Volcanic cloud remote sensing products at the Met Office for Near Real-Time Applications - Present and Future Outlook

Peter Francis, Michael Cooke, Maria Athanassiadou,
Sarah Millington & Roger Saunders

Met Office, United Kingdom

© Crown copyright Met Office

Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

How do we use satellite products?

- Real time monitoring of volcanic plumes to inform VAAC forecasters, and hence improve VA guidance
  - Horizontal extent
  - Trajectory (ash height)
  - Radiative ash height estimate
  - Estimate of column mass loading
- Constraining the initialisation of dispersion model runs:
  - To aid specification of source term
  - As part of data inversion process
- Use satellite datasets for post-event validation of the model predictions (together with other observations)

© Crown copyright Met Office

The London Volcanic Ash Advisory Centre (VAAC)

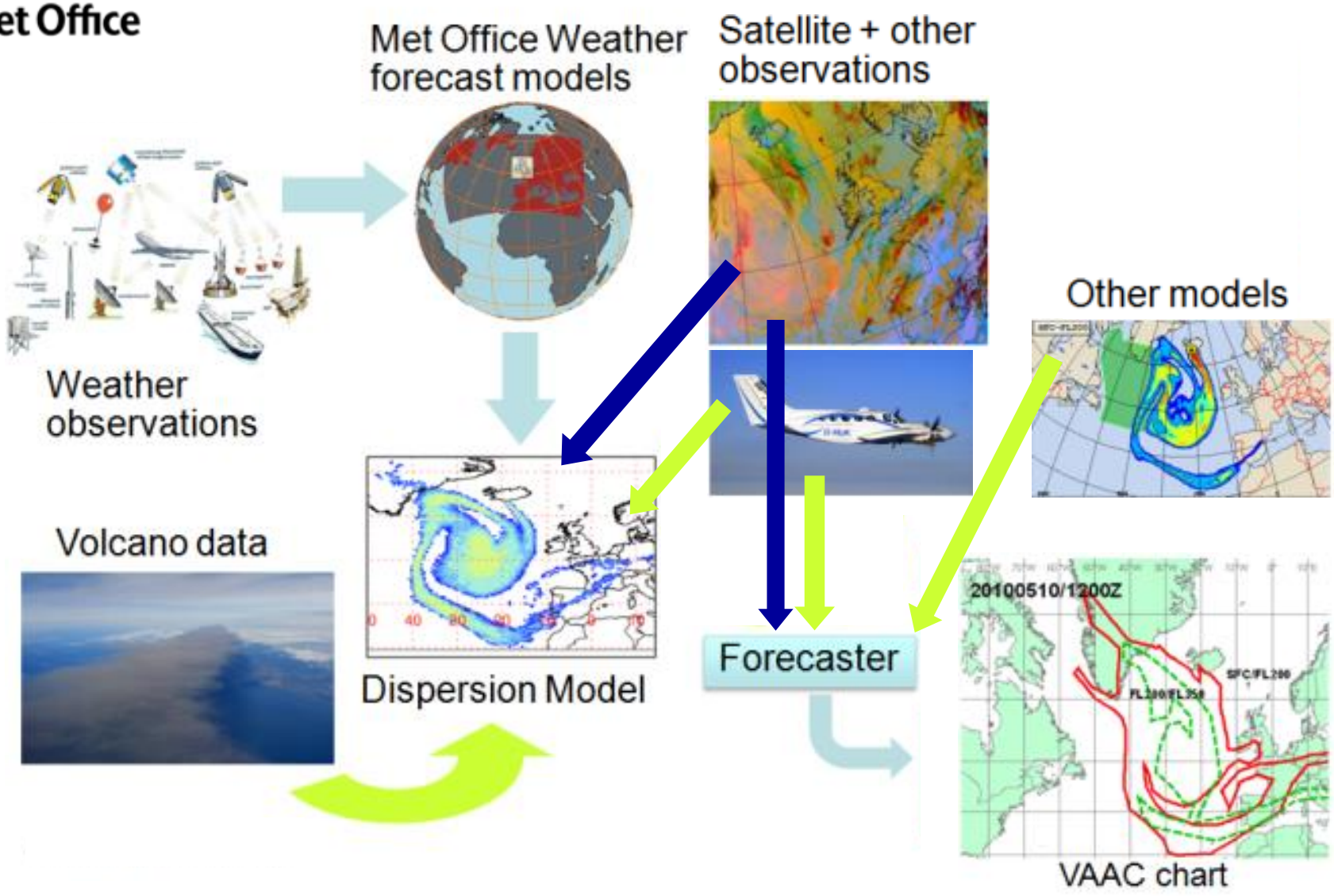
- An International Civil Aviation Organization (ICAO) designated centre
- Responsible for issuing advisories for volcanic eruptions originating in Iceland and the north-eastern corner of the North Atlantic
- Hosted and run by the Met Office from its Exeter UK headquarters
- Specialist forecasters who produce volcanic ash advisories and guidance products using a combination of:

- satellite-based, ground-based and aircraft observations
- weather forecast models and dispersion models

- One of 9 VAACs worldwide, London VAAC provides a reciprocal back-up facility with Toulouse VAAC, operated by Meteo-France.

© Crown copyright Met Office

The VAAC process



© Crown copyright Met Office

How do we use satellite products?

- Real time monitoring of volcanic plumes to inform VAAC forecasters, and hence improve VA guidance
  - Horizontal extent
  - Trajectory (ash height)
  - Radiative ash height estimate
  - Estimate of column mass loading
- Constraining the initialisation of dispersion model runs:
  - To aid specification of source term
  - As part of data inversion process
- Use satellite datasets for post-event validation of the model predictions (together with other observations)

© Crown copyright Met Office

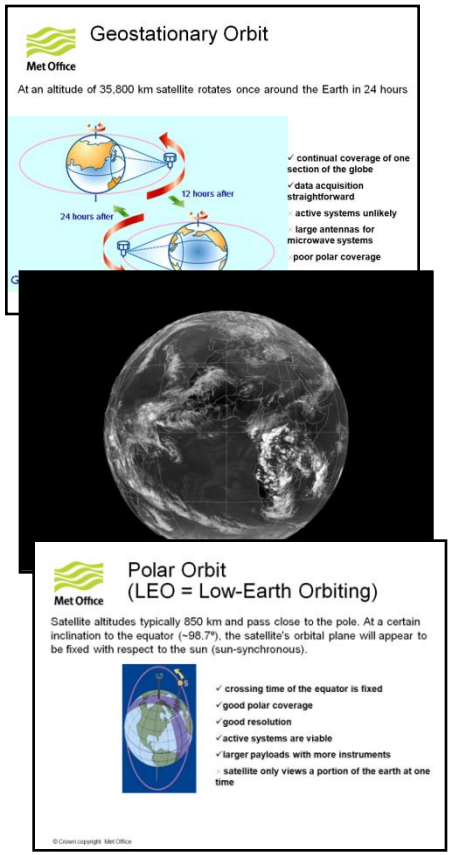
Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

Which satellites/instruments do we use?

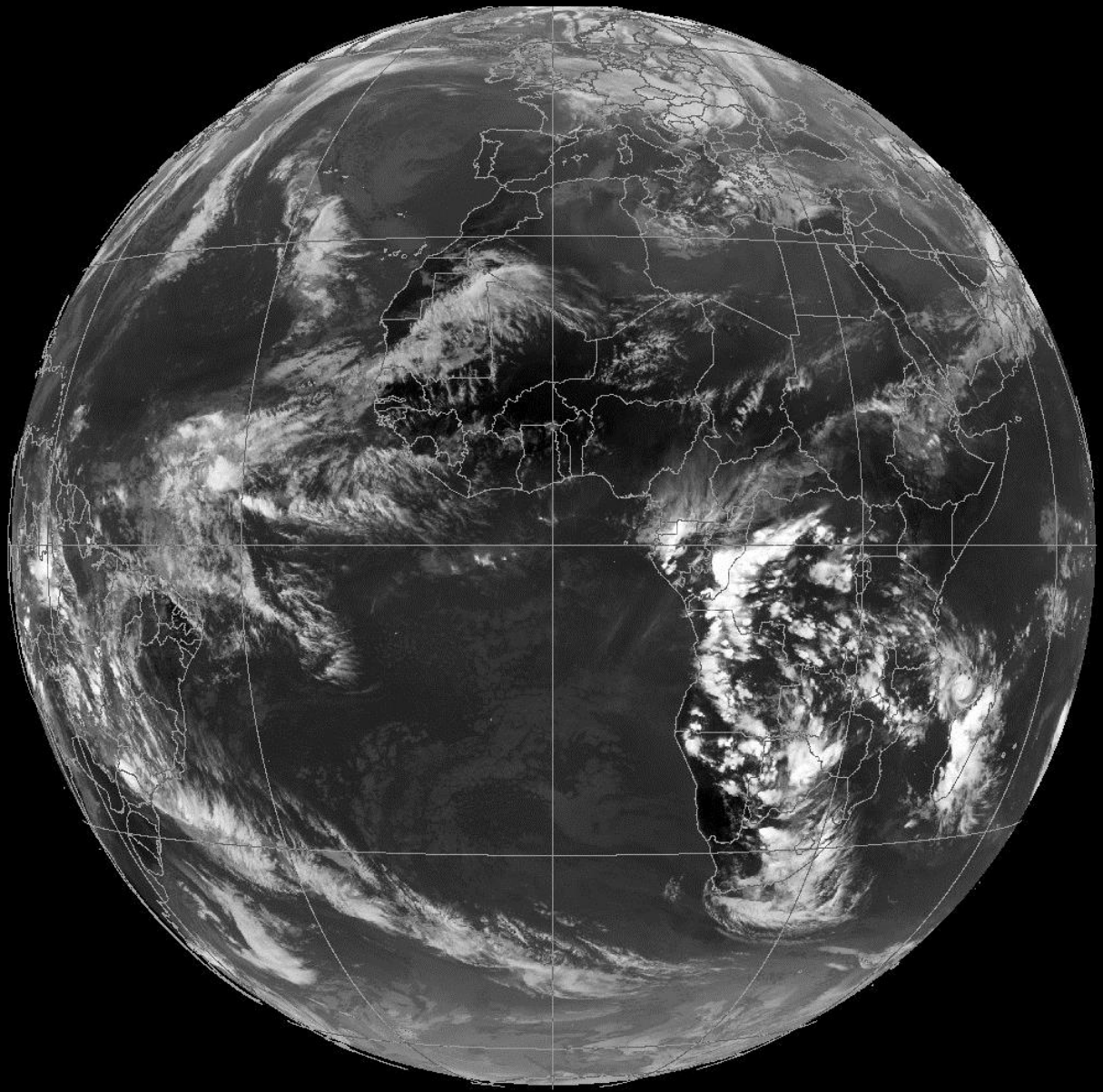
Orbits



Satellites

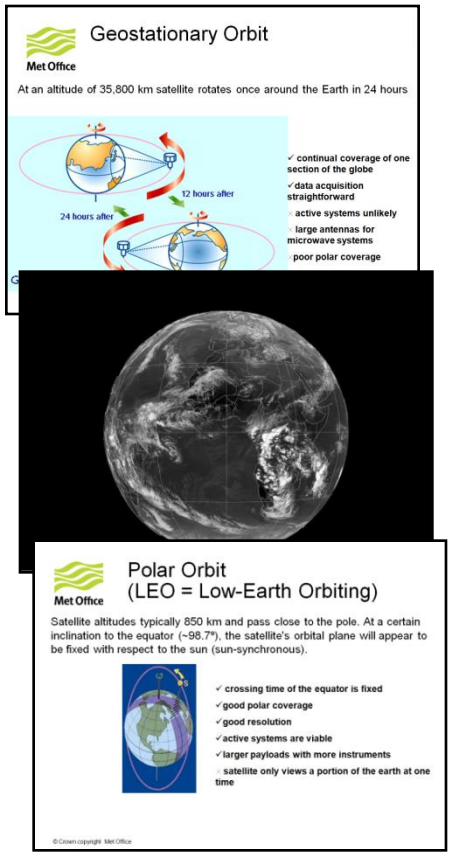
Instruments

© Crown copyright Met Office



Which satellites/instruments do we use?

Orbits

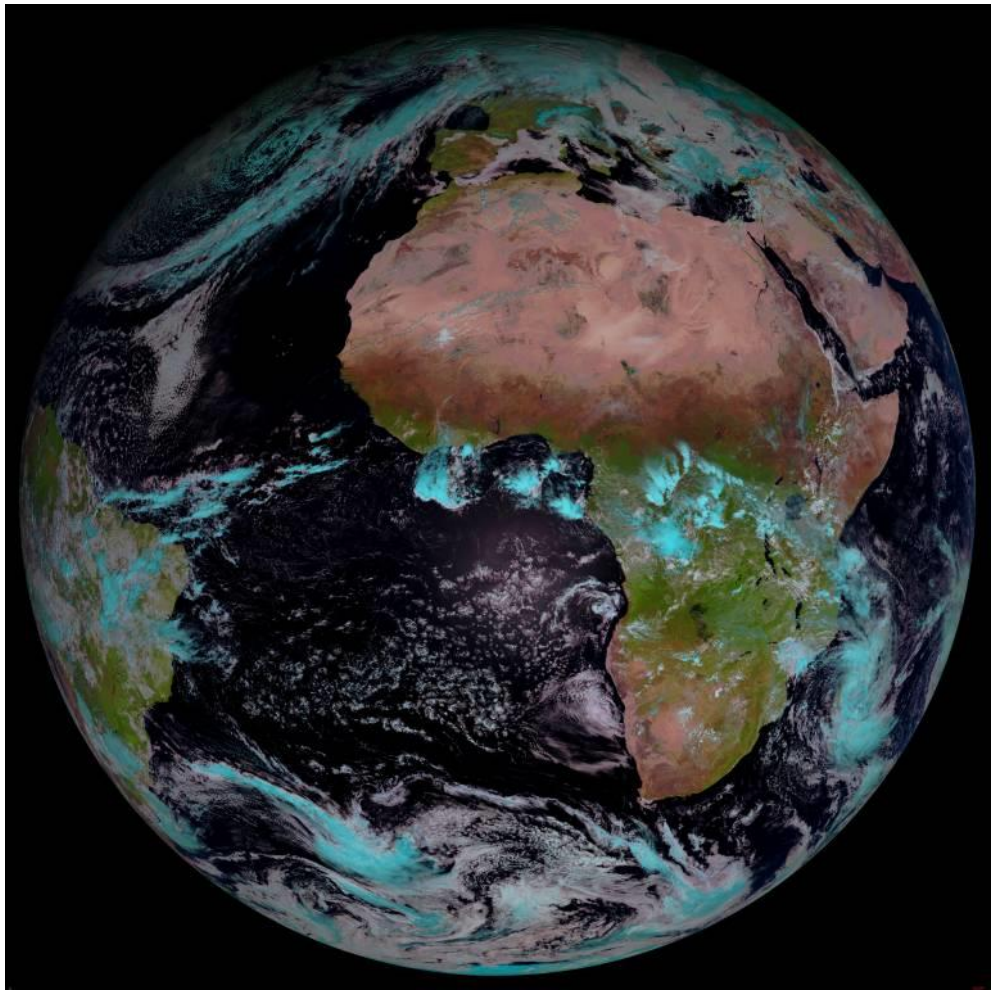


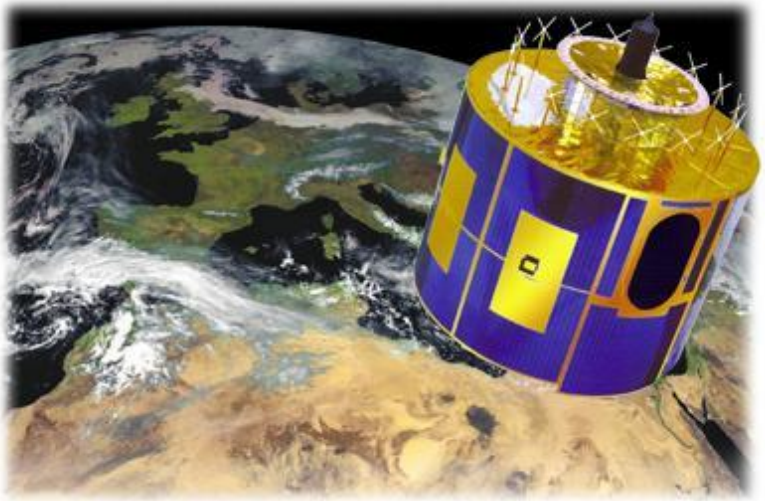
Satellites

Instruments

© Crown copyright Met Office

SEVIRI - the European Geostationary Imager



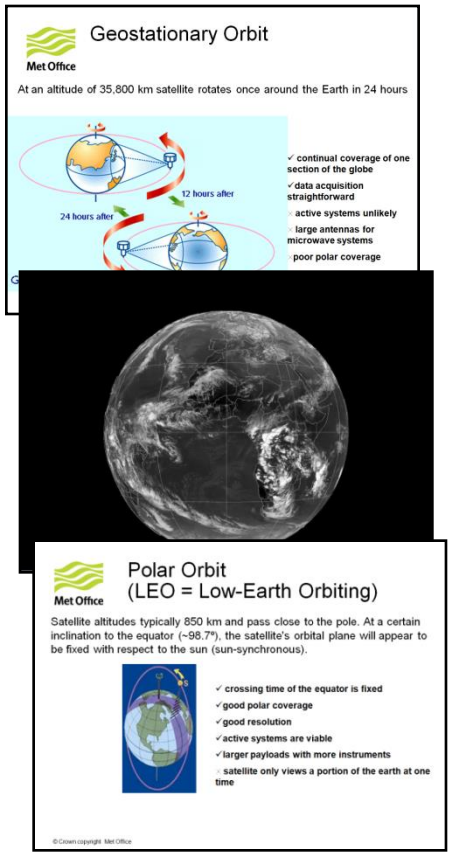


- Scans Africa, Europe, Middle East and Atlantic every 15 minutes
- 3/1 km spatial resolution at 0° N, 0° E
- 12 channels (different wavelengths)
- Meteosat-10 operational, Met-9/Met-8 backup

© Crown copyright Met Office

Which satellites/instruments do we use?

Orbits



Satellites

Instruments

© Crown copyright Met Office

Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

Satellite products used at London VAAC

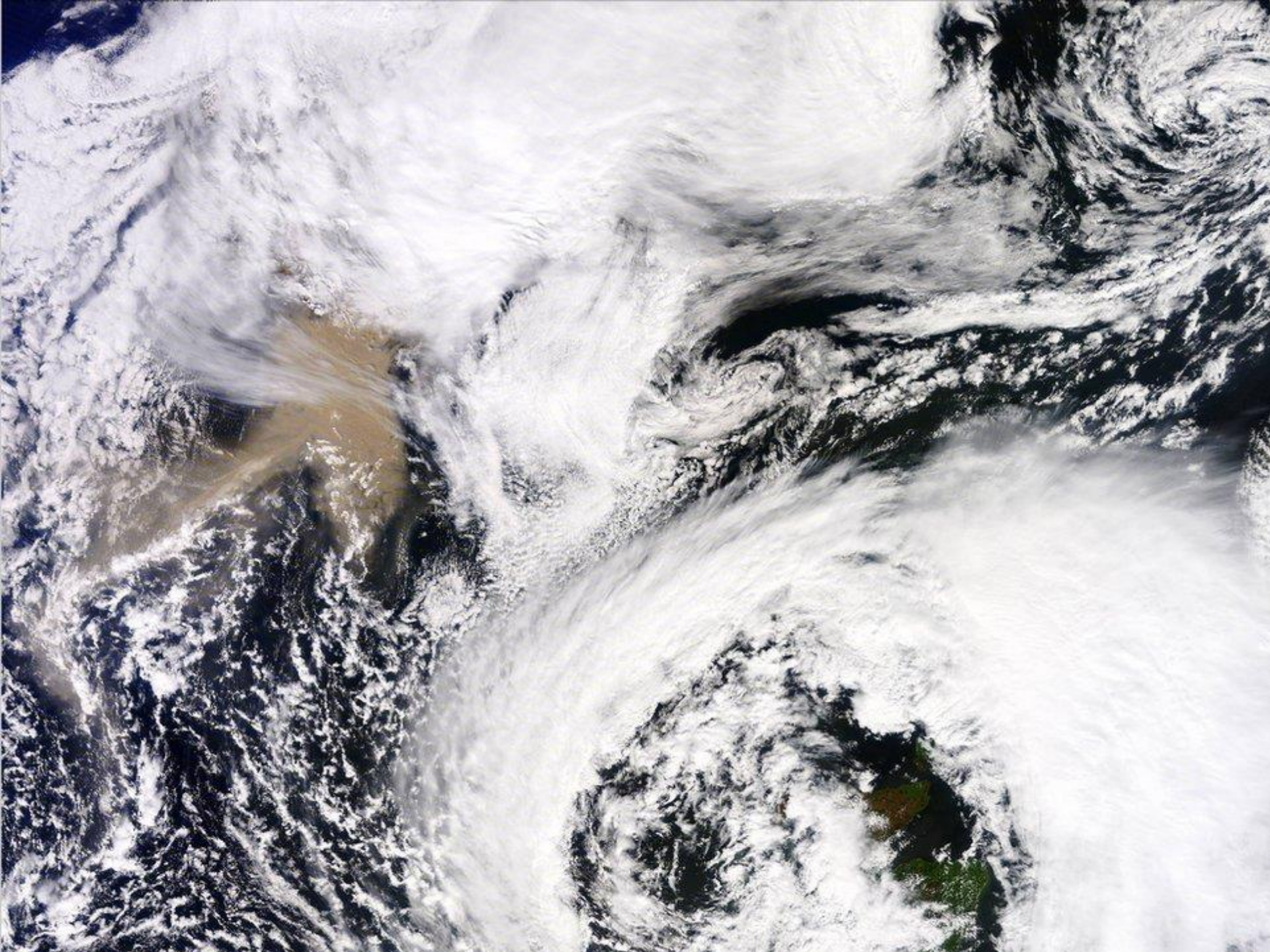
- Qualitative imagery of ash
- Quantitative ash detection
- Quantitative ash property retrievals
- Simulated satellite imagery
- SO_2 products

© Crown copyright Met Office

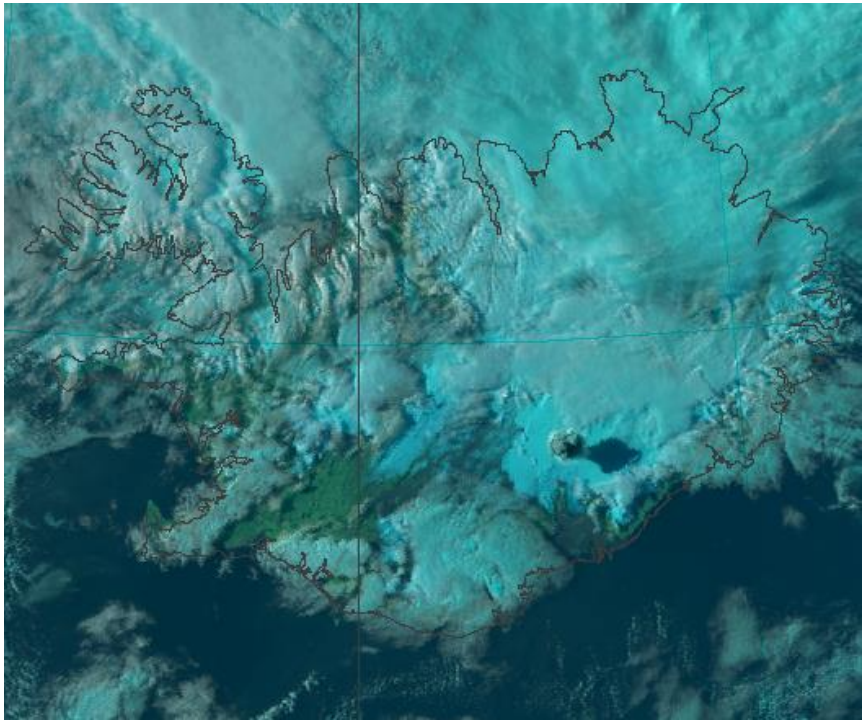
Satellite products used at London VAAC

- Qualitative imagery of ash
- Quantitative ash detection
- Quantitative ash property retrievals
- Simulated satellite imagery
- SO_2 products

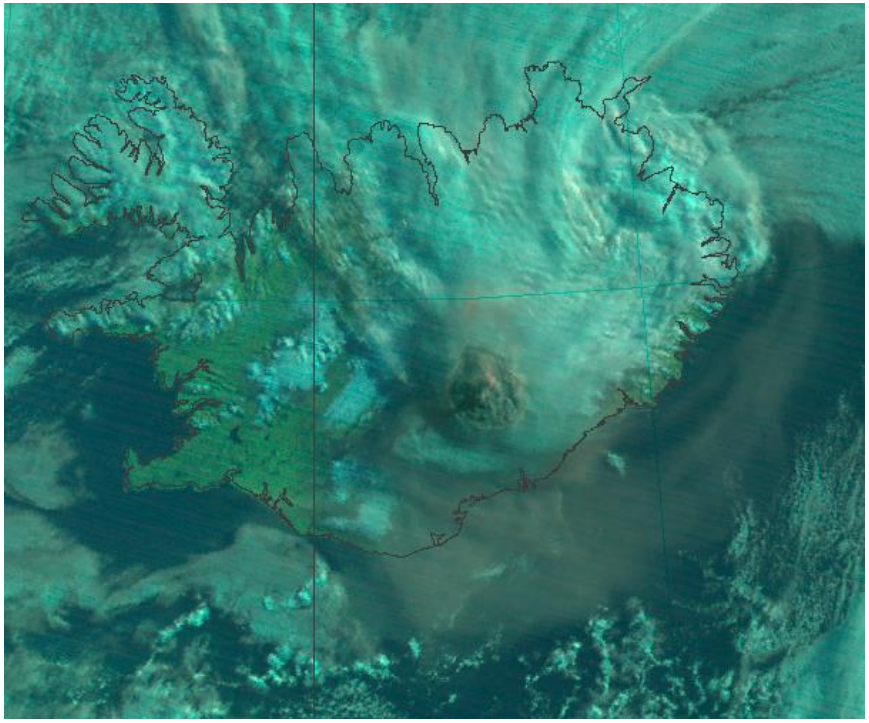
© Crown copyright Met Office



“AVHRR” visible imagery



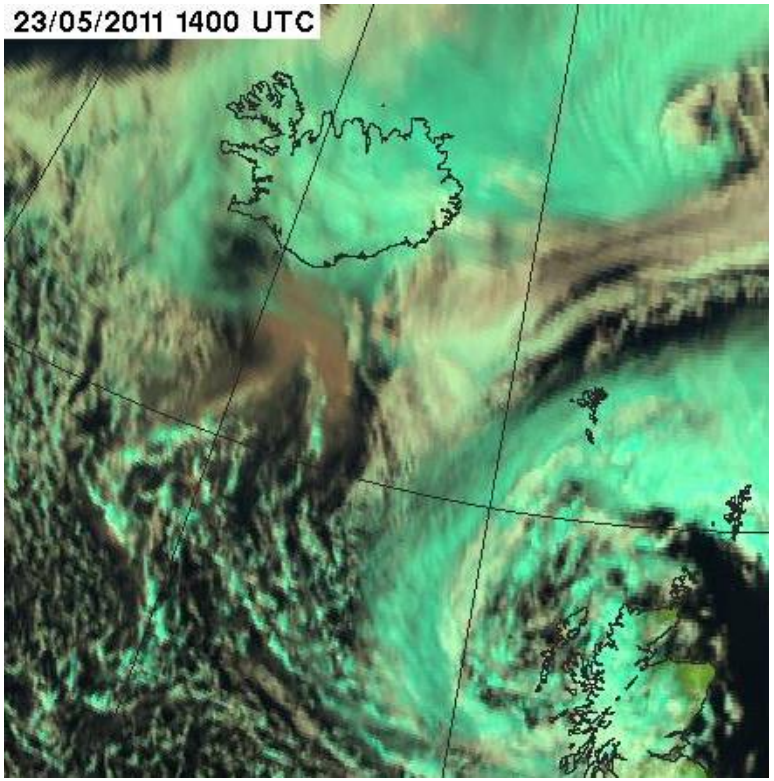
21st May 2011, 1918Z
NOAA-16



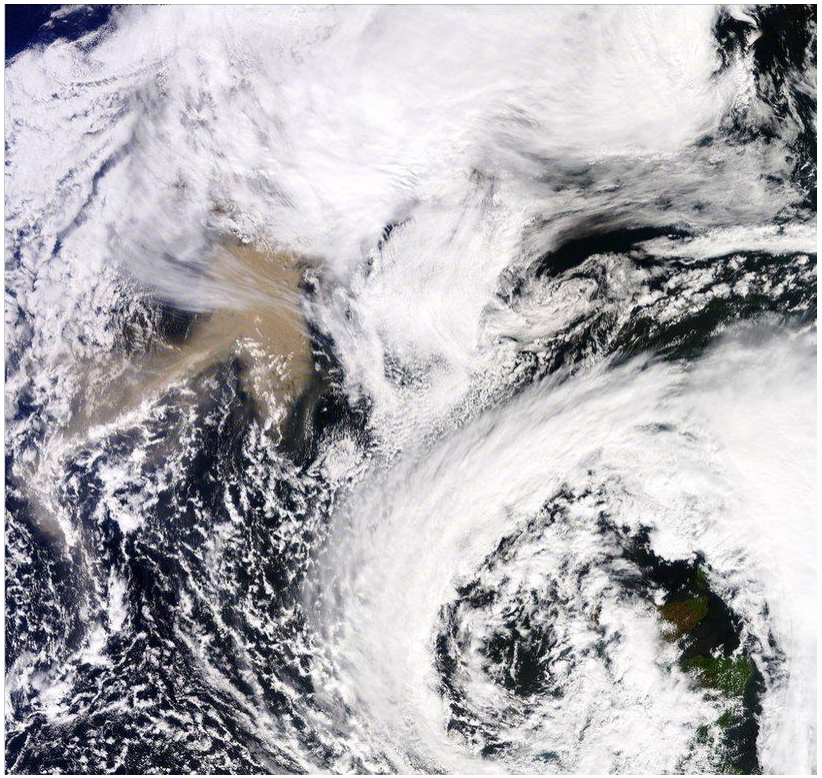
22nd May 2011, 0551Z
FY-1D MVISR

© Crown copyright Met Office

MSG/SEVIRI visible imagery



SEVIRI
23rd May 2011, 1400Z

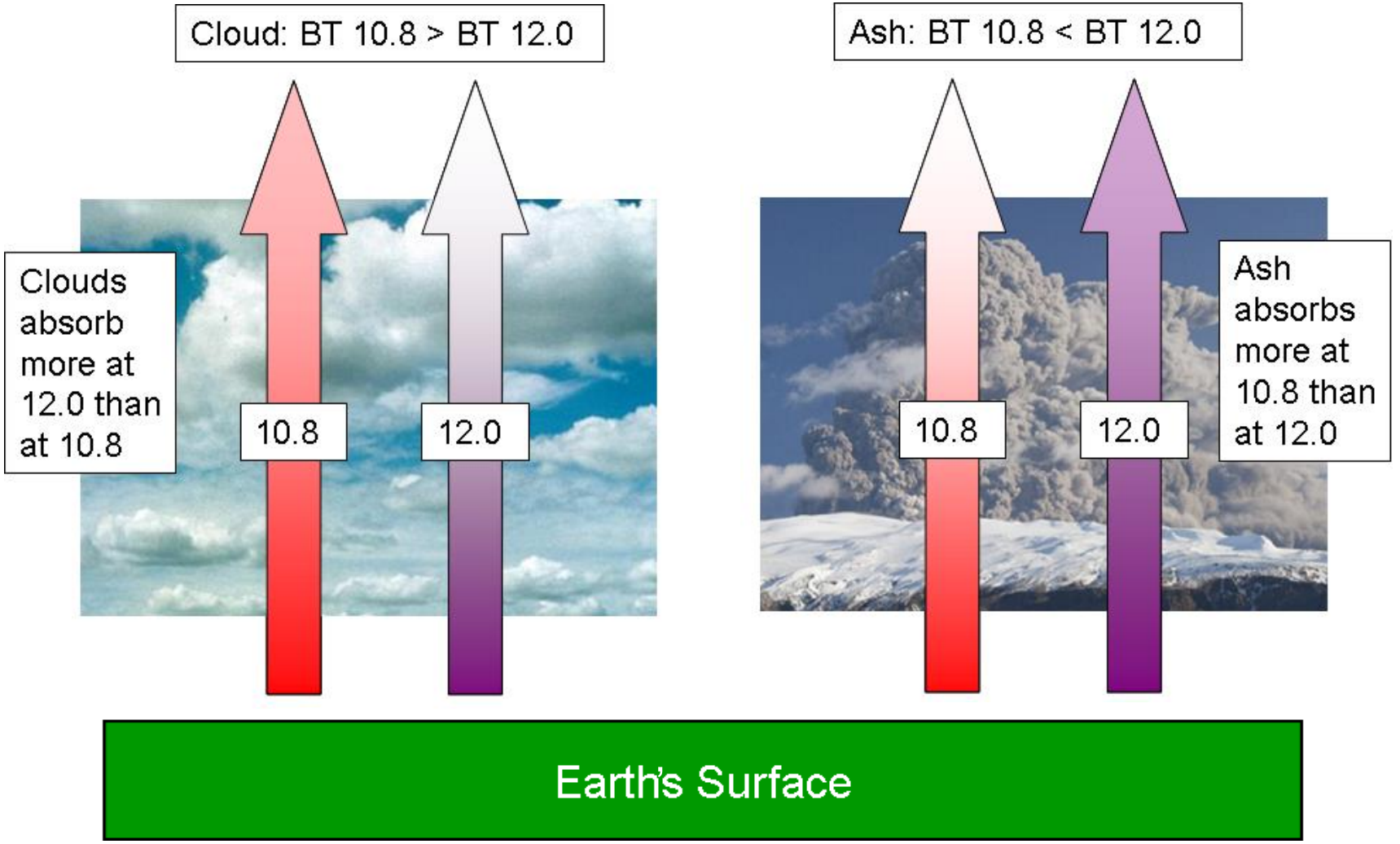


MODIS
23rd May 2011, 1352Z

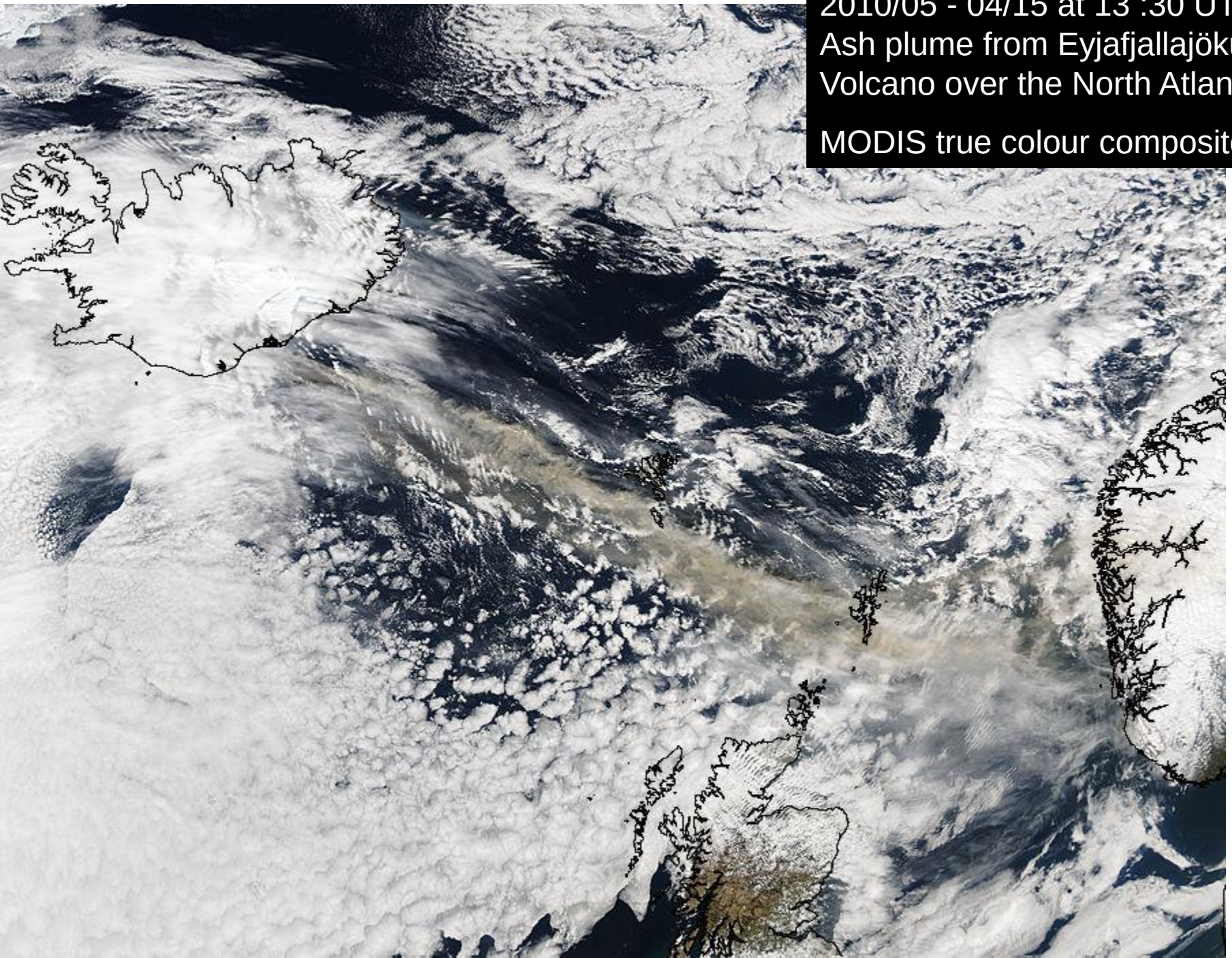
© Crown copyright Met Office

Thermal infrared difference imaging

Optical characteristics of ash and water/ice are different in the 8-12 μm atmospheric window

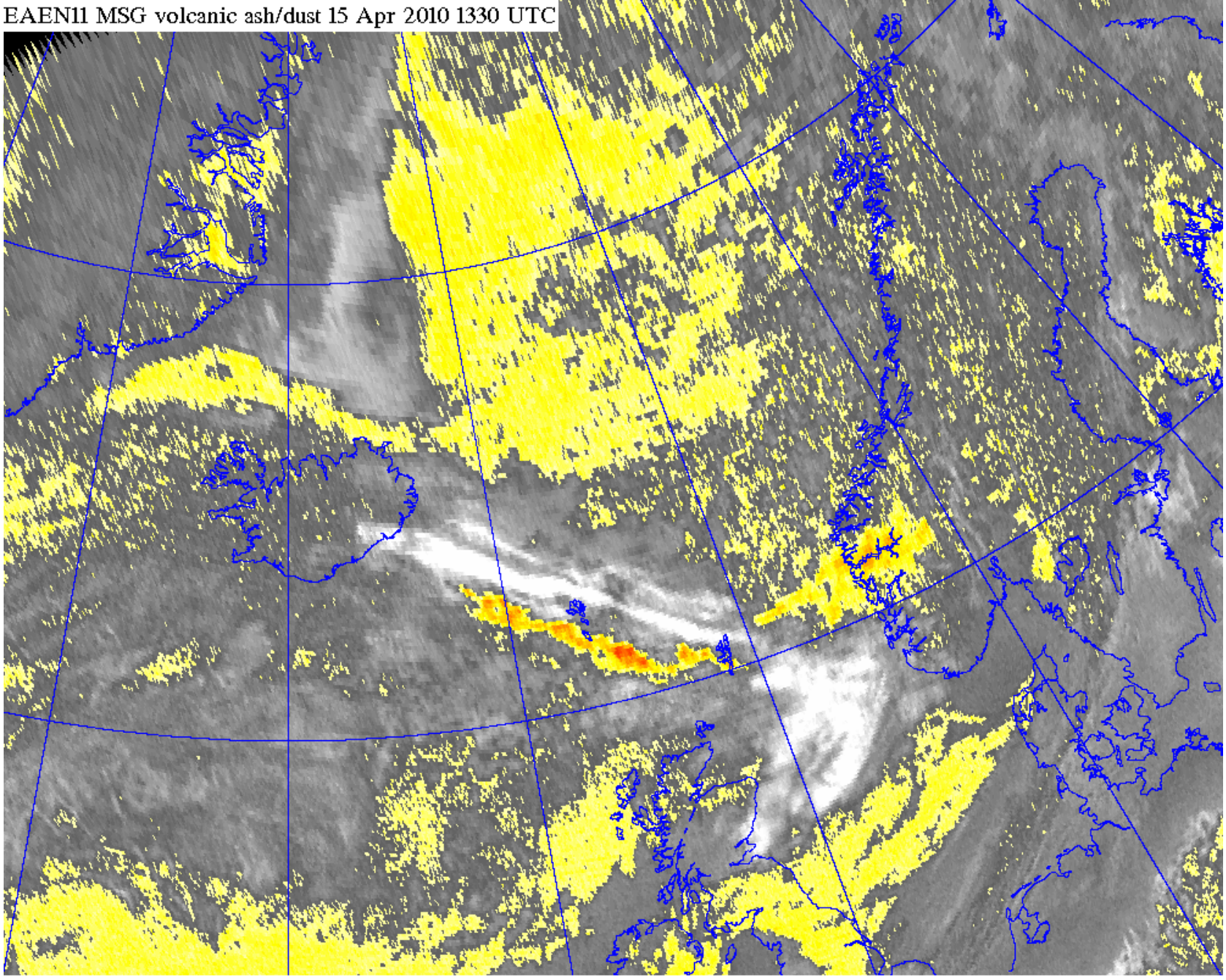


© Crown copyright Met Office



2010/05 - 04/15 at 13 :30 UTC
Ash plume from Eyjafjallajökull Volcano over the North Atlantic -

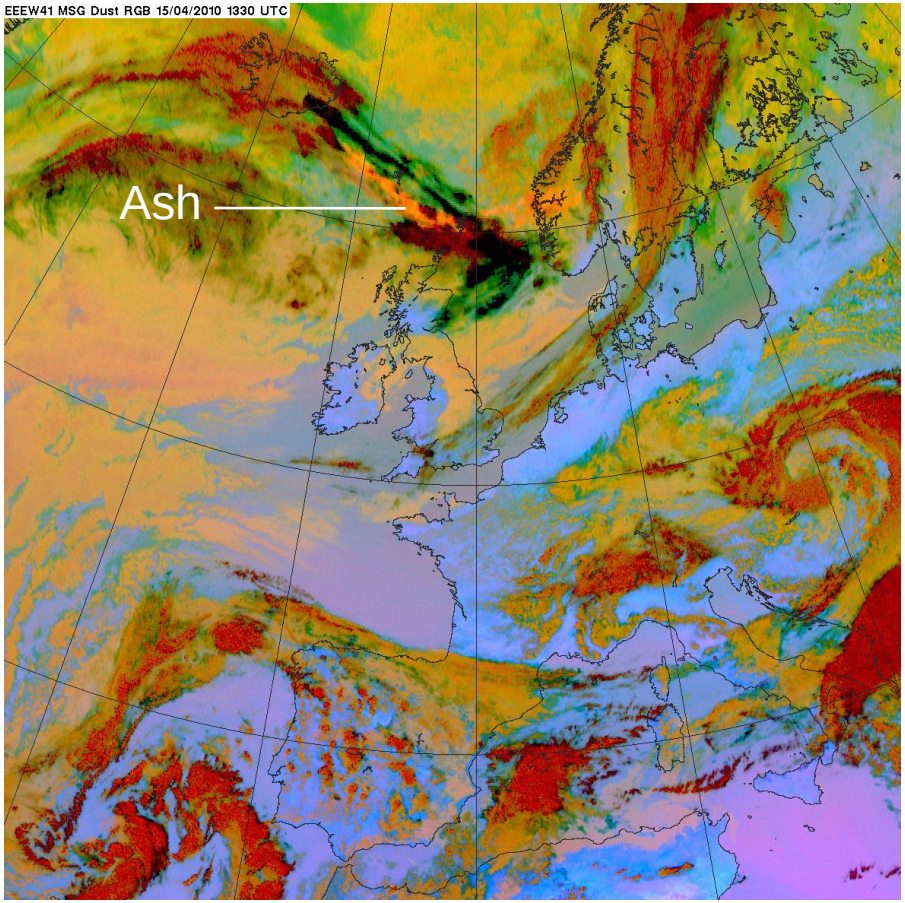
MODIS true colour composite



© Crown copyright Met Office

Eyjafjallajökull

MSG Dust RGB

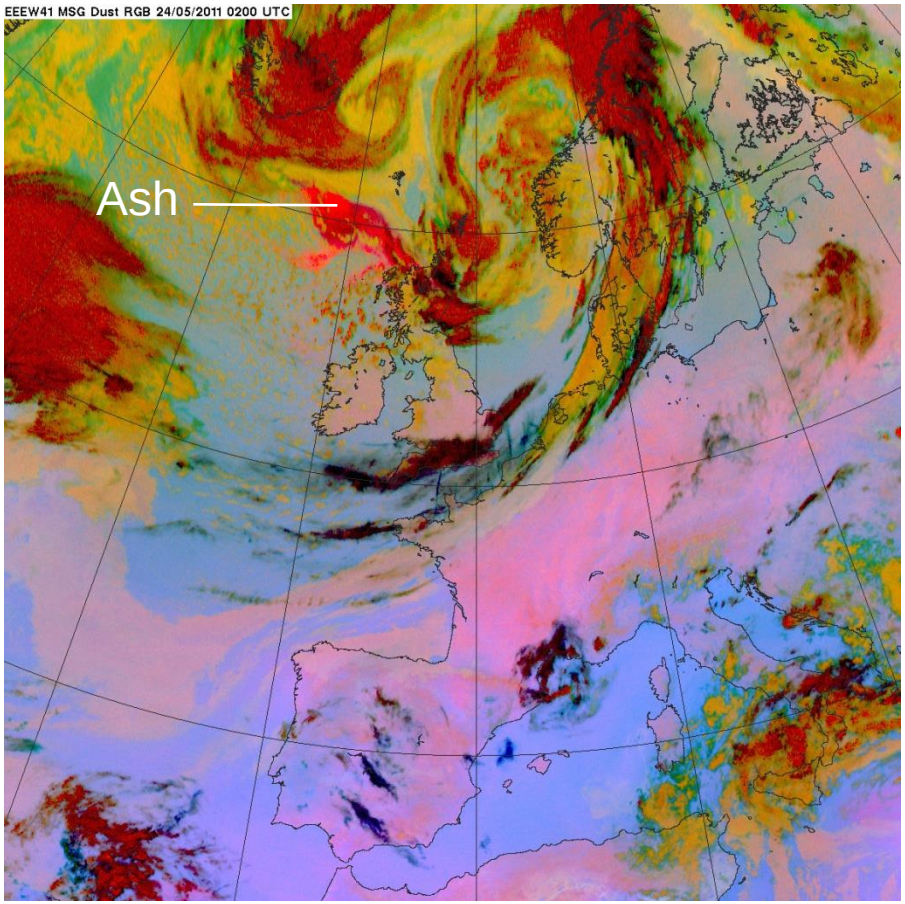


2010/04/15 1330 UTC

© Crown copyright Met Office

Grímsvötn

MSG Dust RGB

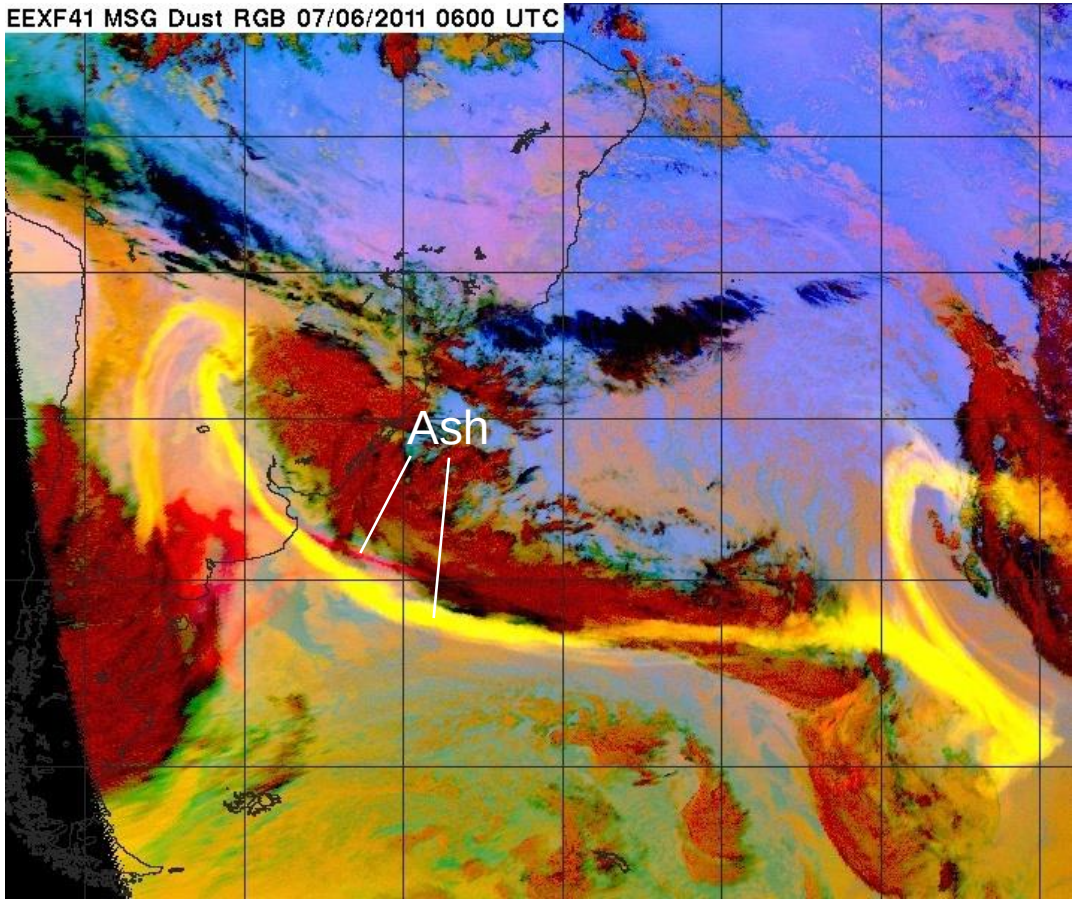


2011/05/24 0200 UTC

© Crown copyright Met Office

Puyehue-Cordón Caulle

MSG Dust RGB

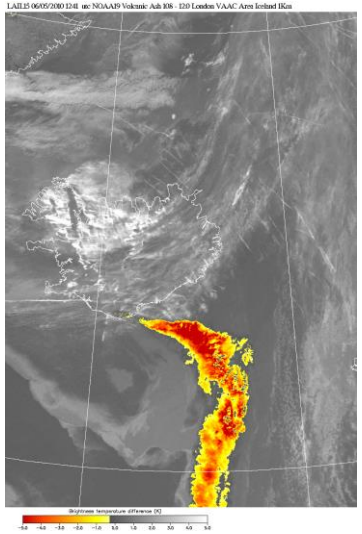


2011/06/07 0600 UTC

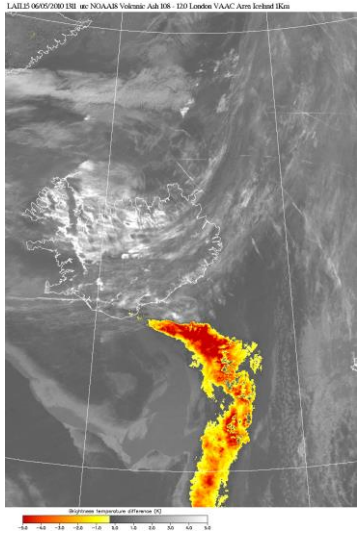
© Crown copyright Met Office

Polar AVHRR imagery from May 2010

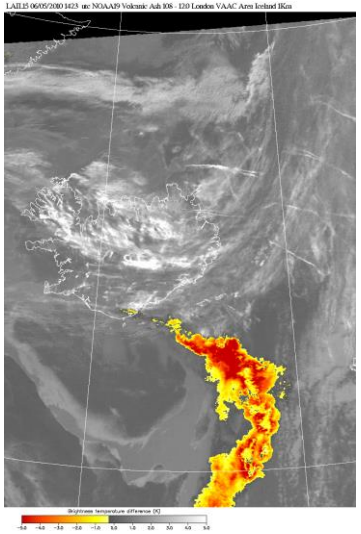
1241Z/6th



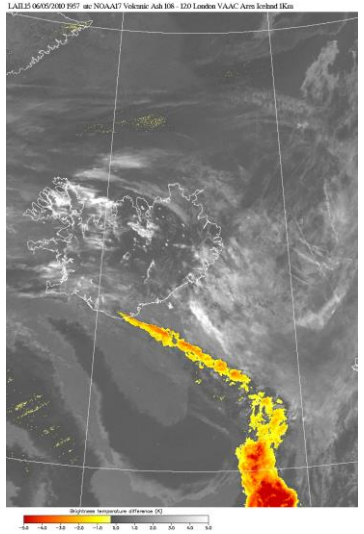
1311Z/6th



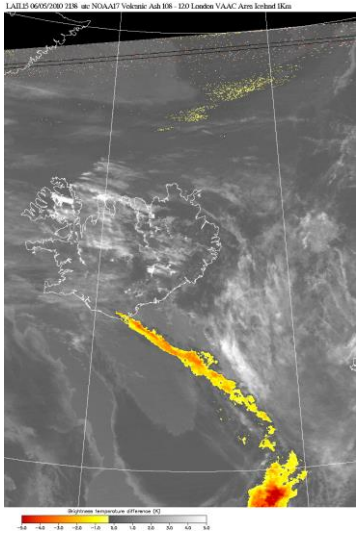
1423Z/6th



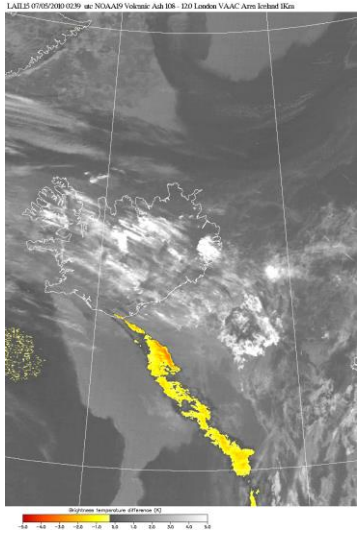
1957Z/6th



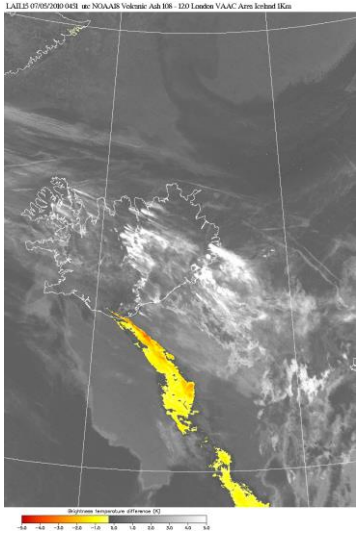
2138Z/6th



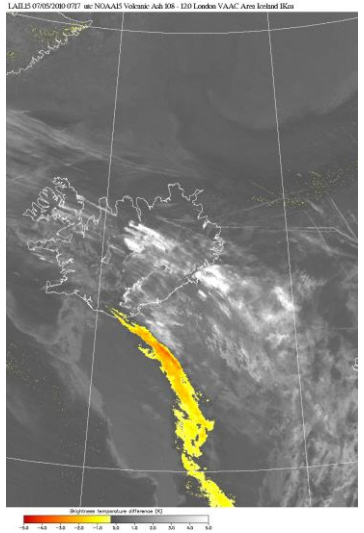
0239Z/7th

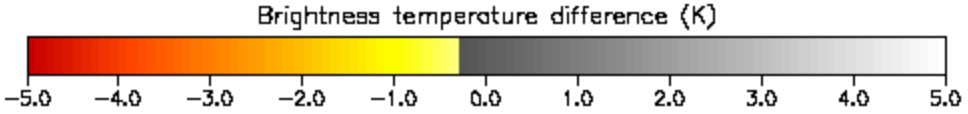


0451Z/7th



0717Z/7th





Volcanic ash images

Yellow/orange/red areas (-ve values) show areas of ash that are:

- **Not optically thick (which would look grey)**
- **Fine ash particles, approx 1-10 μm**

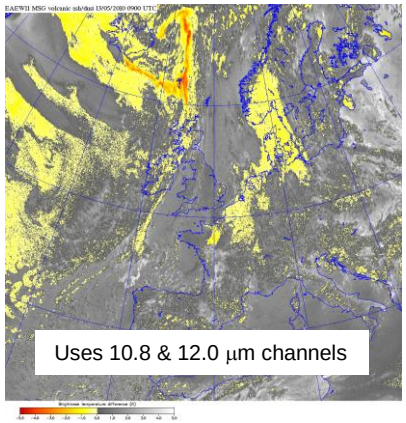
Satellite products used at London VAAC

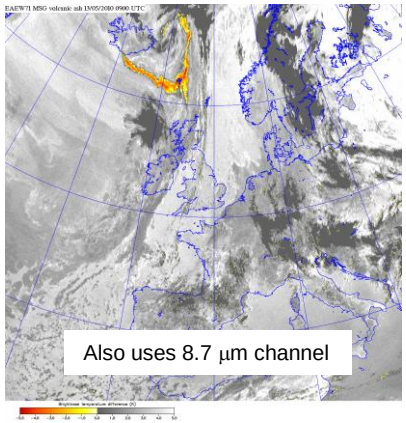
- Qualitative imagery of ash
- Quantitative ash detection
- Quantitative ash property retrievals
- Simulated satellite imagery
- SO_2 products

© Crown copyright Met Office

Improving ash detection

•Although the simple “channel-difference” (BTD) type of product is useful, it is also desirable to have a more sophisticated detection scheme in order to produce the mask on which to apply the volcanic ash retrieval calculations (see later)



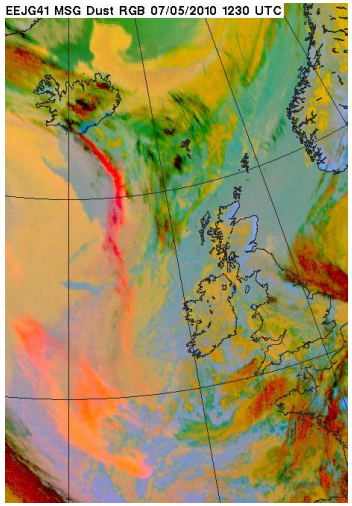


•Specifically, the background NWP model’s temperature and humidity profiles are useful pieces of additional information which do not get used in the simple BTD products described thus far – these can, to some extent, allow for the effects of the intervening atmosphere on the top-of-atmosphere radiances

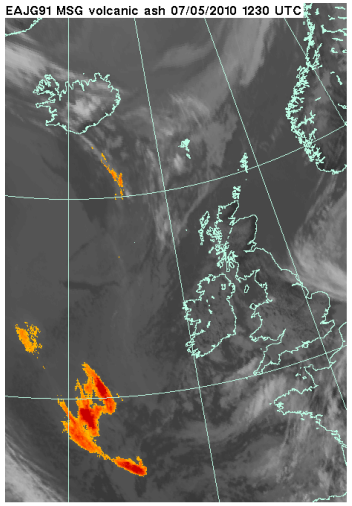
© Crown copyright Met Office

A series of 5 tests to arrive at final ash mask

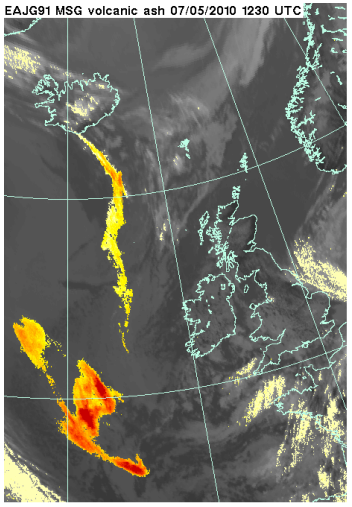
Dust RGB



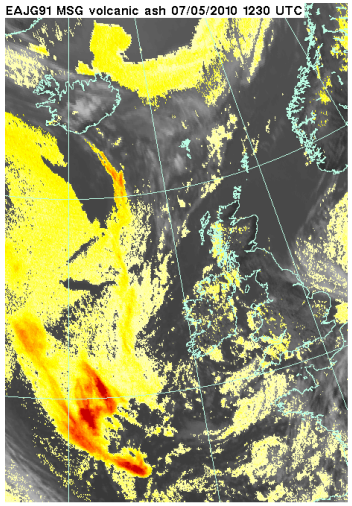
Test 1 (strict 2-chan BTD)



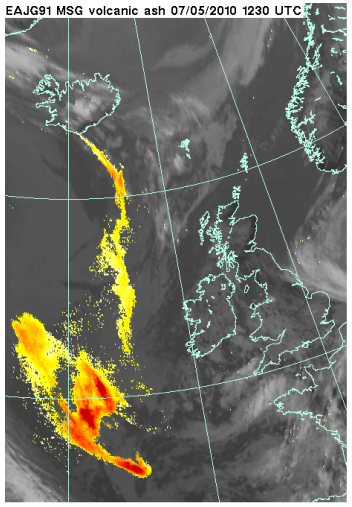
Test 2 (3-chan BTD)



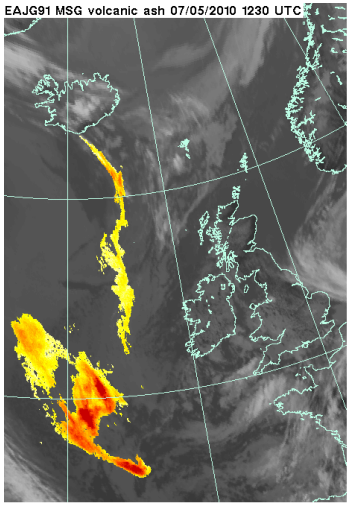
Test 3 (2-chan BTD with NWP)



Test 4 (β-ratio false alarm removal with NWP)



Test 5 (noise)



© Crown copyright Met Office

Satellite products used at London VAAC

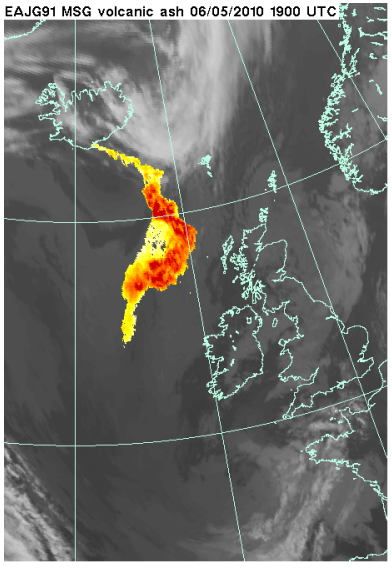
- Qualitative imagery of ash
- Quantitative ash detection
- Quantitative ash property retrievals
- Simulated satellite imagery
- SO_2 products

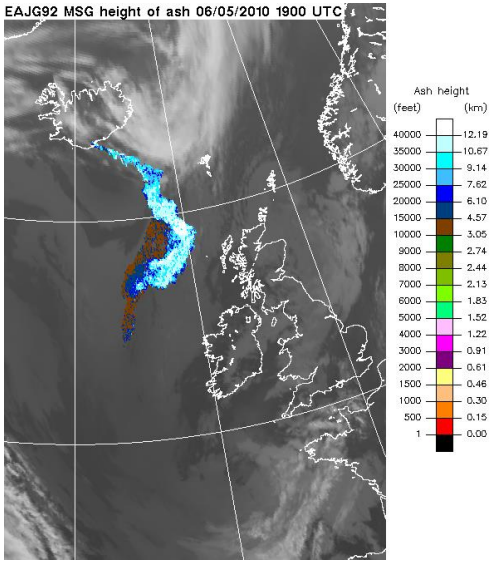
© Crown copyright Met Office

1D-Var scheme developed to retrieve quantitative volcanic ash information from SEVIRI data

Uses channels at 10.8 μm, 12.0 μm and 13.4 μm

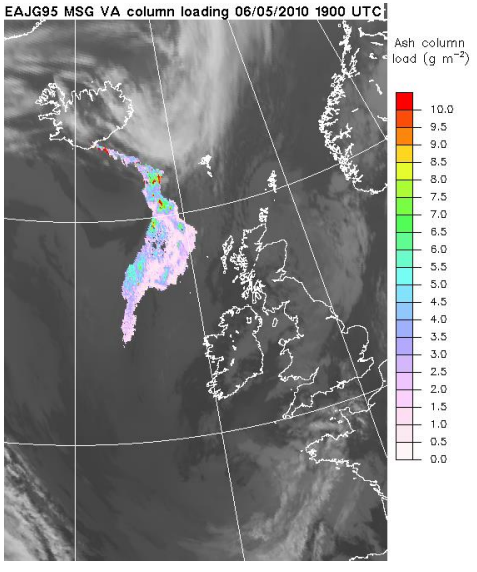
Improved detection

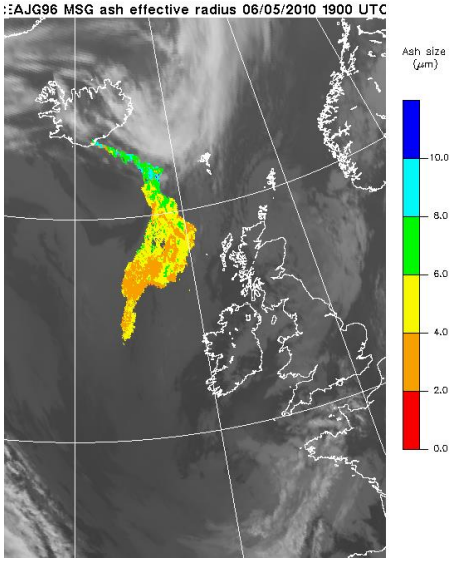




Ash(-top) height

Ash column loading

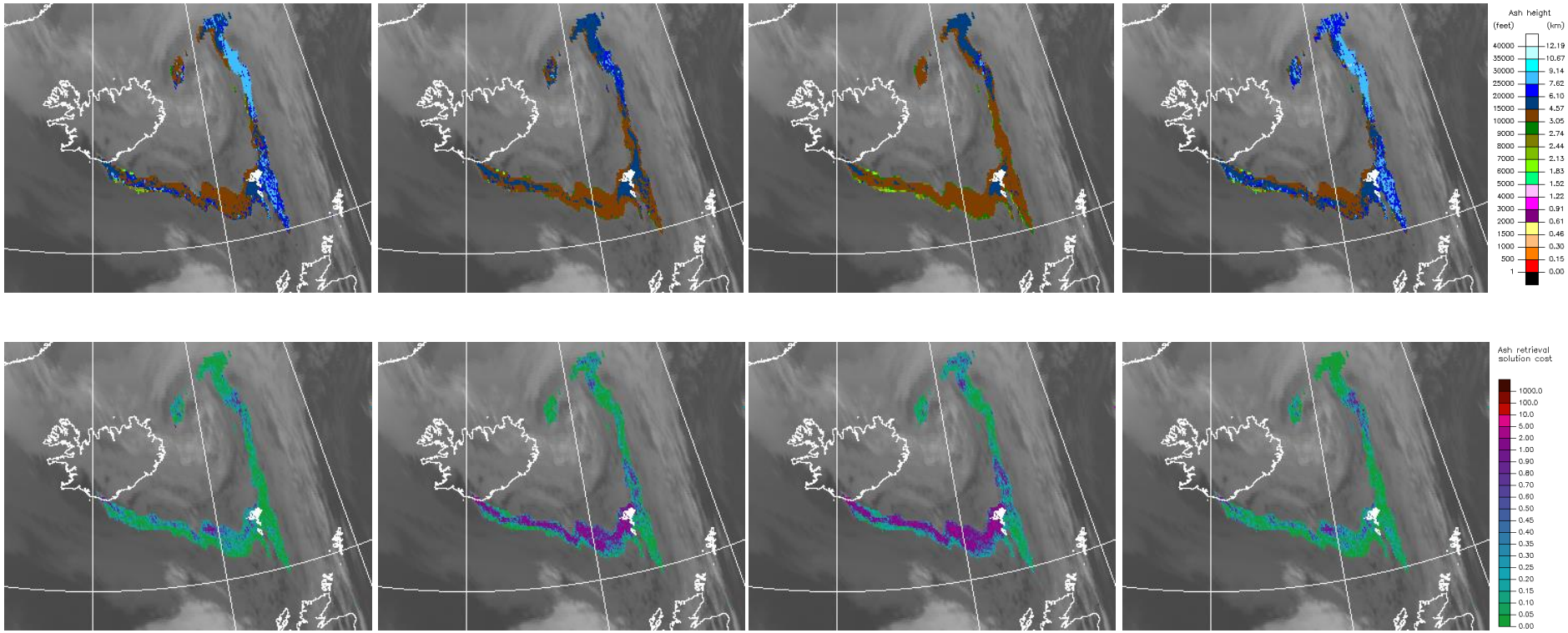




Ash size

Ash height retrievals – effect of different refractive indices, and their solution costs

2010/05/13 0800 UTC



Pollack (andesite)

Pollack (obsidian)

Balkanski

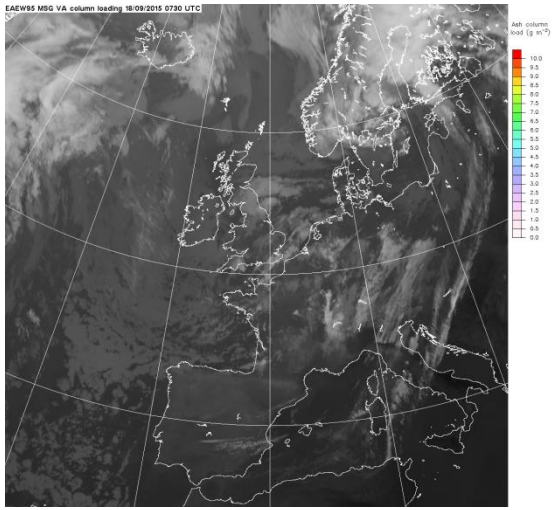
Volz

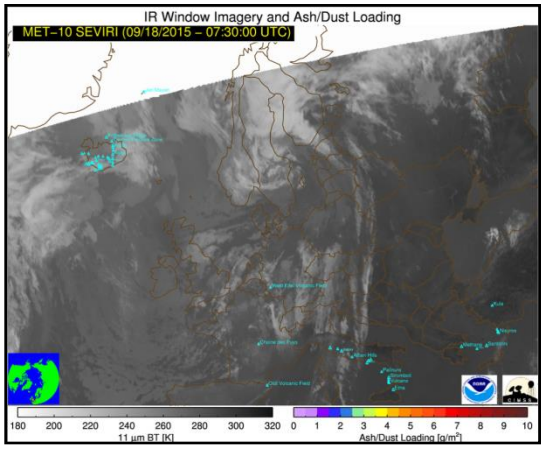
1D-Var final cost gives a measure of how well the solution has managed to fit the observations

© Crown copyright Met Office

Ash detection and retrieval products also monitored from other Near-Real-Time sources during eruptions

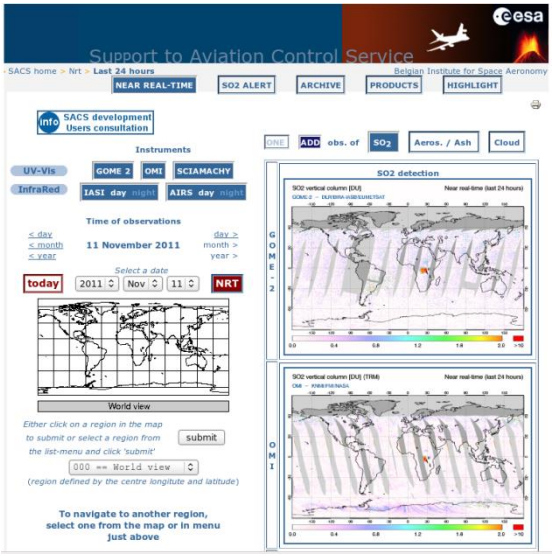
Met Office





VOLCAT (SSEC)

EUMETSAT



SACS

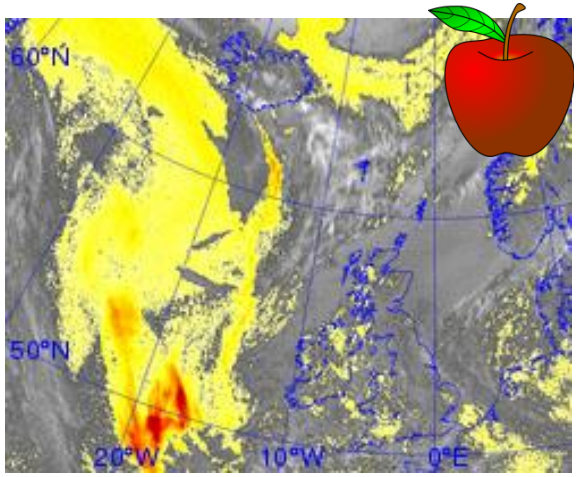
Satellite products used at London VAAC

- Qualitative imagery of ash
- Quantitative ash detection
- Quantitative ash property retrievals
- Simulated satellite imagery
- SO_2 products

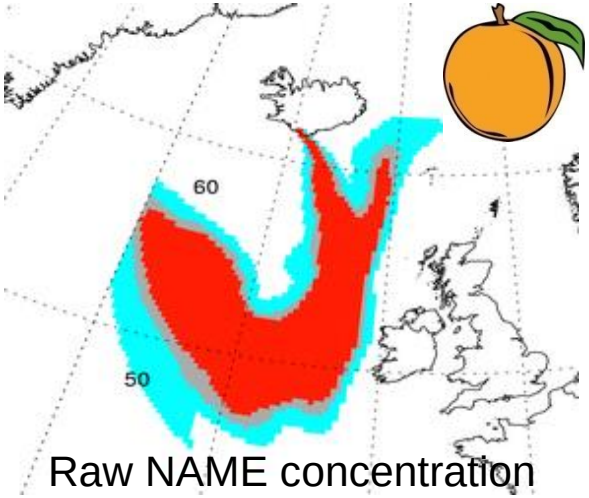
© Crown copyright Met Office

Why simulate imagery?

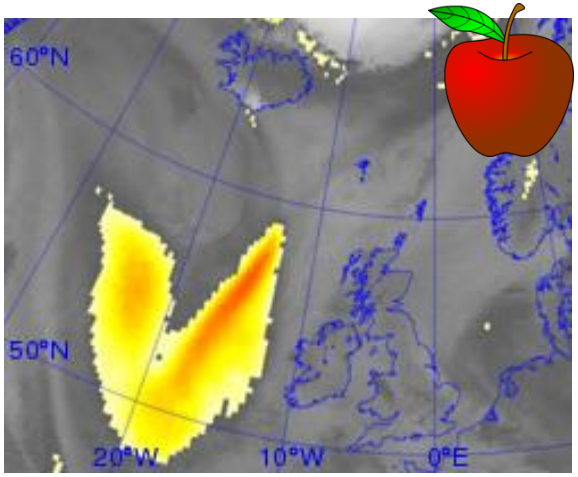
7 May 2010 1200 UTC



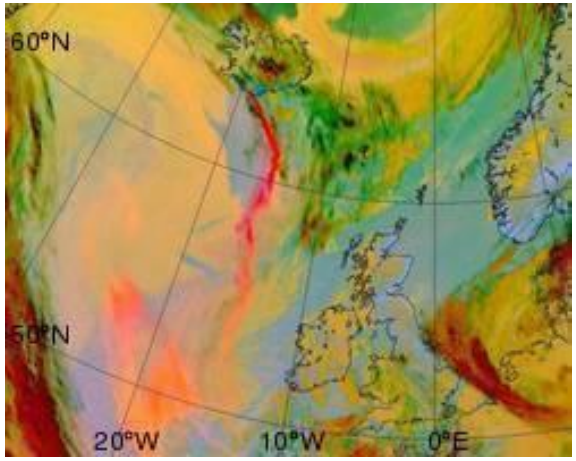
BT10.8 – BT12.0



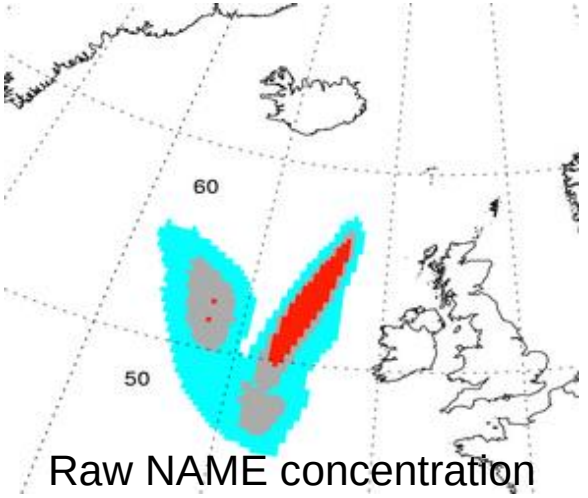
Raw NAME concentration for FL000-FL200



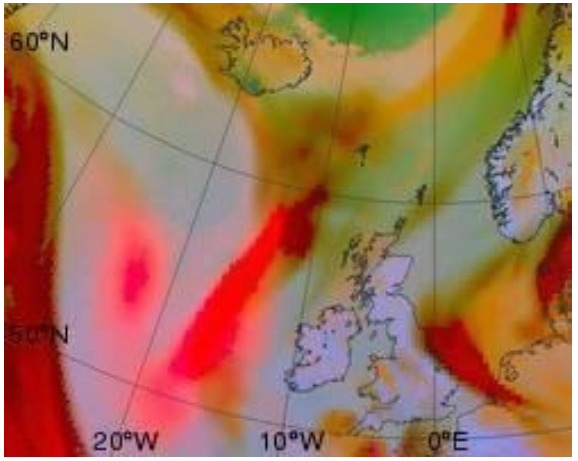
BT10.8 – BT12.0



Dust RGB



Raw NAME concentration for FL200-FL350

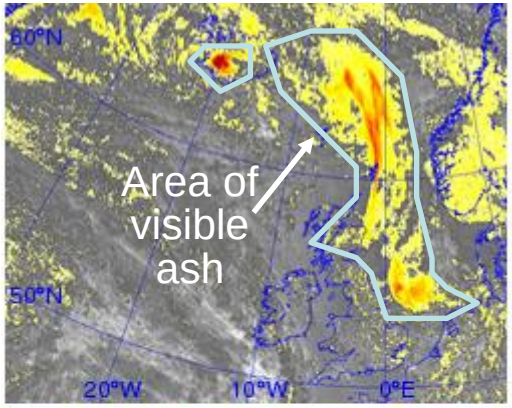


Dust RGB

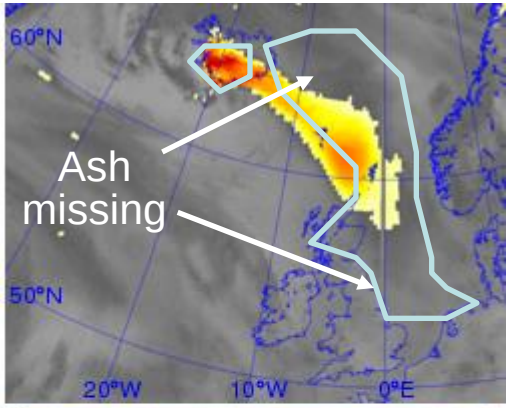
© Crown copyright Met Office

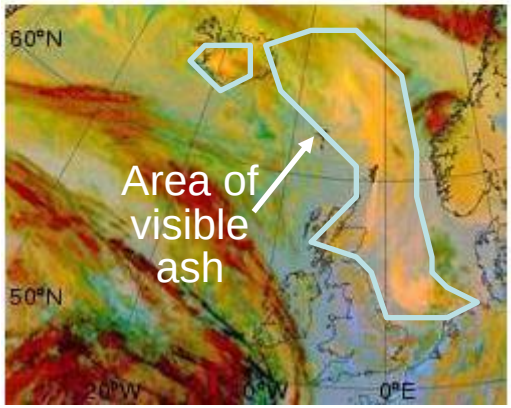
Eyjafjallajokull,17 May 2010 12Z

Satellite



Simulated





- Ash correct over Iceland, but needs ash further east and south over North Sea

© Crown copyright Met Office

Satellite products used at London VAAC

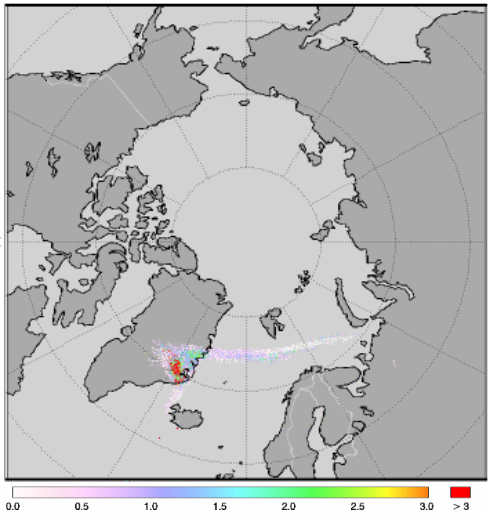
- Qualitative imagery of ash
- Quantitative ash detection
- Quantitative ash property retrievals
- Simulated satellite imagery
- SO_2 products

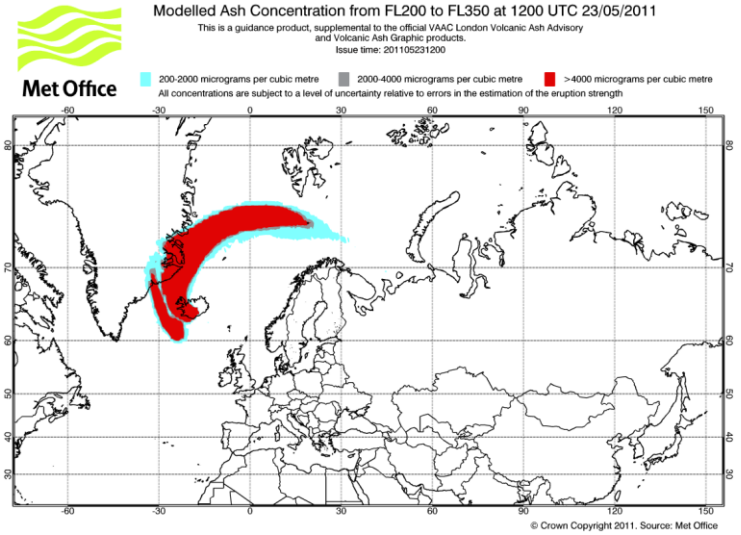
© Crown copyright Met Office

Ash index and SO_2 column 23rd May 2011

Ash Index

IASI – ULB/BIRA-IASB

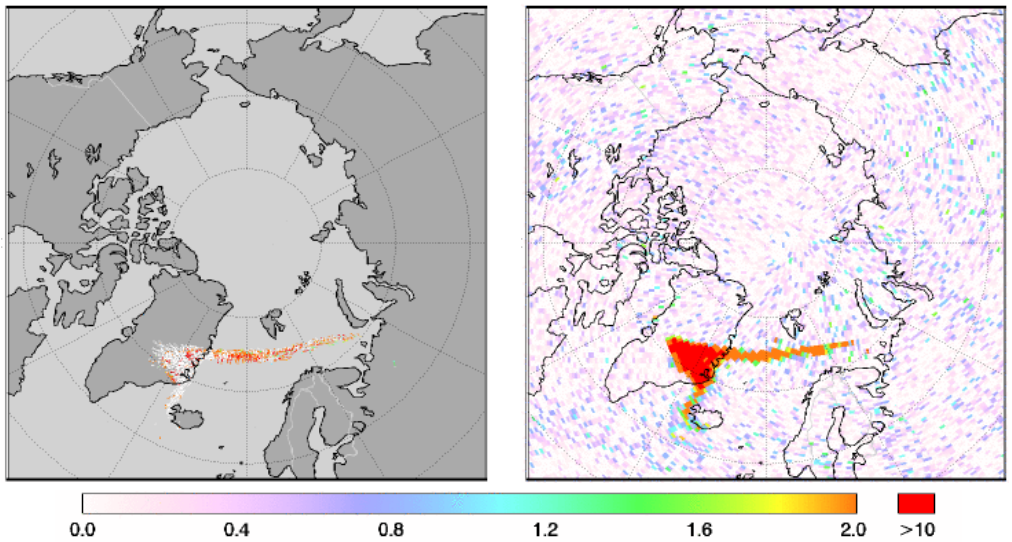




NAME concentrations
FL200-FL350
T+0 issued 201105231200

SO2 vertical column (DU)

IASI – ULB/BIRA-IASB

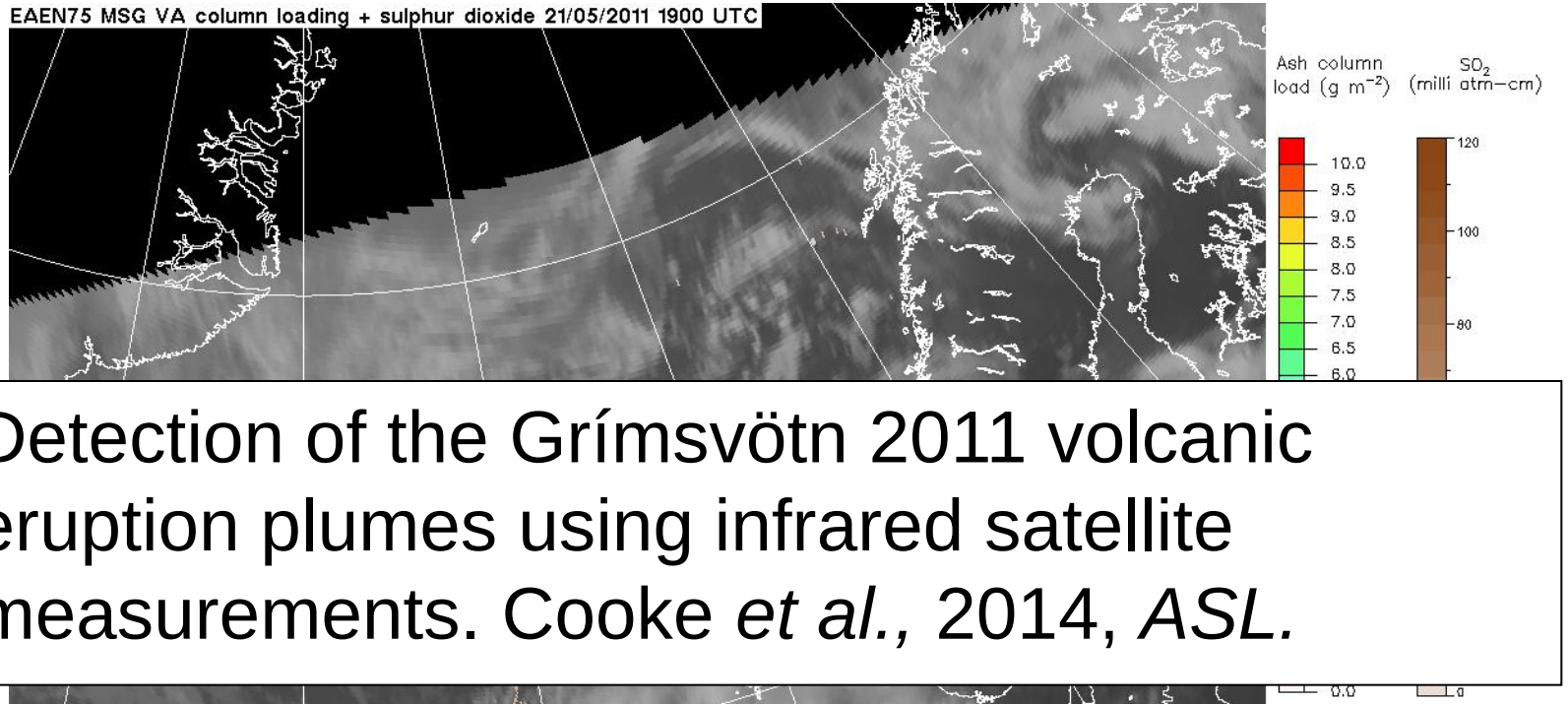


SO2 vertical column (DU)

GOME-2 – DLR/BIRA-IASB

© Crown copyright Met Office

SEVIRI Sulphur Dioxide + Ash

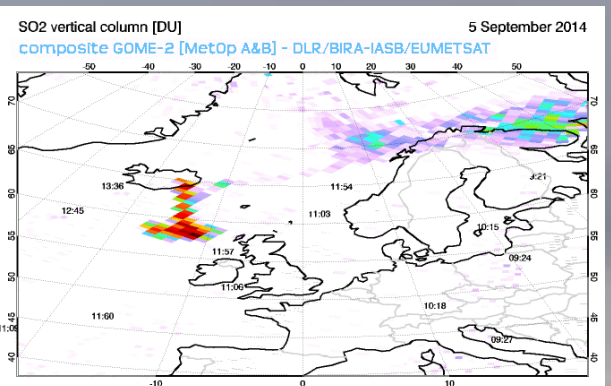


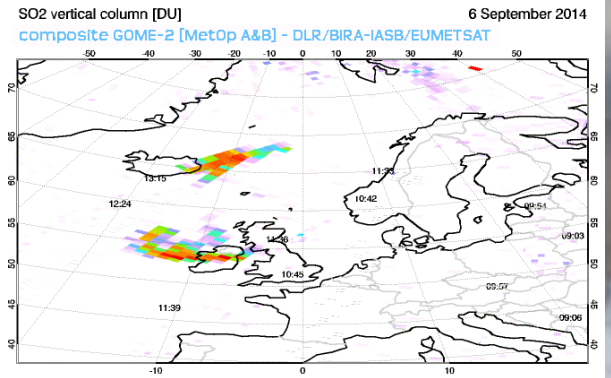
Detection of the Grímsvötn 2011 volcanic eruption plumes using infrared satellite measurements. Cooke *et al.*, 2014, *ASL.*

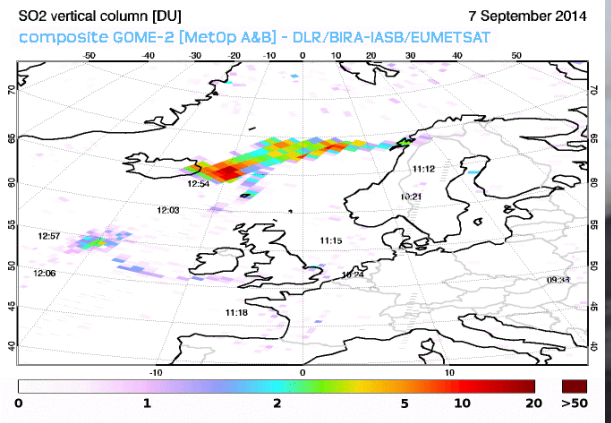
Volcanic Gases

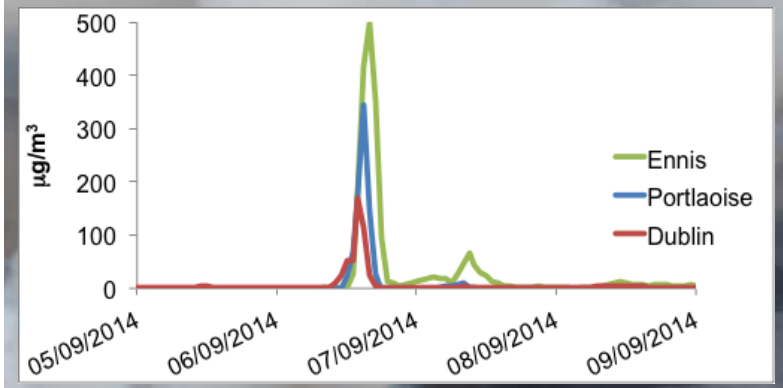
Bárðarbunga: 5-7 Sept 2014

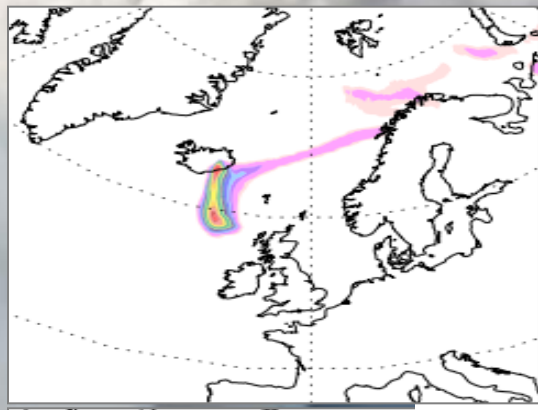
Met Office

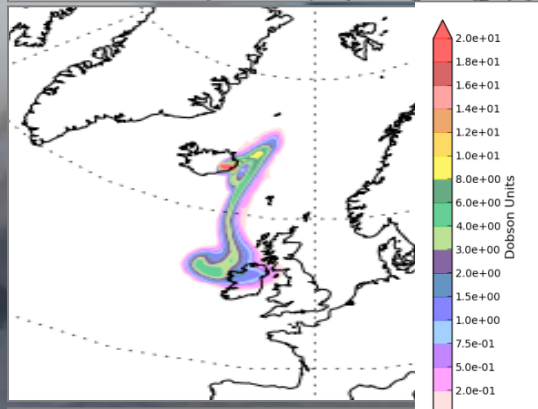


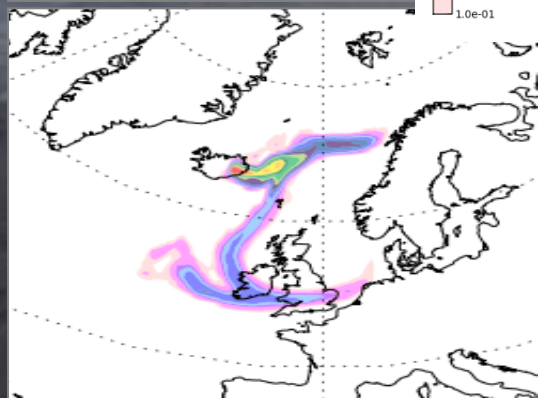












Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

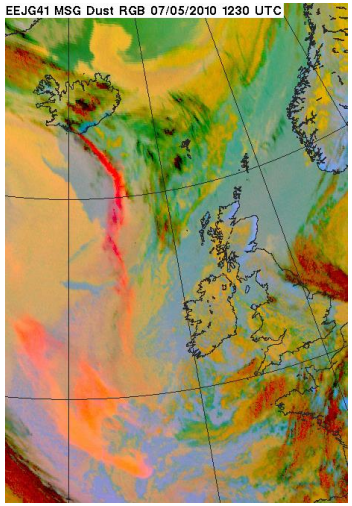
Further Developments

- Further improvements to operational ash detection?
- Comparisons between different quantitative ash retrievals?
- Multi-layer retrievals?
- Greater use of hyper-spectral sounding data?
- Towards a global geostationary capability

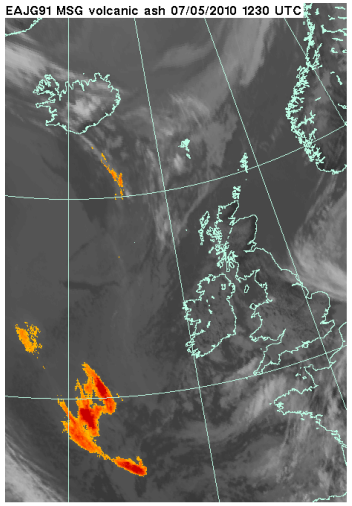
© Crown copyright Met Office

A series of 5 tests to arrive at final ash mask

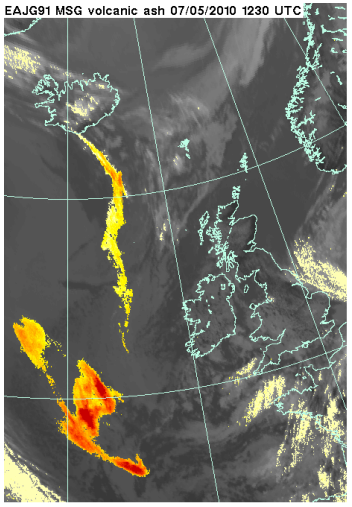
Dust RGB



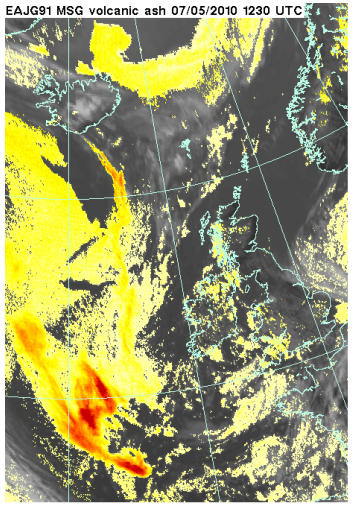
Test 1 (strict 2-chan BTD)



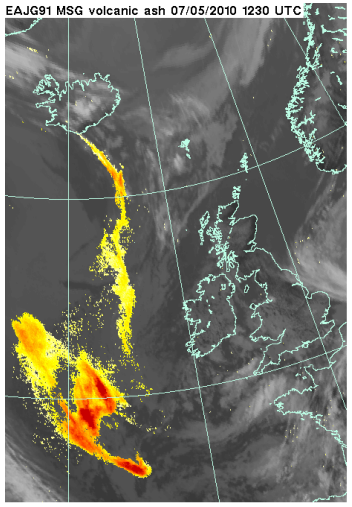
Test 2 (3-chan BTD)



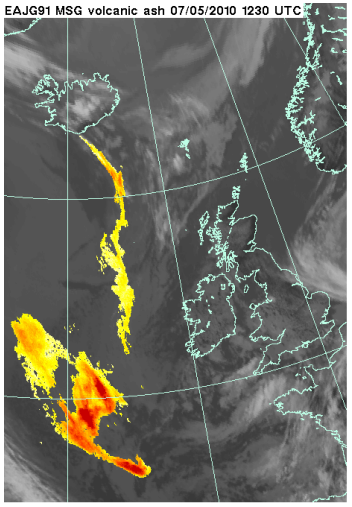
Test 3 (2-chan BTD with NWP)



Test 4 (β-ratio false alarm removal with NWP)



Test 5 (noise)



© Crown copyright Met Office

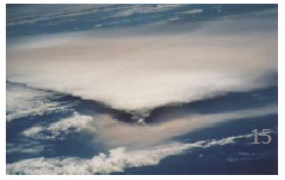
Pavolonis *et al.* ash detection

Volcanic Cloud Detection

The VOLCAT detection approach is multi-faceted and employs several different conceptual models to identify volcanic clouds across the spectrum of eruption cloud types.

- **Spectral cloud objects [spectral signature]**
- **Plume [spectral signature + geometric properties]**
- **Puff [spectral signature + cloud growth]**
- **Major Explosion [cloud growth]**
- **Tracking in time [spectral signature + feature tracking]**





© Crown copyright Met Office

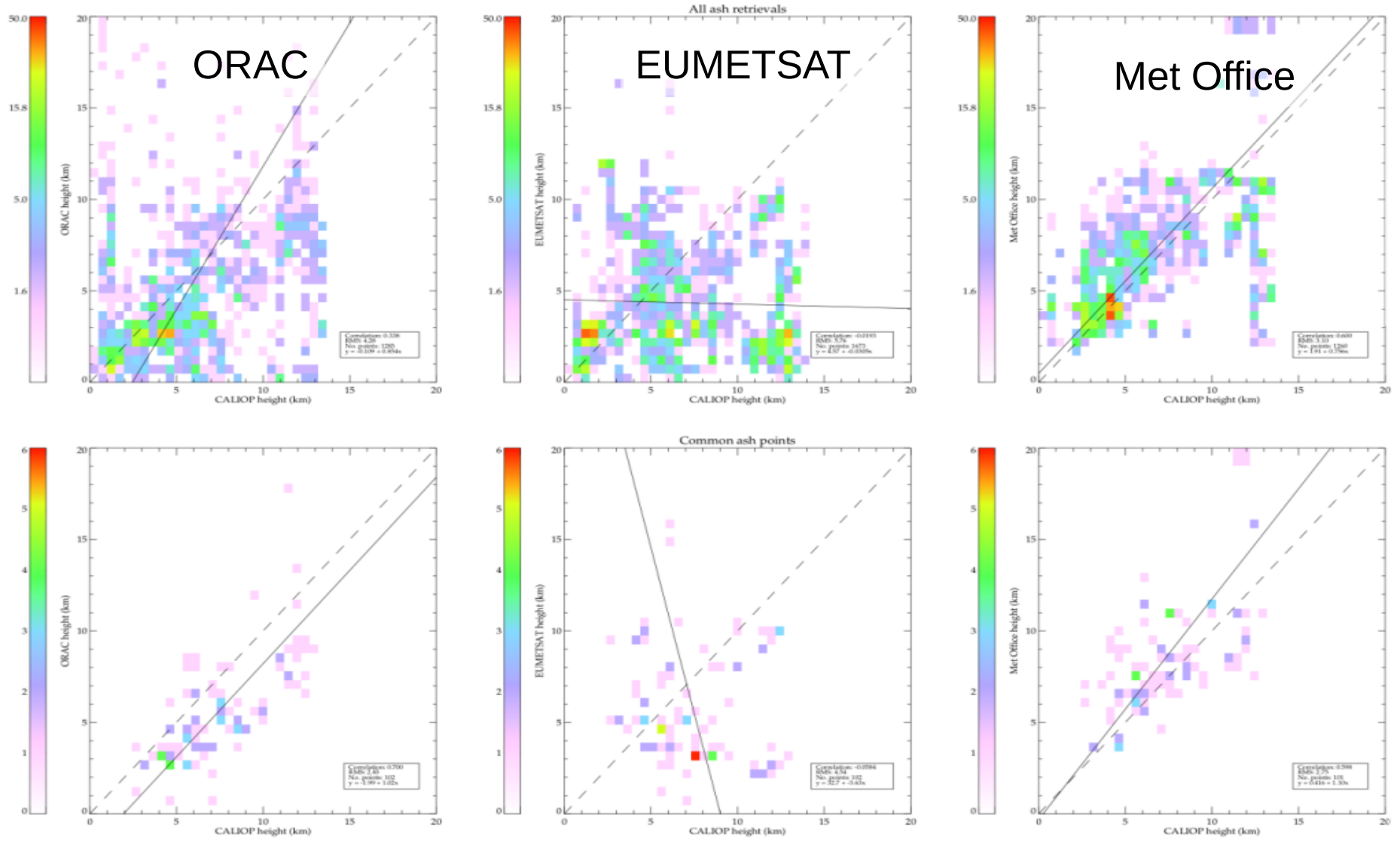
Further Developments

- Further improvements to operational ash detection?
- Comparisons between different quantitative ash retrievals?
- Multi-layer retrievals?
- Greater use of hyper-spectral sounding data?
- Towards a global geostationary capability

© Crown copyright Met Office

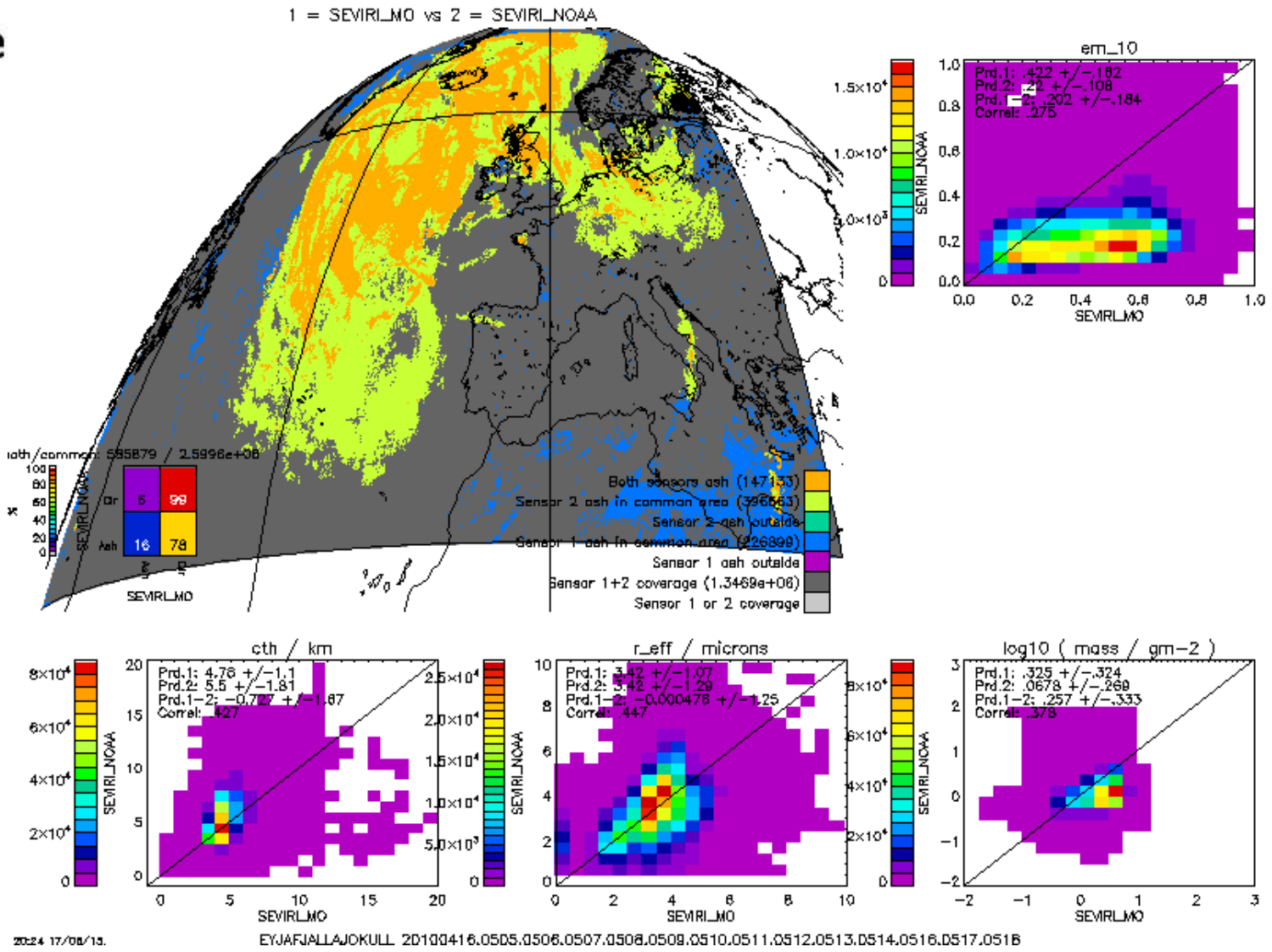
Height validation against CALIOP

RAL Space



Important for agreement to take points observed in common
But ash detections quite different…

SEVIRI, all Eyja cases, v NOAA



© Crown copyright Met Office

Further Developments

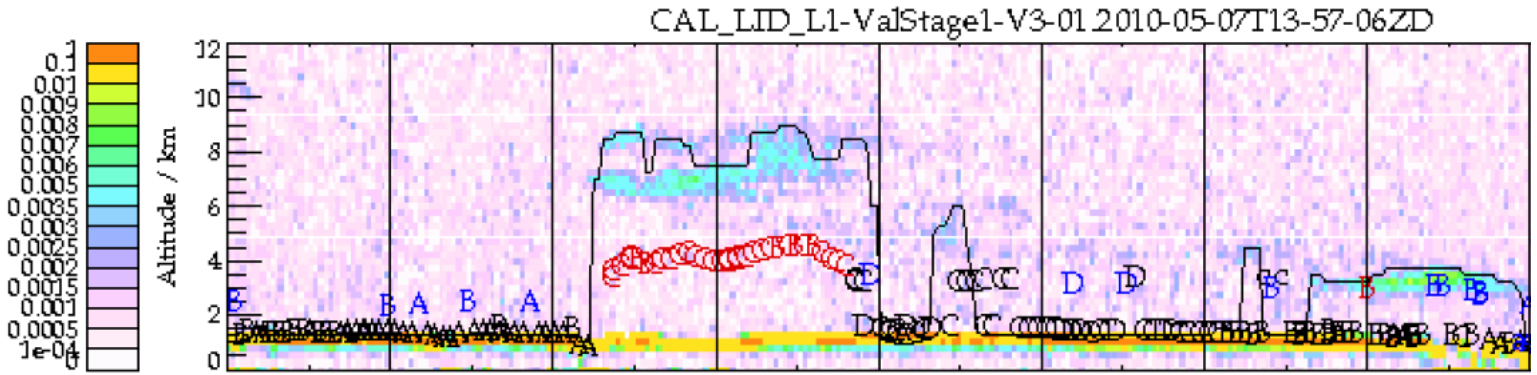
- Further improvements to operational ash detection?
- Comparisons between different quantitative ash retrievals?
- Multi-layer retrievals?
- Greater use of hyper-spectral sounding data?
- Towards a global geostationary capability

© Crown copyright Met Office

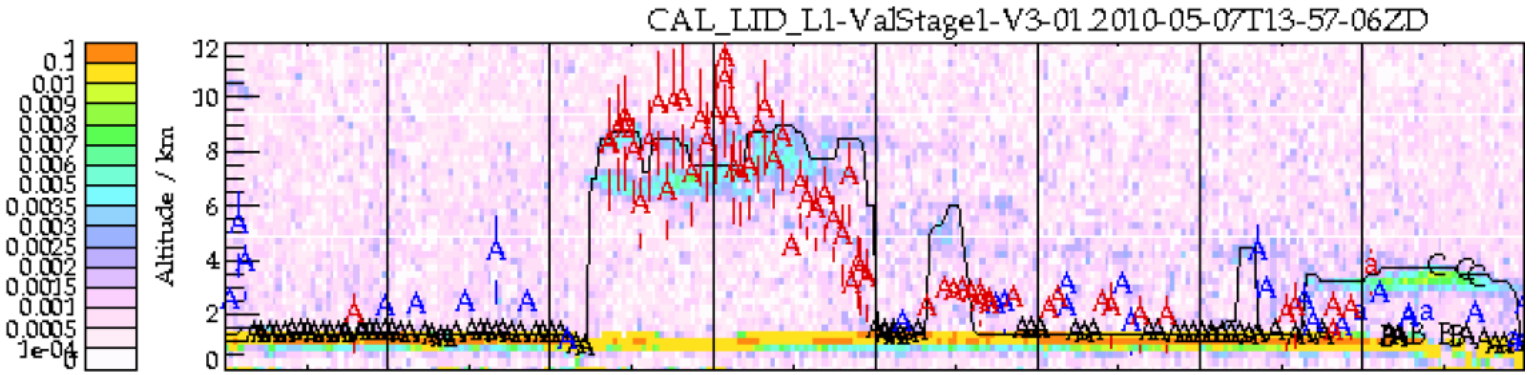
Two-Layer Retrievals

Recent research:
Watts *et al.* (2011)
Siddans & Poulsen (2011)

One-layer



Two-layer



© Crown copyright Met Office

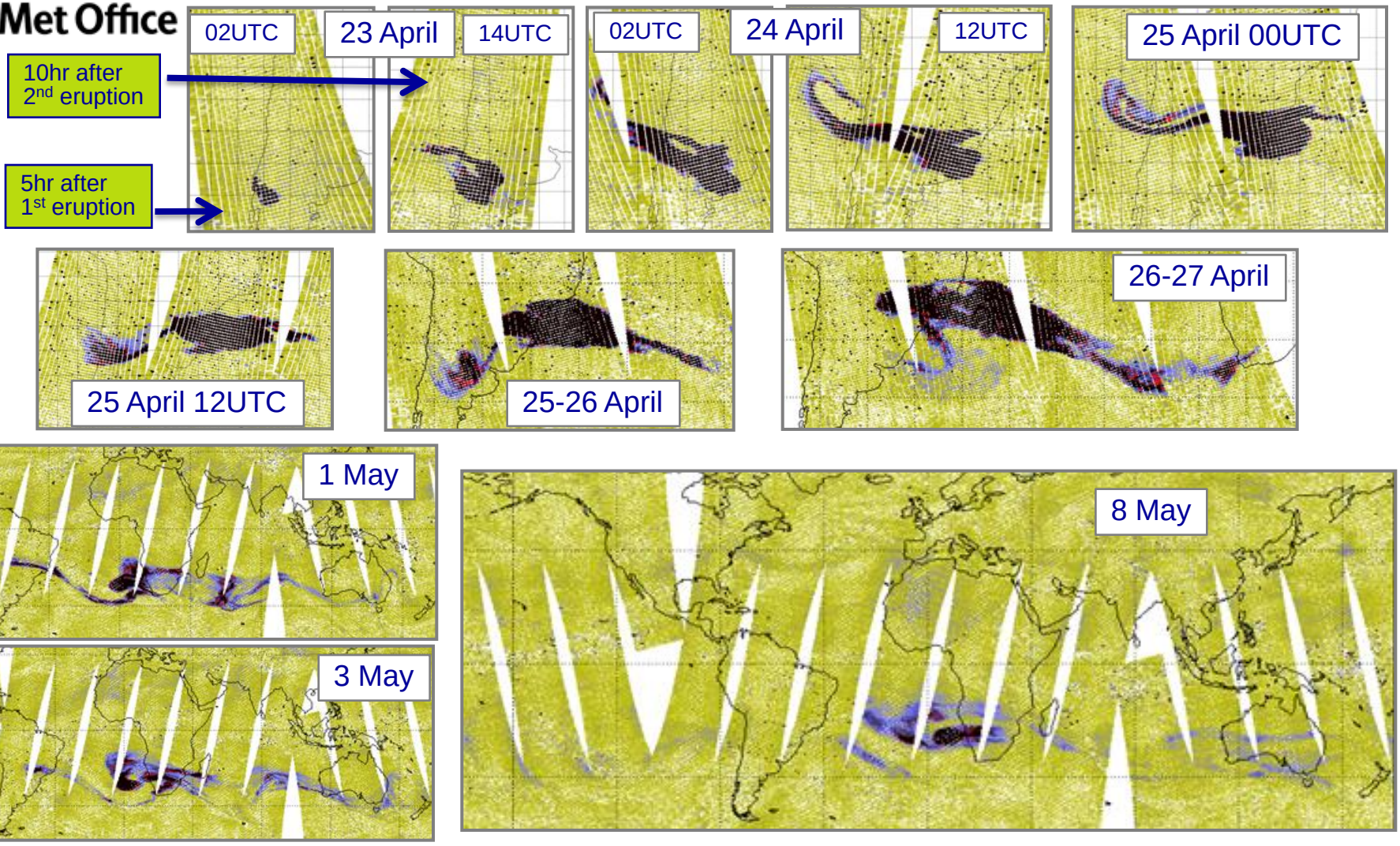
Further Developments

- Further improvements to operational ash detection?
- Comparisons between different quantitative ash retrievals?
- Multi-layer retrievals?
- Greater use of hyper-spectral sounding data?
- Towards a global geostationary capability

© Crown copyright Met Office

Calbuco SO_2 plume from IASI

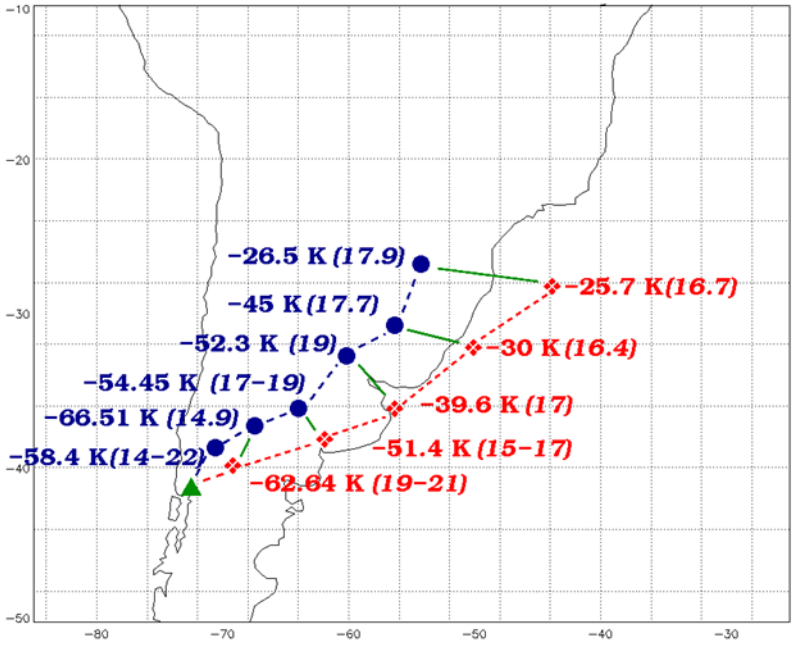
Met Office



© Crown copyright Met Office

SO_2 – Calbuco plume heights (early days)

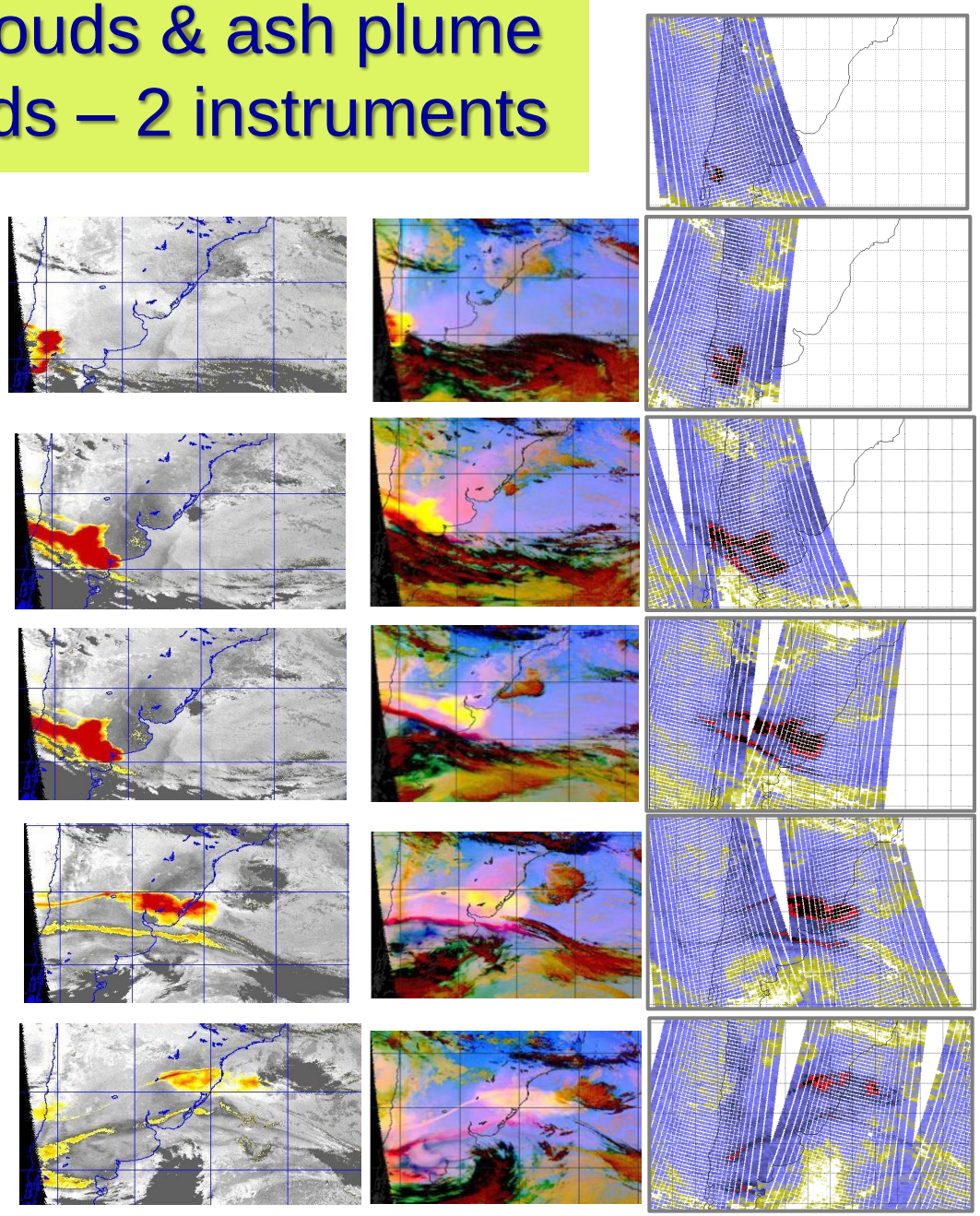
- Dots represent the position of the min DBT (~ max concentration)
- In Blue: from first eruption
- In Red: from second eruption
- Numbers in parentheses are the plume height
- Numbers to the front of the parenthesis are the min DBTs observed in each pass
- Green triangle is the volcano
- Times between each dot ~ 12 hrs



© Crown copyright Met Office

Calbuco clouds & ash plume in 3 methods – 2 instruments

- Left panel:
  - 3 channel detection scheme Francis et al., 2012
  - SEVIRI
- Middle panel:
  - RGB image
  - SEVIRI
  - Yellow ~ ash and SO_2
    Very good agreement with SO_2 plume from IASI
  - Pinky Red ~ Ash
- Right panel:
  - IASI ash & cloud
  - IASI
  - Dark red black →ash
  - Yellow-White → clouds



© Crown copyright Met Office

Further Developments

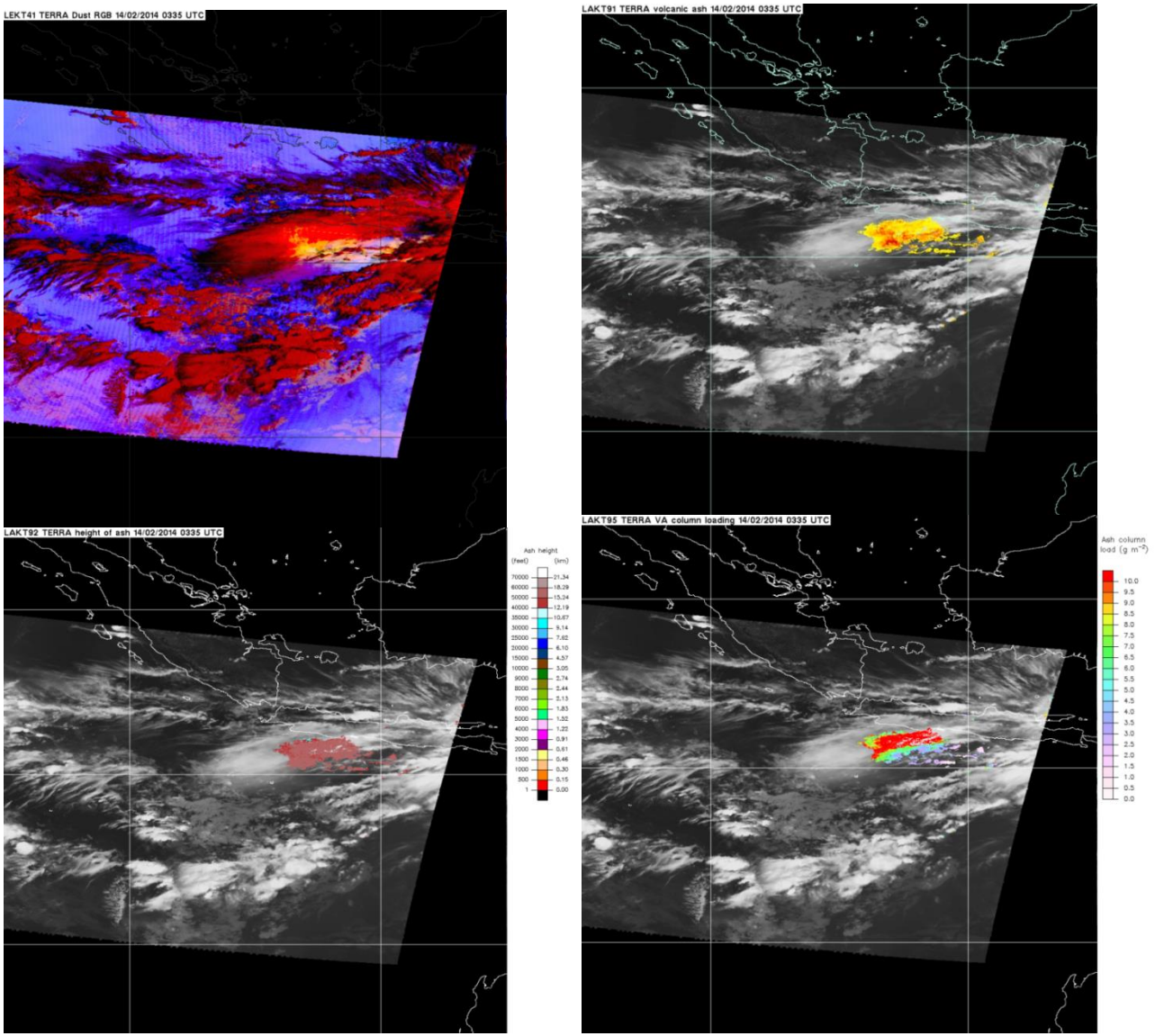
- Further improvements to operational ash detection?
- Comparisons between different quantitative ash retrievals?
- Multi-layer retrievals?
- Greater use of hyper-spectral sounding data?
- Towards a global geostationary capability

© Crown copyright Met Office

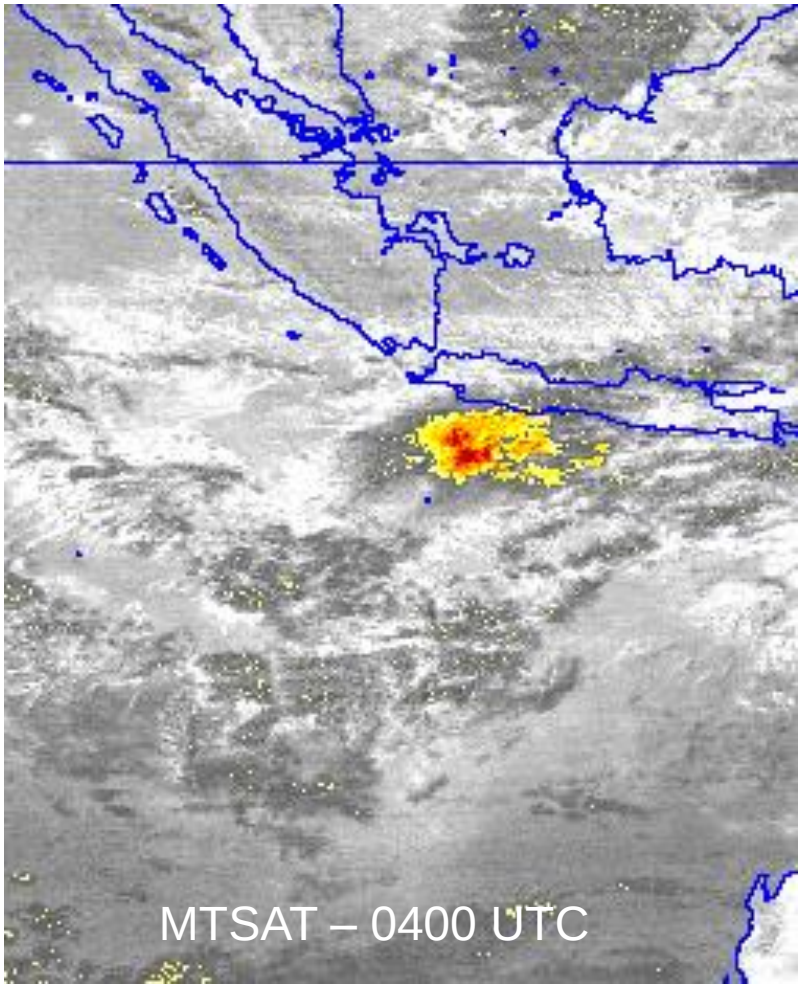
Polar orbiter imagery outside the London VAAC Area

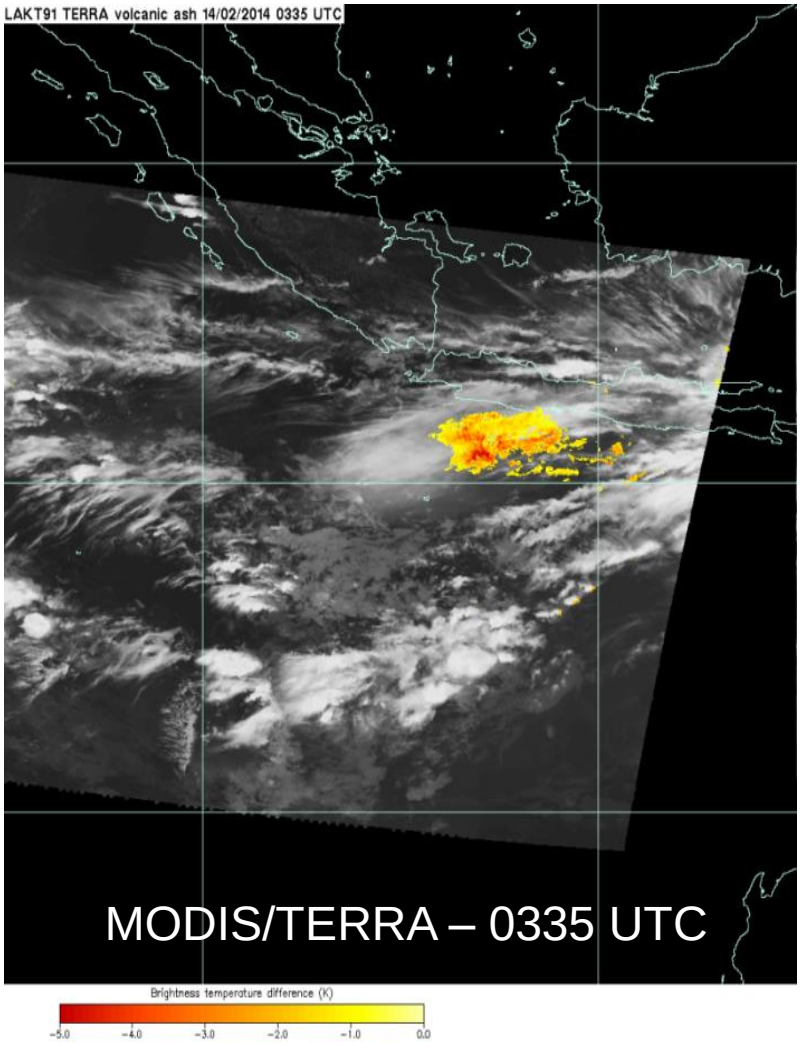
Kelut
14th Feb 2014,
0335 UTC

MODIS/TERRA

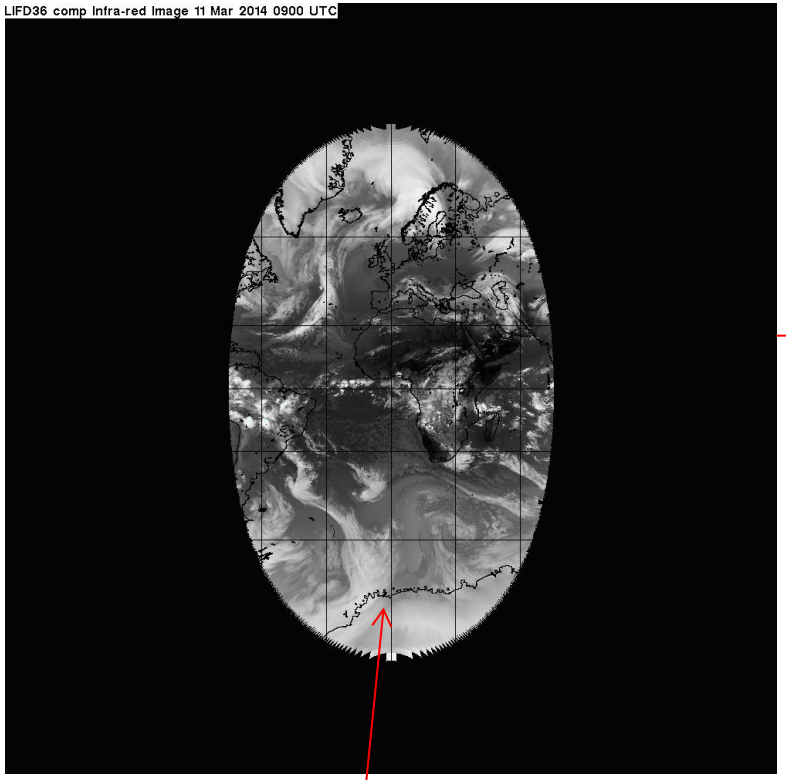


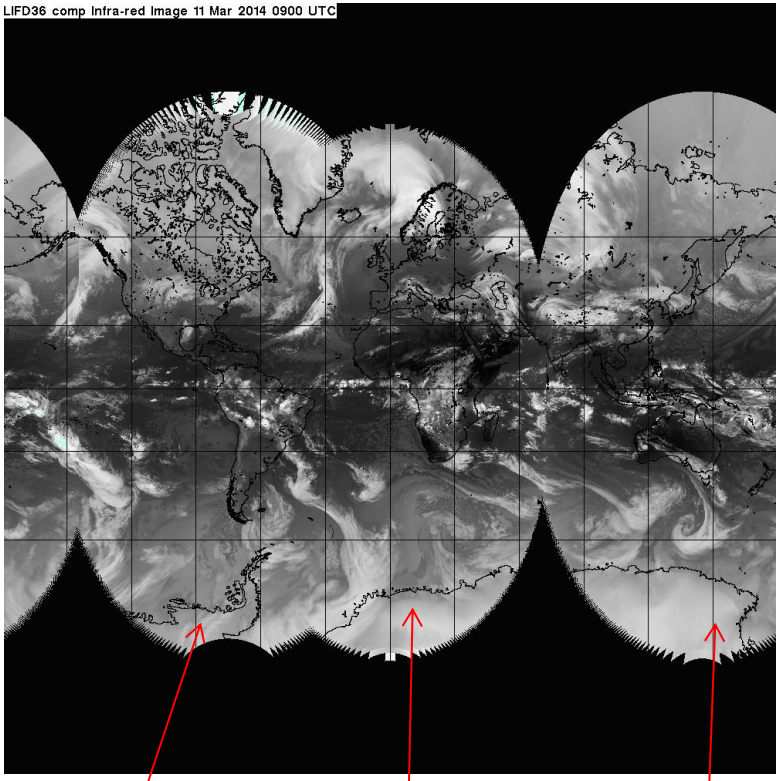
Geo v LEO, Kelut, 2014/02/14





Towards Global Geostationary Coverage





SEVIRI Full Disc

GOES-R launches 2016/17

SEVIRI

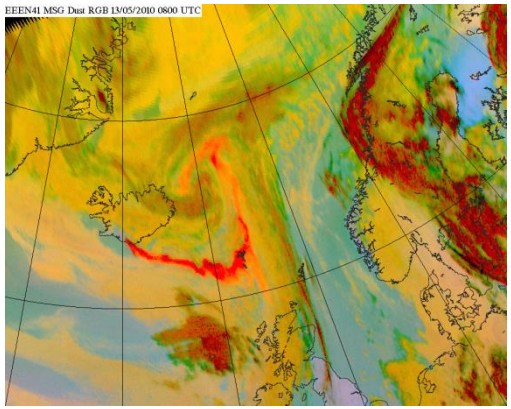
Himawari-8 launched 2014

How do we use satellite products?

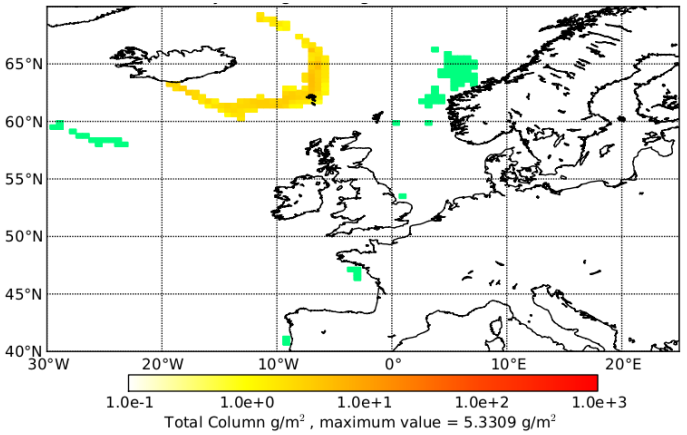
- Real time monitoring of volcanic plumes to inform VAAC forecasters, and hence improve VA guidance
  - Horizontal extent
  - Trajectory (ash height)
  - Radiative ash height estimate
  - Estimate of column mass loading
- Constraining the initialisation of dispersion model runs:
  - To aid specification of source term
  - As part of data inversion process
- Use satellite datasets for post-event validation of the model predictions (together with other observations)

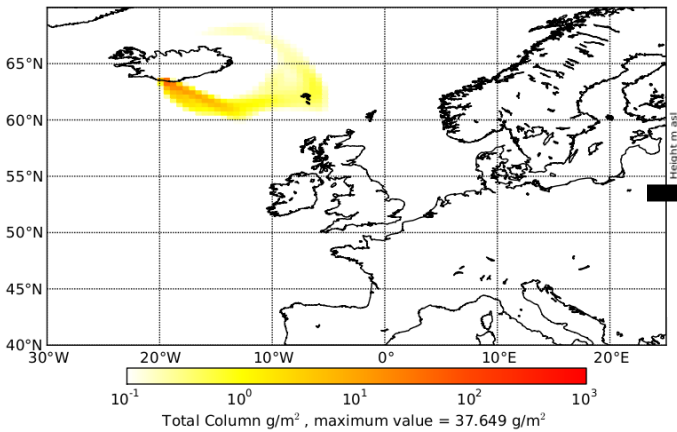
© Crown copyright Met Office

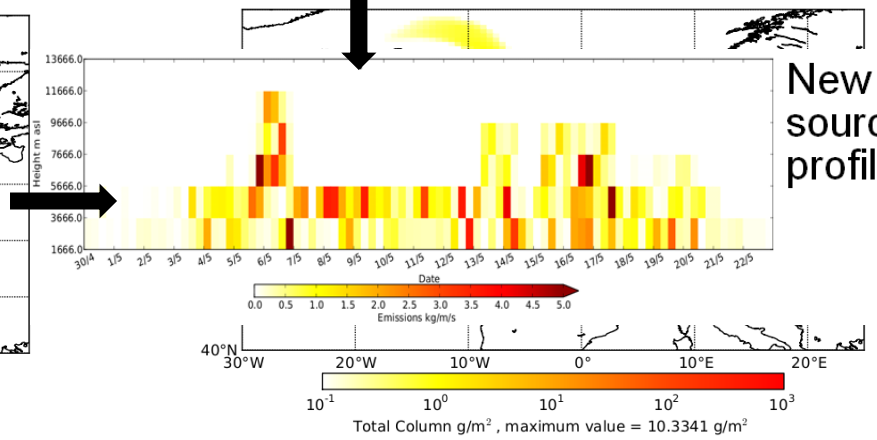
Use of satellite retrievals in model data inversion – development work



Satellite total column retrieval







New fine ash source term profile

From model *a priori*

From model after data inversion, *i.e.* a new modelled plume closer to the satellite observations

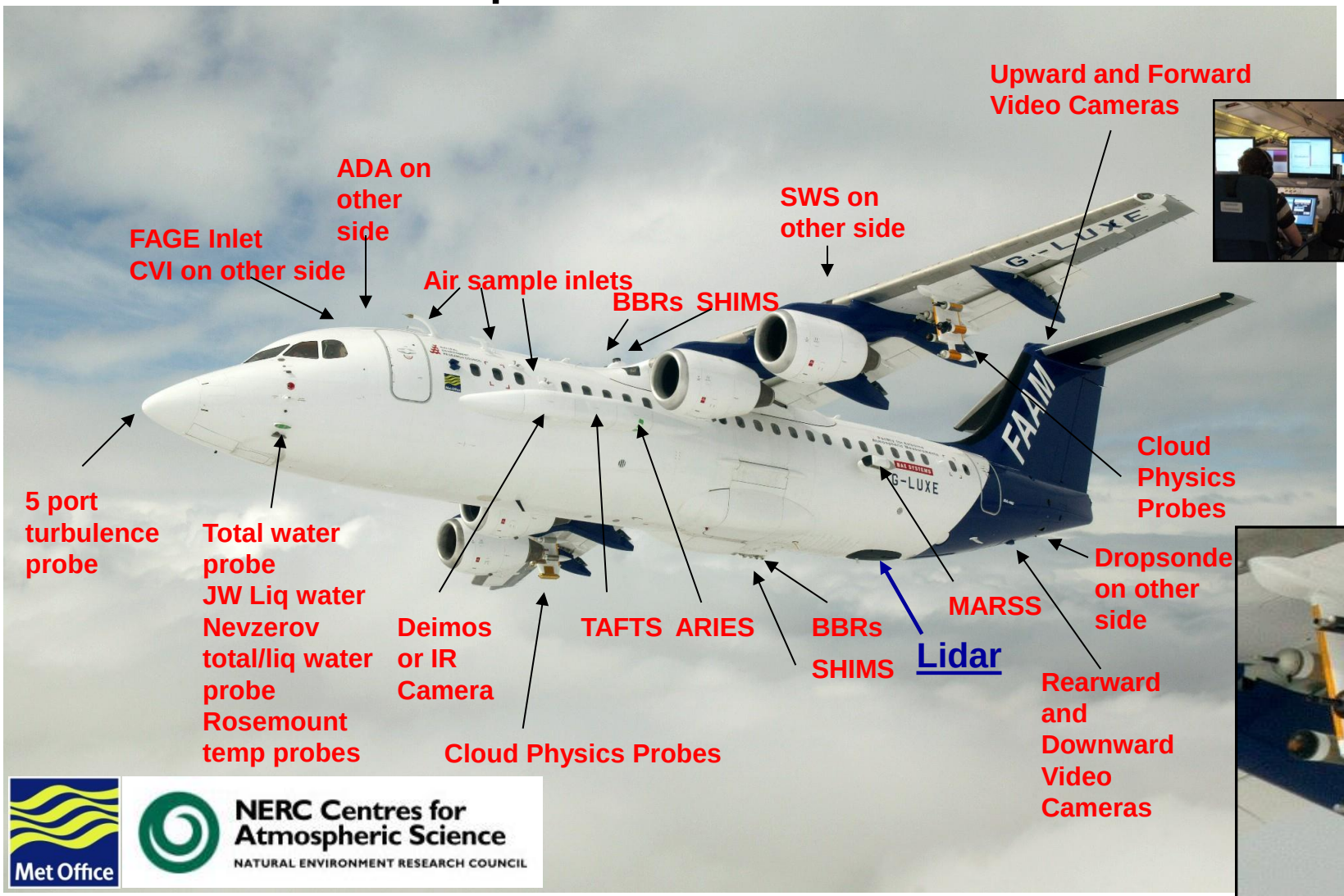
© Crown copyright Met Office

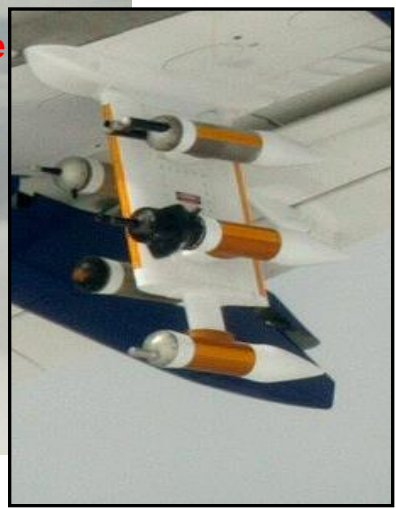
Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

FAAM BAe–146–301
Atmospheric Research Aircraft



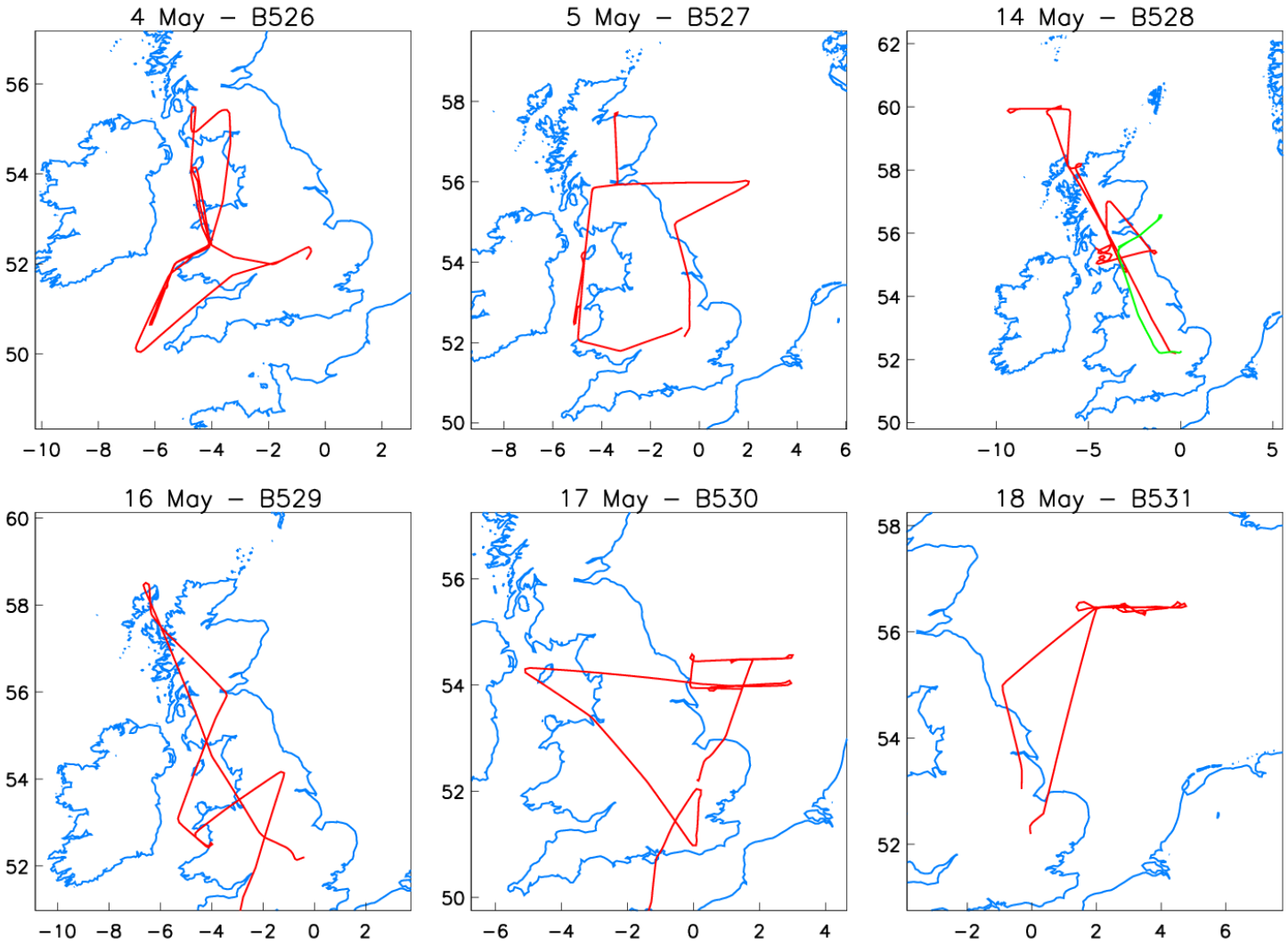


NERC Centres for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

© Crown copyright Met Office

Volcanic ash flights

Early flights (20-22 April): no significant ash.

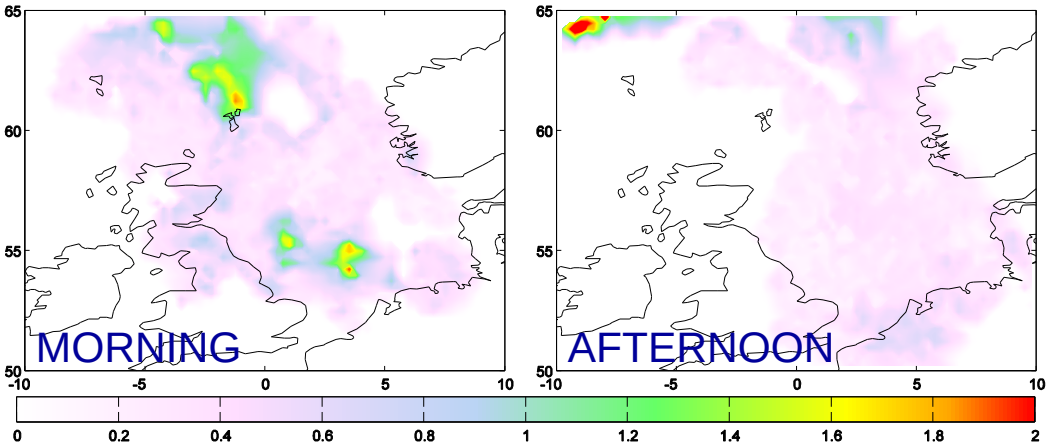


Due to safety restrictions, targeted areas had forecasted concentrations < 2000 μg/m³.

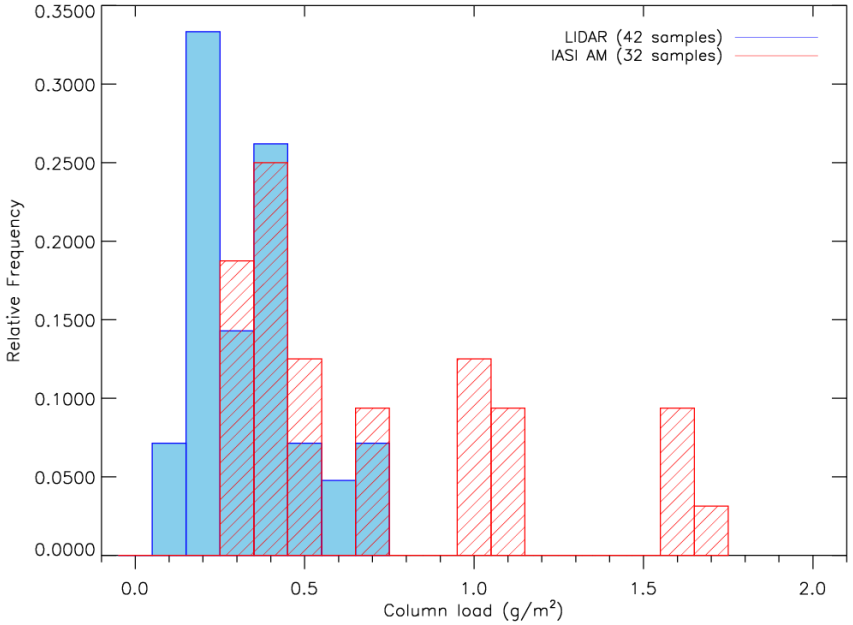
© Crown copyright Met Office

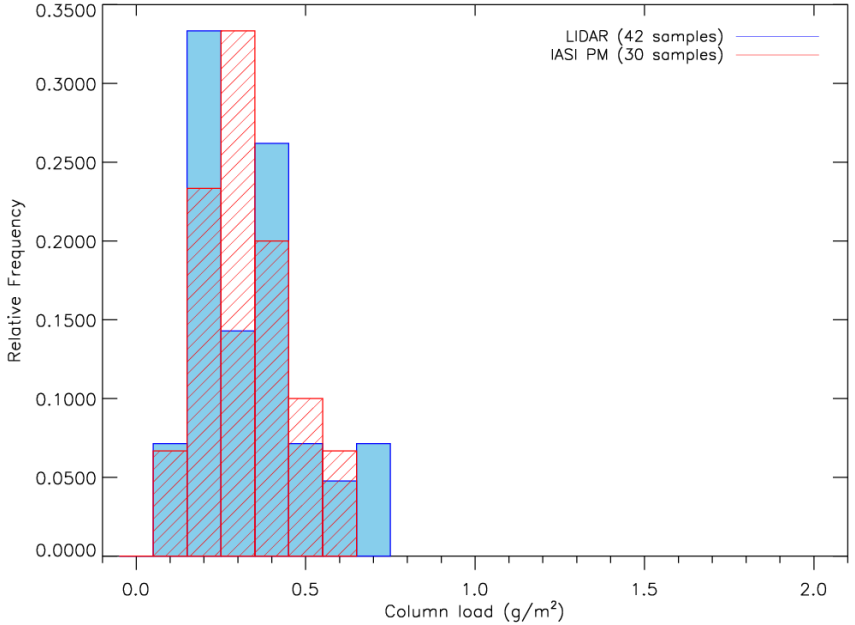
17 May

IASI Infrared Spectrometer
on board the Metop-A satellite



courtesy of L. Clarisse (ULB, Belgium)

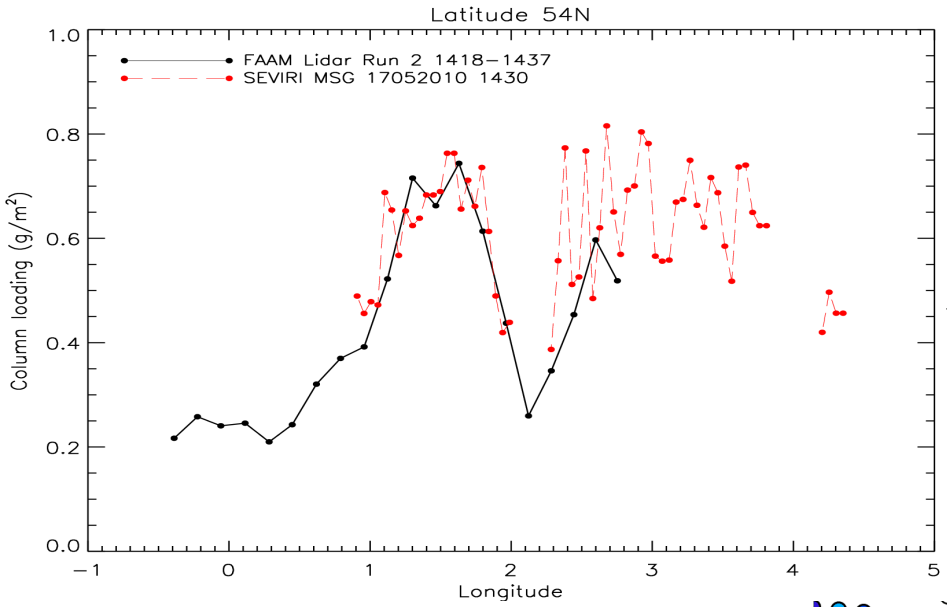


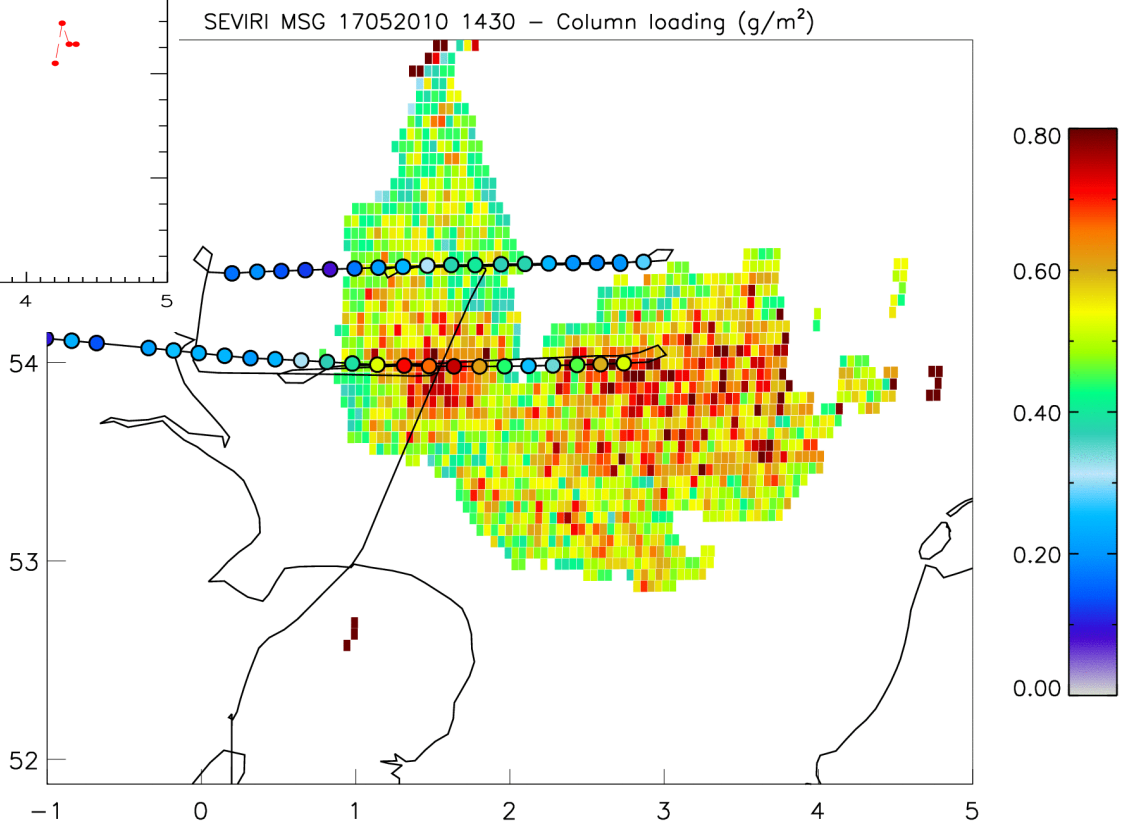


© Crown copyright Met Office

17 May

SEVIRI multichannel imager
on board Meteosat-9



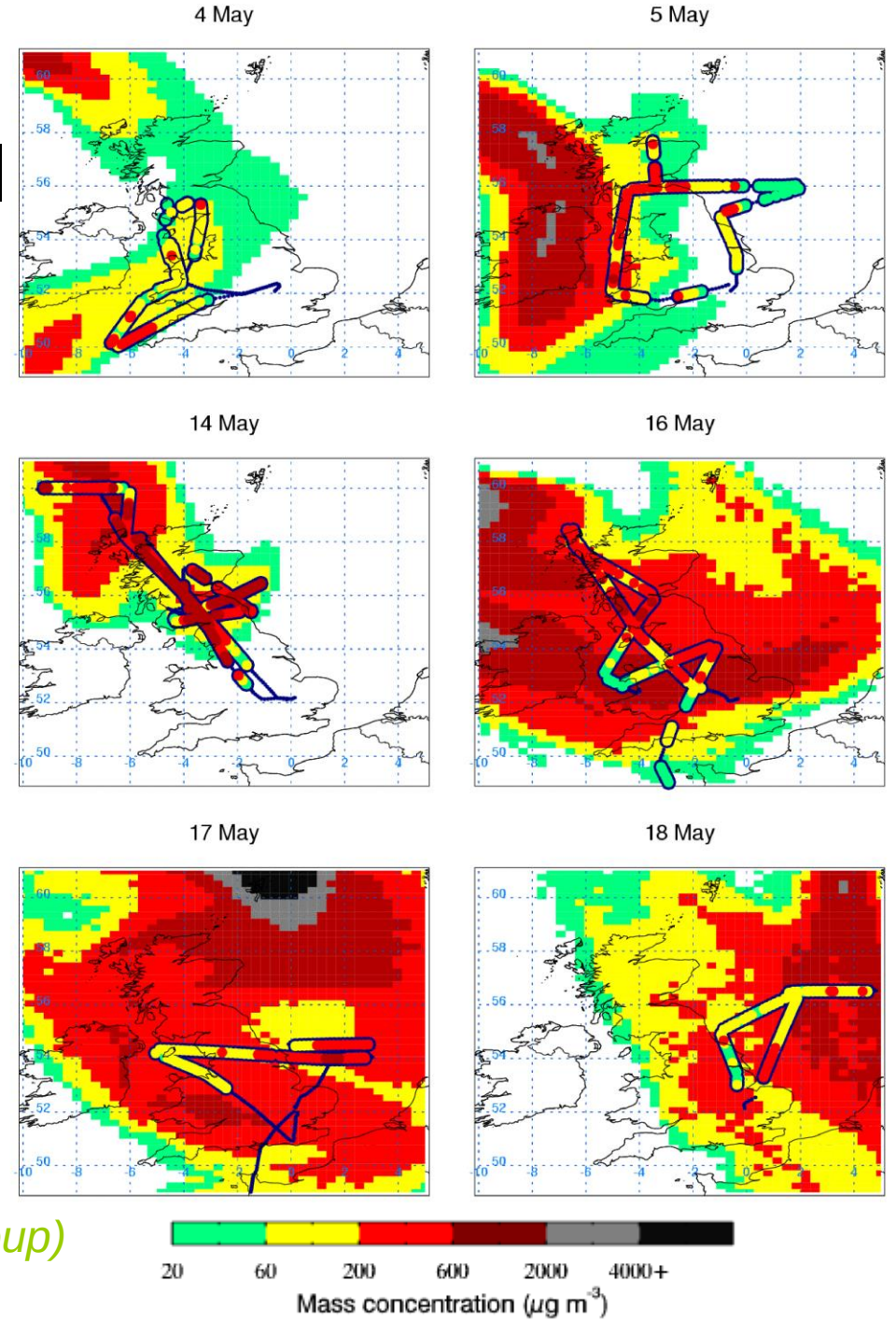


17 May 2010

© Crown copyright Met Office

Airborne lidar vs. NAME model

- reasonable overall magnitude
- positional errors sometimes
- model uncertainties: source term, meteorology, sub-scale processes



courtesy of H. Webster (Atmospheric Dispersion Group)

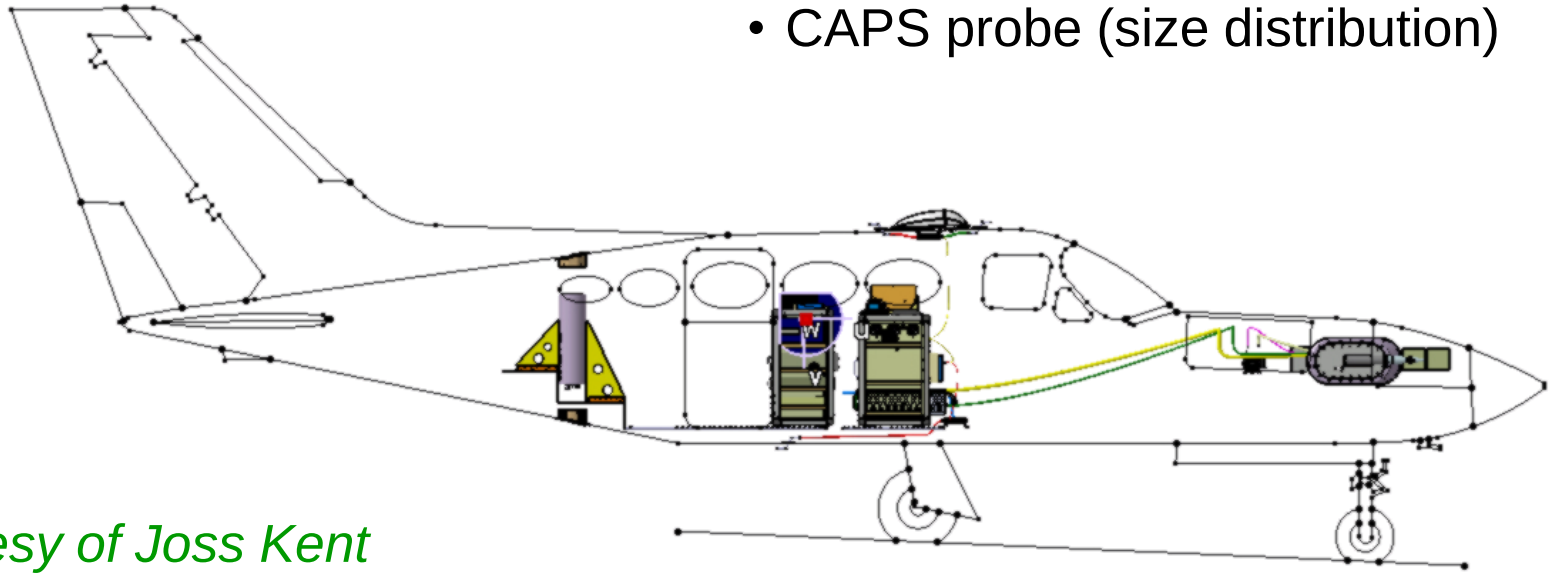
© Crown copyright Met Office

Outlook – MOCCA

Met Office Civil Contingencies Aircraft

Cessna 421C <u>with piston engines</u>

- SO_2 Analyser
- Nephelometer (optical properties)
- Leosphere ALS450 Lidar
- CAPS probe (size distribution)



courtesy of Joss Kent

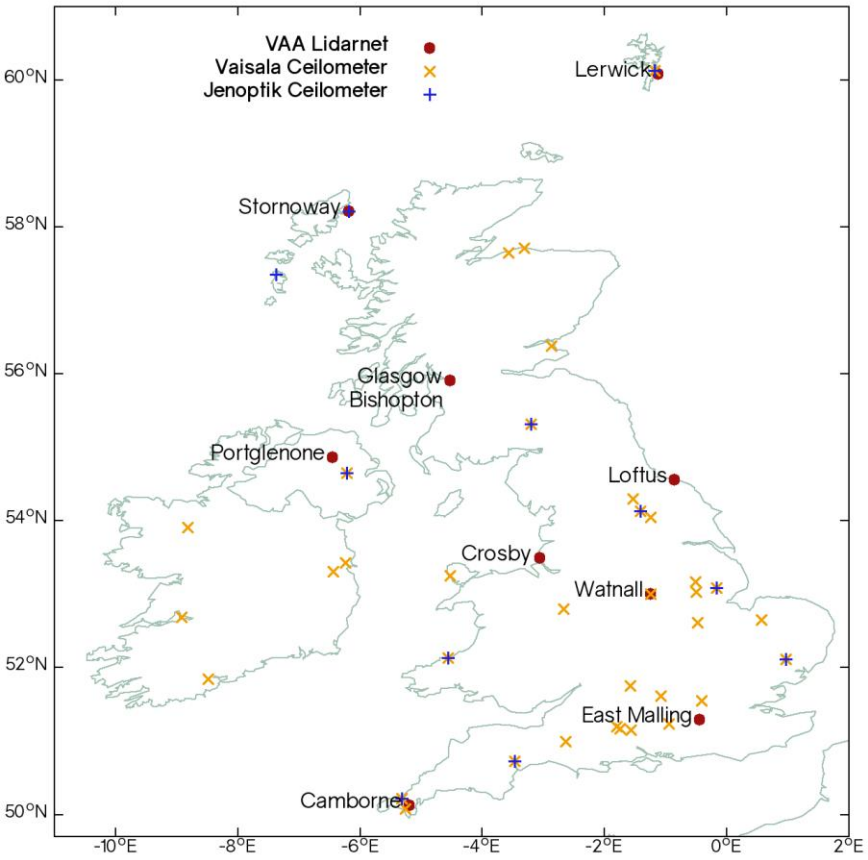
© Crown copyright Met Office

Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

Towards an operational lidar & sun photometer network



- **Purpose:** volcanic ash detection (customer: CAA - Hazard Centre/ London VAAC)
- **Infrastructure**: network (9 fixed sites) + mobile platform
- **Products:**
  - NRT: range-corrected signal and volume depolarization ratio (lidar) + AOD and Ångström coefficient (sunphotometer).
  - Post-processed: aerosol backscatter and extinction coefficients , lidar ratio and linear particle depolarisation ratio (lidar) + Aeronet retrievals including polarisation (sunphotometer)

© Crown copyright Met Office

courtesy of M. Adam and J. Buxman

Overview

- How do we use satellite products?
- Which satellites/instruments do we use?
- Different types of satellite products monitored at the London VAAC
- Ongoing research and development
- Airborne remote sensing
- Ground-based remote sensing
- Summary

© Crown copyright Met Office

Summary

- Satellite data represent the most important observations of volcanic emissions away from the source
- They are crucial in constraining the results from dispersion models such as NAME
- The additional channels of the SEVIRI and MODIS imagers give important additional information on ash amount, height, *etc.*
- The availability of these channels on future geostationary imagers in the near future (Himawari-8/-9, GOES-R) will allow the development of consistent high-quality volcanic ash products over much of the globe
- The spectral coverage and resolution of hyperspectral infrared sounders such as IASI potentially allows for the retrieval of more quantitative information on detection and characterisation of volcanic ash and SO2

© Crown copyright Met Office


Thank you for your attention
– any questions?