 15:30 UTC

coarse mode
(> ~3 µm)

accum. mode
(0.15-0.5 µm)

total CN (>10 nm)

non-volatile CN

100 µg/m³
(20-200)

(cpt Leipzig: A. Ansmann, M. Tesche, P. Seifert et al.)
Eyjafjallajökull volcano plume, 29 April, late afternoon time
Eyjafjallajökull volcano plume, May 1, noon time
Eyjafjallajökull volcano plume, May 1, noon time
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Eyjafjallajökull volcano plume, May 1, noon time
May 2, 15 UTC: North Atlantic, 450 km dist., 60 N, age 7 h

Outside plume (in-situ)

Within plume (in-situ)

1. overflight

70 km

8.2 km

Ash plume

range-corrected backscatter signal @ 2 μm

Plume of 1. overflight (50 minutes earlier)

View direction of plot from N=>S
Aerosol properties in top of volcanic plume

Condensation particles

Cloud & coarse particles

Date & time (UT)

Ambient concentration (particles/cm^3)

Flight altitude (km)

Cloud & coarse particles FSSP-300 results

Date & time (UT)

Ambient concentration (particles/cm^3)

Pressure altitude (km)
Mass concentrations in the plume over the North Atlantic

\[ \frac{dN}{d\log D_p} \quad \text{(cm}^{-3}) \]

\[ D_p \quad \text{(µm)} \]

\[ \chi = 1.36, \rho = 1 \text{ g/cm}^3 \]

\[ \chi = 1.36, \rho = 2.45 \text{ g/cm}^3 \]

May 2, 2010 - 60°N

PCASP-100X

- FSSP-300, \( m = 1.54 + 0.0i \)
- FSSP-300, \( m = 1.50 + 0.0008 i \)

\[ dN / d\log D \]

\[ p \] (cm\(^{-3}\))

\[ \text{particle diameter (µm)} \]

\[ \text{no signal in the 2-DC probe (} D_p > 30 \text{ µm)!} \]

\[ \text{distance settled within 7 h (km)} \]

\[ (273 \text{ K, 1013 hPa, no turbulence}) \]

\[ \text{no signal in the 2-DC probe (} D_p > 30 \text{ µm)!} \]

\[ \text{distance settled within 7 h (km)} \]

\[ \text{assuming a particle density of 3 g/cm}^3 \]

\[ m = 1.54 + 0i \]

PM2.5 30 µg/m³

FSSP-300 "total" 1200 µg/m³

\[ D_{\text{eff}} 7 \mu m \]

preliminary!

\[ m = 1.50 + 0.008i \]

PM2.5 30 µg/m³

FSSP-300 "total" 10000 µg/m³

\[ D_{\text{eff}} 26 \mu m \]

preliminary!
Comparison with Saharan dust (SAMUM-1, 2006, 17 flights)

Aerosol-optical depth (AOD, @532)

Munich
17.04. (plume age: 3 days): 0.8
19.04. (plume age: 5 days): 0.4

Leipzig
17.04. (plume age: 3 days): 1.0
19.04. (plume age: 5 days): 0.5

For comparison:
Sahara, SAMUM-1: 0.4 - 0.6
Further DLR Falcon flights

May 9: Southern Germany: < 10 µg/m³

May 13: English Channel: MSG detected thin ash cloud < 30 µg/m³, without VAAC warning

May 16: England and North Sea: thick volcanic ash plume
> 2000 µg/m³

May 17: North Sea VA 450 µg/m³, observed also by MSG and Lidar Cabauw
Conclusions (science & operations)

- 17 Falcon flights April 19 - May 18, 2010
- Satellite data, ground based Lidar, model predictions
- Many scientific results
- Particles diameters up to 30 µm (mainly silicate, ammonia sulfate, more Na, K than in Saharan dust)
- Mass loading: 100 µg/m³ Leipzig, >3000 µg/m³ North Atlantic, England
- One hour of flight in 450 µg/m³ without engine damage
- SO₂: 4 – 200 nmol/mol

- Mid-European airspace closure justified until Sat. April 17; then ageing of ash load
- Southern German airspace closure May 9 (6 days aged VA): questionable
- Closure over UK, May 16, 1-2 days aged plume: fully justified
- Keflavik/Iceland free of ash as predicted on April 19 - May 2
- Quality of forecasts reliable enough for aviation
- Fresh and heavy VA is well predictable, but >3 days aged VA: far more difficult
- Improved linking between operations and academia needed
- Continue operations of the DLR Falcon as Emergency Aircraft
Thank you for your interest!
## Summary of all flights

<table>
<thead>
<tr>
<th>Date</th>
<th>Flight ID</th>
<th>Take-off time (UTC)</th>
<th>Landing time (UTC)</th>
<th>Mission objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 April 2010</td>
<td>#100419a</td>
<td>14:12:02</td>
<td>17:54:50</td>
<td>Aged ash plume over Germany &amp; NL (air space in Europe largely closed)</td>
</tr>
<tr>
<td>22 April 2010</td>
<td>#100422a</td>
<td>14:14:14</td>
<td>15:35:09</td>
<td>Lidar survey over Germany</td>
</tr>
<tr>
<td></td>
<td>#100422b</td>
<td>17:12:55</td>
<td>20:29:30</td>
<td>Aged ash plume south of Norway (embedded in clouds)</td>
</tr>
<tr>
<td>23 April 2010</td>
<td>#100423a</td>
<td>11:45:56</td>
<td>14:57:46</td>
<td>Aged ash plume over Germany, Poland &amp; Baltic Sea</td>
</tr>
<tr>
<td>29 April 2010</td>
<td>#100429a</td>
<td>12:00:10</td>
<td>14:09:06</td>
<td>Ferry flight (to Edinburgh)</td>
</tr>
<tr>
<td></td>
<td>#100429b</td>
<td>15:39:59</td>
<td>18:28:50</td>
<td>Flight to Iceland with lidar survey of ash plume and in-situ profiling at Keflavik airport</td>
</tr>
<tr>
<td>1 May 2010</td>
<td>#100501a</td>
<td>10:50:29</td>
<td>14:05:03</td>
<td>Lidar survey of fresh ash plume near volcano and in-situ profiling at Keflavik airport</td>
</tr>
<tr>
<td>2 May 2010</td>
<td>#100502a</td>
<td>12:58:36</td>
<td>16:17:57</td>
<td>Return flight with in-situ measurement in the top of the fresh plume over the North Atlantic</td>
</tr>
<tr>
<td>3 May 2010</td>
<td>#100503a</td>
<td>11:04:40</td>
<td>13:31:27</td>
<td>Ferry flight to Oberpfaffenhofen</td>
</tr>
<tr>
<td>9 May 2010</td>
<td>#100509a</td>
<td>14:26:52</td>
<td>18:01:24</td>
<td>Aged ash plume over Germany (Munich airport &amp; air space closed for ~6 hours)</td>
</tr>
<tr>
<td>13 May 2010</td>
<td>#100513a</td>
<td>10:06:25</td>
<td>11:20:04</td>
<td>Ferry flight to Niederrhein</td>
</tr>
<tr>
<td></td>
<td>#100513b</td>
<td>12:44:26</td>
<td>15:49:47</td>
<td>Aged ash plume north of English Channel</td>
</tr>
<tr>
<td>16 May 2010</td>
<td>#100516a</td>
<td>09:11:17</td>
<td>11:07:31</td>
<td>Ferry flight to Newquay (UK)</td>
</tr>
<tr>
<td></td>
<td>#100516b</td>
<td>12:34:50</td>
<td>16:01:16</td>
<td>Aged ash plume over Irish Sea and northern England (UK air space partly closed)</td>
</tr>
<tr>
<td>17 May 2010</td>
<td>#100517a</td>
<td>10:38:47</td>
<td>13:29:50</td>
<td>Aged ash plumes over Germany, NL &amp; North Sea</td>
</tr>
<tr>
<td></td>
<td>#100517b</td>
<td>14:36:54</td>
<td>17:57:00</td>
<td>Aged dense ash plume over North Sea, extensive in situ measurement</td>
</tr>
<tr>
<td>18 May 2010</td>
<td>#100518a</td>
<td>07:25:32</td>
<td>10:34:56</td>
<td>Aged ash plume survey over Germany &amp; North Sea (German air space closure was under consideration)</td>
</tr>
</tbody>
</table>
The situation in April 2010

TERRA MODIS measurements on April 17, 2010

Source: NASA Earth Observatory
The $2 \times 10^{-3} \text{ g/m}^3$ is the expected ash concentration associated with the Met Office computer model level of $1 \times 10^{-16} \text{ g/m}^3$.

Similarly, $2 \times 10^{-4} \text{ g/m}^3$ equates to the model level of $1 \times 10^{-17} \text{ g/m}^3$.

The diagram illustrates:

- **2 mg/m$^3$**
- **200 µg/m$^3$**
- **2 x $10^{-3}$ g/m$^3$ Limit of OEM Tolerable Zone**
- **2 x $10^{-4}$ g/m$^3$**

**NO FLY ZONE**

**ENHANCED PROCEDURES ZONE (EPZ)**

**NORMAL OPERATIONS**

Padhraic Kelleher
Head of Airworthiness
UK Civil Aviation Authority, May 5, 2010
Saharan dust

Weinzierl et al., 2009, TELLUS
Modelled Ash Concentration from FL000 to FL200 at 1200 UTC 16/05/2010

Issue time: 201005160000

This is a guidance product generated from model data and is supplemental to the official VAAC London Volcanic Ash Advisory and Volcanic Ash Graphic products.

- Red: Predicted area where volcanic ash may be encountered
- Black: Predicted area of ash concentrations that exceed acceptable engine manufacturer tolerance levels

© Crown Copyright 2010. Source: Met Office
DLR-Falcon flight over Southern Germany, May 9, 2010

17:53 UTC: profile measurements at Munich airport and over Maisach lidar

mass loading below 10 µg/m³

<- Measurements performed by the Met. Institute of the LMU Munich
Coarse particles

Coarse particles

probably volcanic ash

clearly volcanic ash

probably volcanic ash mixed in the boundary layer
Volcanic ash mass concentrations from aircraft measurement?

- **mass concentration is what everyone wants, but it is not a direct measurement.** Estimate is (highly) uncertain at present for the following reasons:
  - total volume (mass) is entirely dominated by supermicron particles
  - this size range is only covered by the upper channels of the one instrument, the FSSP-300, in our case
  - FSSP-300 gives clear indication of presence of supermicron particles in the volcanic ash plume
  - different refractive index (e.g. with/without) absorption can change mass concentration by one order of magnitude!
  - density of volcanic ash is not known; values discussed in the community vary between 1 and 3 g/cm³
  - any aircraft aerosol in situ payload not capable of measuring up to some tens of µm particle size will not cover the relevant size range of volcanic ash and is unable to determine mass concentrations in ash