Observing and Modelling Near- to Far-Field Plume Processes: Update on the VANAHEIM Project

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Characterisation of the Near-Field Eyjafjallajökull Volcanic Plume and its Long-range Influence

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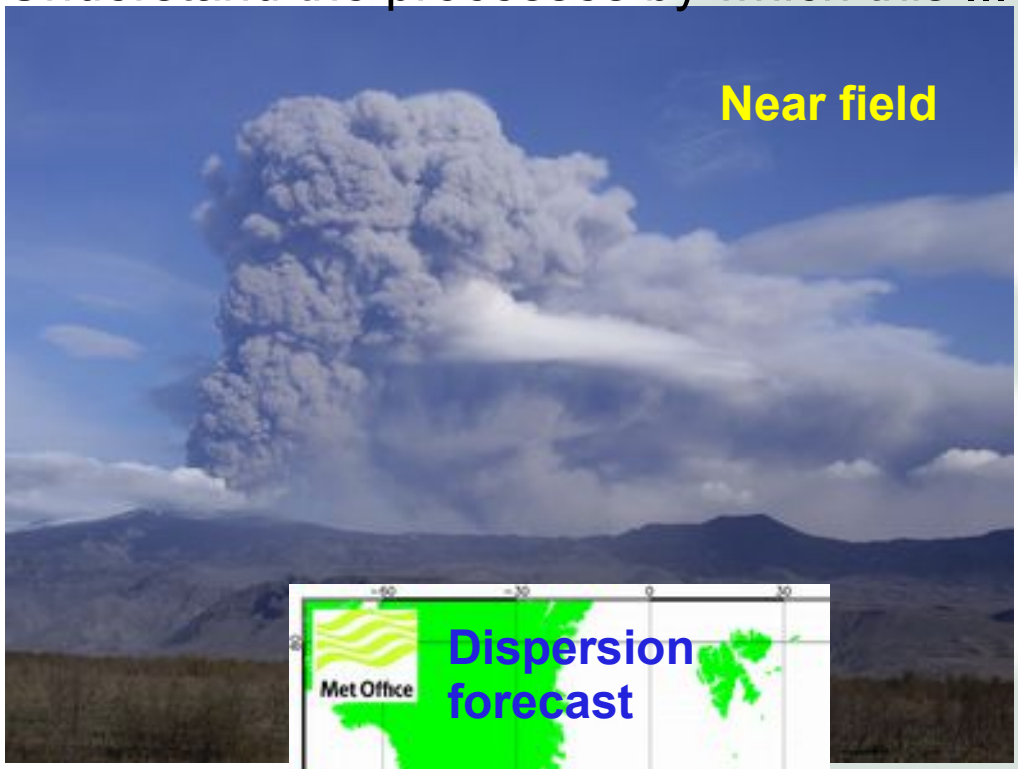
Alan Woolley, Alan Gadian, Ralph Burton, NCAS
Sue Loughlin, BGS
Matt Watson, Andrew Hogg, Jeremy Phillips, Bristol
Don Grainger, Oxford
Hugo Ricketts, James Dorsey, Manchester
Ken Carslaw, Leeds
Paul Palmer, Edinburgh

Met Office	Icelandic Meteorological Office
Institute of Earth Sciences, University of Iceland	Department of Physics, University of Iceland
University of Geneva	Civil Aviation Authority
National Institute of Geophysics & Volcanology, Italy	Norwegian Institute for Air Research
Deutsches Zentrum für Luft- und Raumfahrt	Rolls-Royce plc
University of Hertfordshire	Lancaster University
University of Cambridge, Dept of Geography	University of Edinburgh
University of Ghent	Cambridge University Hospitals Trust
NASA Goddard Space Flight Center	Barcelona Supercomputer Center

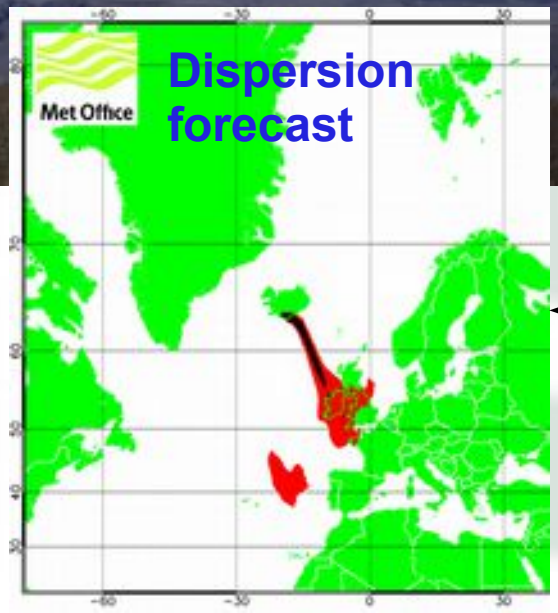
VANAHEIM partner organisations

VANAHEIM: what it aims to achieve

Understand the processes by which this ...

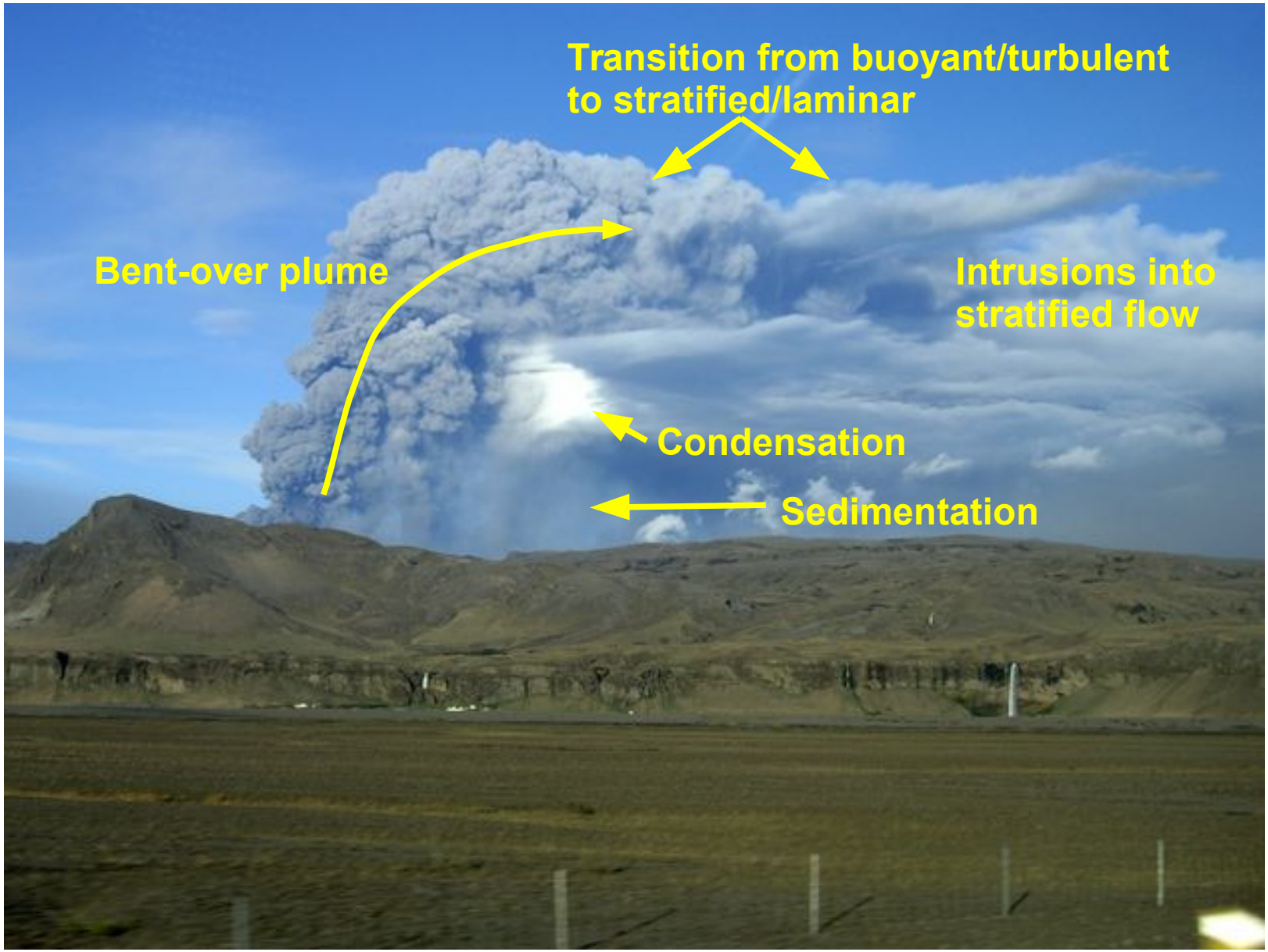


... becomes this ...



... in order to help develop this

For example, these processes ...



The near field processes are crucial ...

For example ...

Ash layers over the Orkney Islands – 16 Ma
Sanday
North Ronaldsay

VANAHEIM Science Objectives

SO1. Very high resolution nested, multiphase flow numerical model of a volcanic plume, based on the WRF weather prediction model.

SO2. Mechanisms for development of observed layered structure of ash plumes.

SO3. Fluid dynamical understanding of the buoyancy effects in ash intrusions.

SO4. Aerosol model for volcanic plumes including detailed physics/chemistry parametrisations to allow forecasts for volcanic gases to be made.

SO5. Develop and refine satellite retrieval algorithms for volcanic ash and trace gases suitable for assimilation into dispersion models.

SO6. Complete analysis of existing Eyjafjallajökull observational data (ground-based & airborne from the UK) and to use this to prepare for future measurements.

SO7. Carry out future observations of volcanic plumes in and around Iceland.

SO8. Combine the computational fluid dynamics, aerosol modelling and chemistry modelling into an integrated modelling system for the near source region.

SO9. Comparisons between model and observations.

Organisational and Impact Objectives

OO1. Thorough analysis and interpretation of existing Eyjafjallajökull atmospheric data from the April/May eruption

OO2. Make necessary preparations to enable future observations to start immediately if the opportunity arises

OO3. Provide assessment of the needs and requirements of future in-depth research

OO4. Coordinate the work with existing activity (e.g. NERC urgency projects) and project partners

OO5. Carry out a field programme of atmospheric measurements should the opportunity arise

IO1. Assist the Icelandic Meteorological Office in building capacity for future volcanic observations (IMO, Met Office, NCAS and BGS MoU)

IO2. Feed into the continued development of the UK Met Office's volcanic ash dispersion forecasting and other international developments

IO3. Tailor our research to address the Met Office requirements for development of algorithms for operational data assimilation schemes

High resolution, time-dependent numerical modelling

Ralph Burton & Stephen Mobbs, NCAS

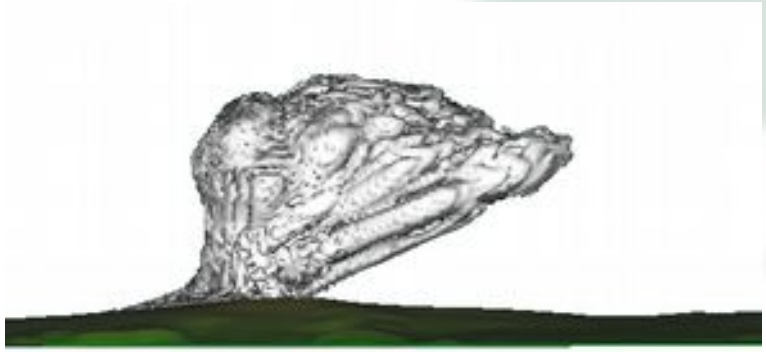
Development of a full multi-phase flow model for the near-field plume: Modification of the Weather Research and Forecasting (WRF) model

- State-of-the art numerical weather prediction model
- Sophisticated physical packages: boundary layer, microphysics, radiation, surface scheme, data assimilation, etc.
- Initialised from global forecasts / analyses or vertical profiles
- Model multiple ash particle sizes/densities
- Add a thermal perturbation (or surface heat flux) to surface, co-located with ash release
- Add specified ash injection speed
- Add sedimentation velocity to ash
- Add Wet / Dry deposition of tracers

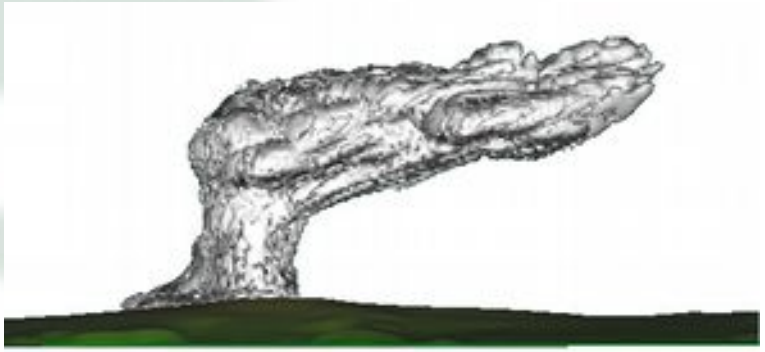
First test: comparison with theoretical plume rise in calm conditions: excellent agreement

High resolution, time-dependent numerical modelling

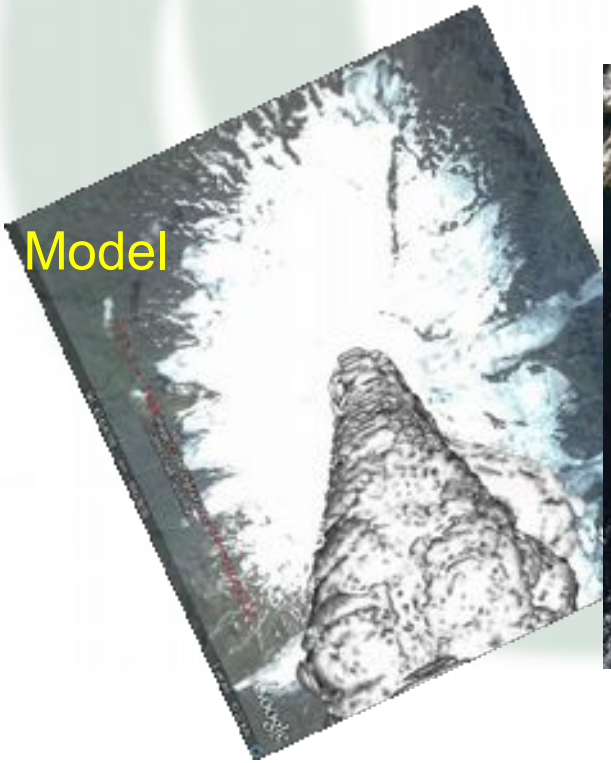
Bent-over Plumes

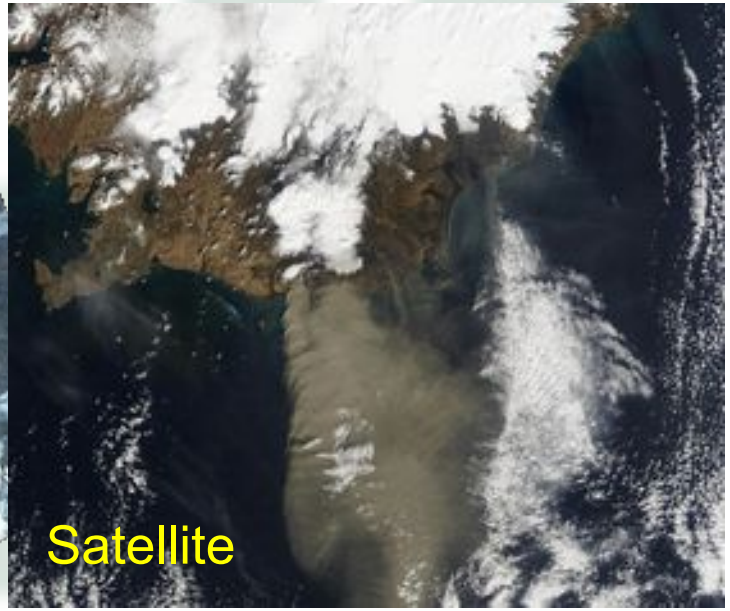


Large ash particles



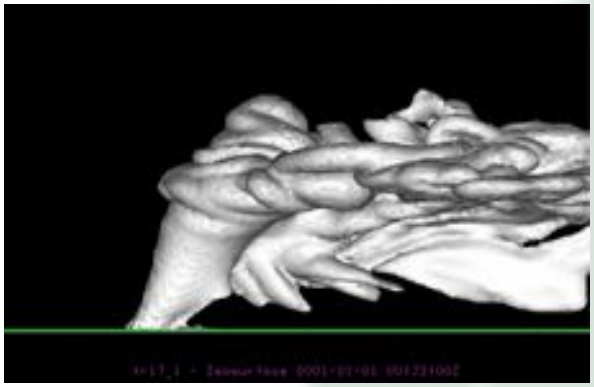
Small ash particles



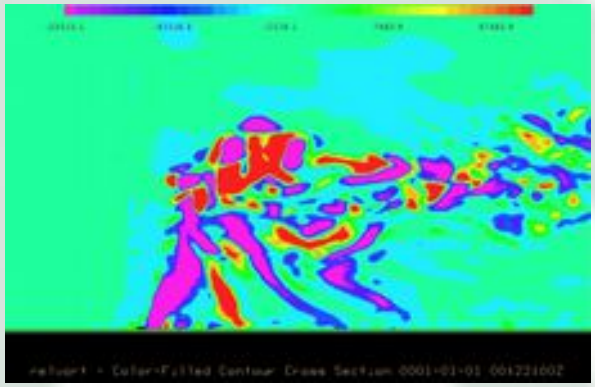


High resolution, time-dependent numerical modelling

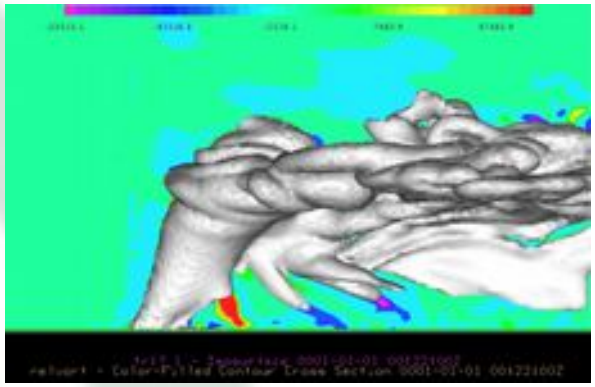
Modelling observed ash transport downwards along vorticity "tubes"



Ash



Relative vorticity



Relative vorticity + ash

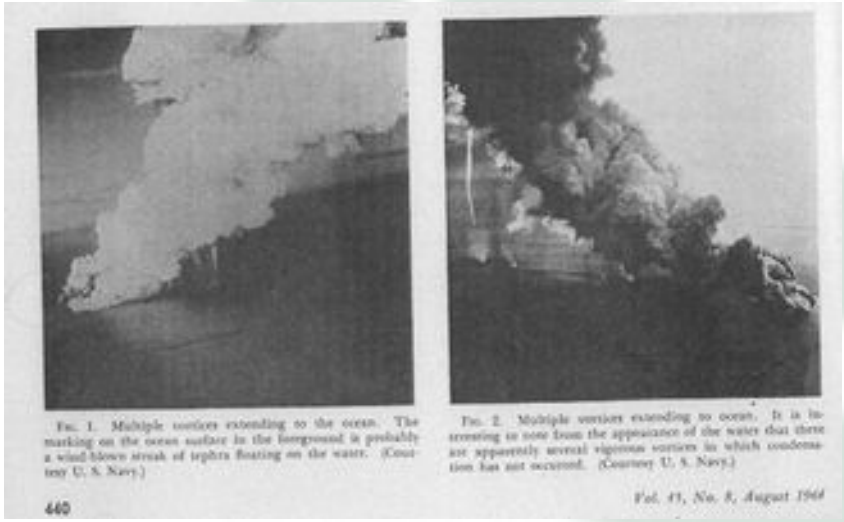


FIG. 1. Multiple vortices extending to the ocean. The marking on the ocean surface in the foreground is probably a wind-blown streak of tephra floating on the water. (Courtesy U. S. Navy.)

FIG. 2. Multiple vortices extending to ocean. It is interesting to note from the appearance of the water that there are apparently several vigorous vortices in which condensation has not occurred. (Courtesy U. S. Navy.)

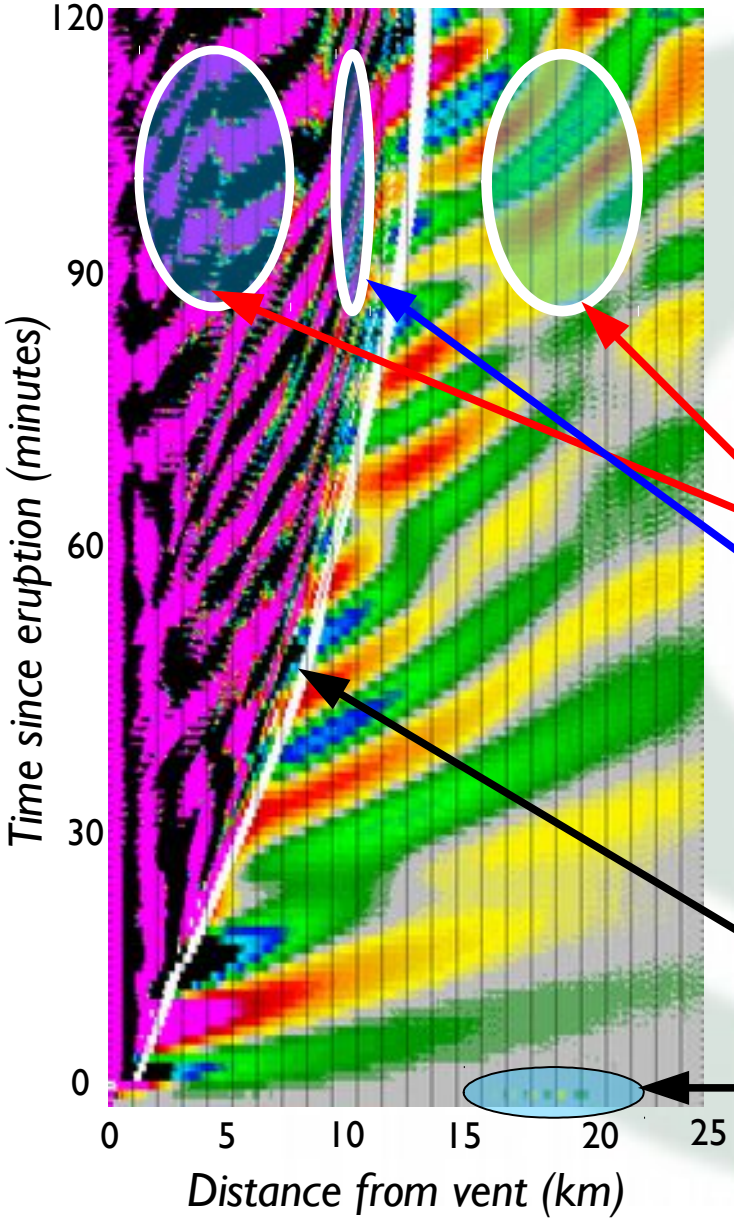
460

Vol. 45, No. 8, August 1964

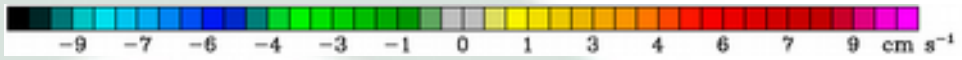
Appears to be the first successful attempt to model this phenomenon, allowing analysis of the physical processes

Thorarinsson *et al.* "Whirlwinds produced by the eruption of Surtsey Volcano," BAMS **45**, 8, 1964

High resolution, time-dependent numerical modelling



Time-distance plot of vertical velocity at height 5 km



vertical velocity

Slower (~5m/s phase speed) wave packet embedded in **faster** (~10m/s phase speed) wave packet.

Fast

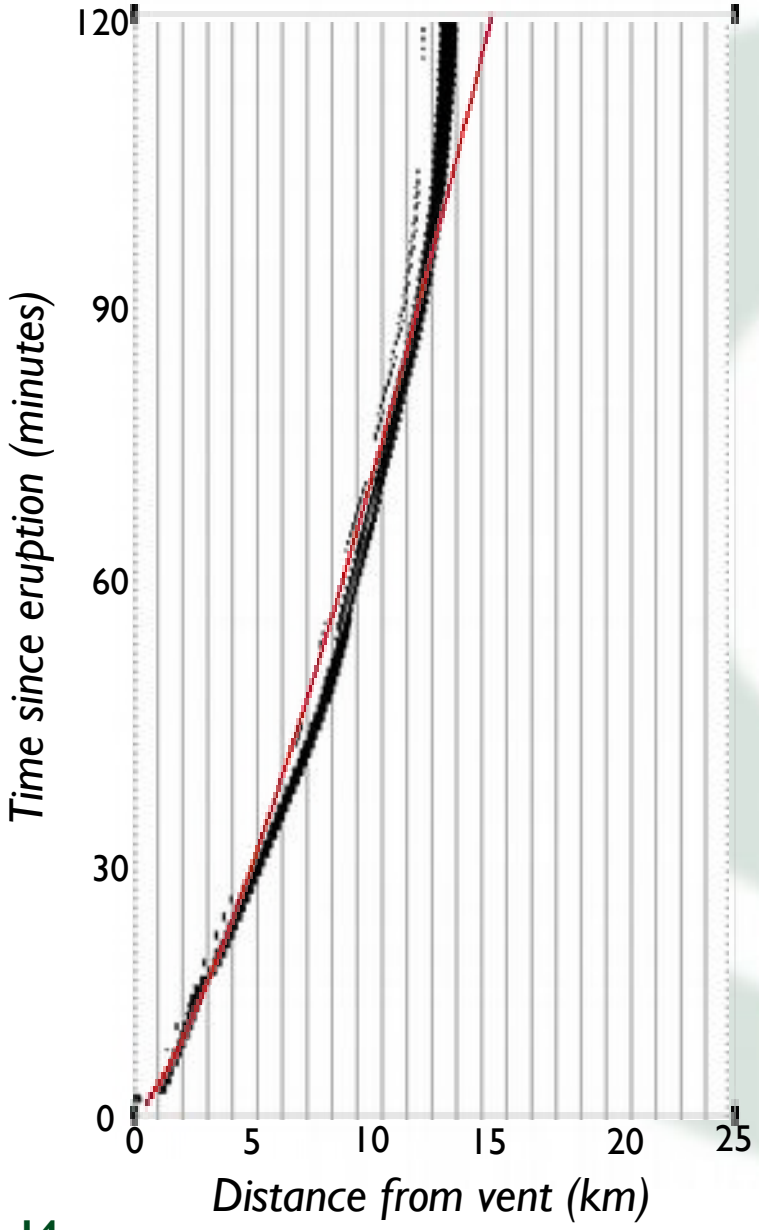
Slow

'Slow' packet has lower wavelength. Edge of plume co-located with the edge of the 'slow' packet

Edge of plume (solid white)

Remnants of initial "shock"
– travels at speed of sound

High resolution, time-dependent numerical modelling



Using mathematical modelling to validate and interpret numerical modelling

New plume spreading theory: Andy Hogg: Bristol

Plume spreads as width ~ $t^{3/4}$

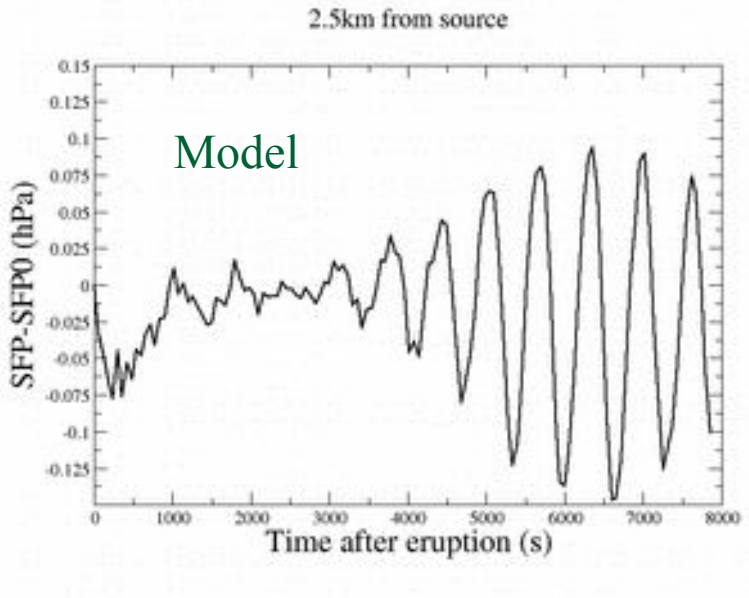
Assuming constant wind speed this also means width ~ distance$^{3/4}$

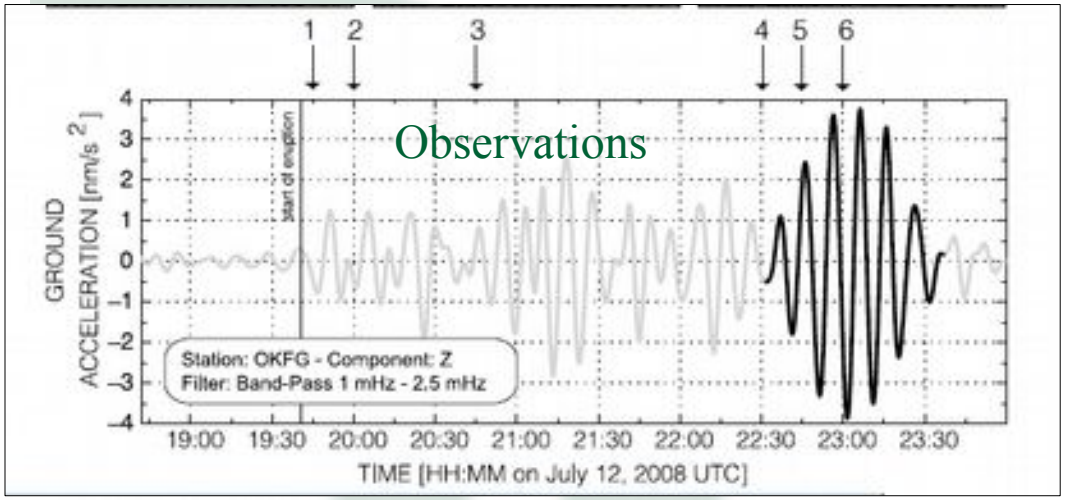
Solid black line is model

Solid red line is width ~ $t^{3/4}$

High resolution, time-dependent numerical modelling

Radiating Atmospheric Gravity Waves





Surface pressure fluctuations

Similar behaviour shown to that observed at Okmok volcano: Angelis *et al.* (2011) *GRL* **38**, L10303

Similar frequency response (observed: 1.7mHz: modelled: 1.6mHz) for duration of “monochromatic” phase.

Mathematical modelling of bent-over plumes

Mark Woodhouse & colleagues, Bristol

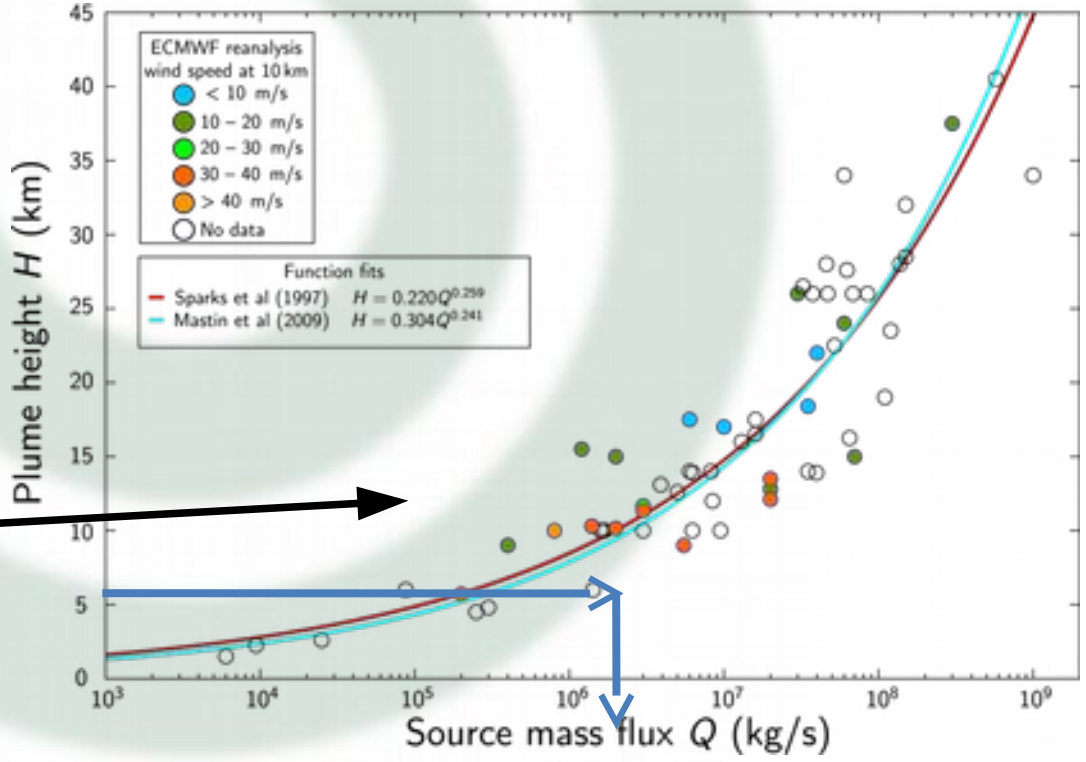
Need height at which material spreads laterally (the *plume height, H*) and the rate at which ash is delivered from the volcano (the *source mass flux, Q*).

Q and *H* related via dynamics of buoyant plume rise.

Relationship between *Q* and *H* has been calibrated using historical eruptions.

Observed plume height can be used to estimate the source mass flux.

This approach does not account for the the effect of wind variation on plume rise.



Mathematical modelling of bent-over plumes

Wind has a very strong on weak effect on volcanic plumes, e.g.
Kirishima volcano, Japan
Eyjafjallajökull, Iceland

Wind enhances mixing, reduces buoyancy and so reduces the height of plume rise.

Simple mathematical models of volcanic plumes have been used to understand plumes rising in calm environments.

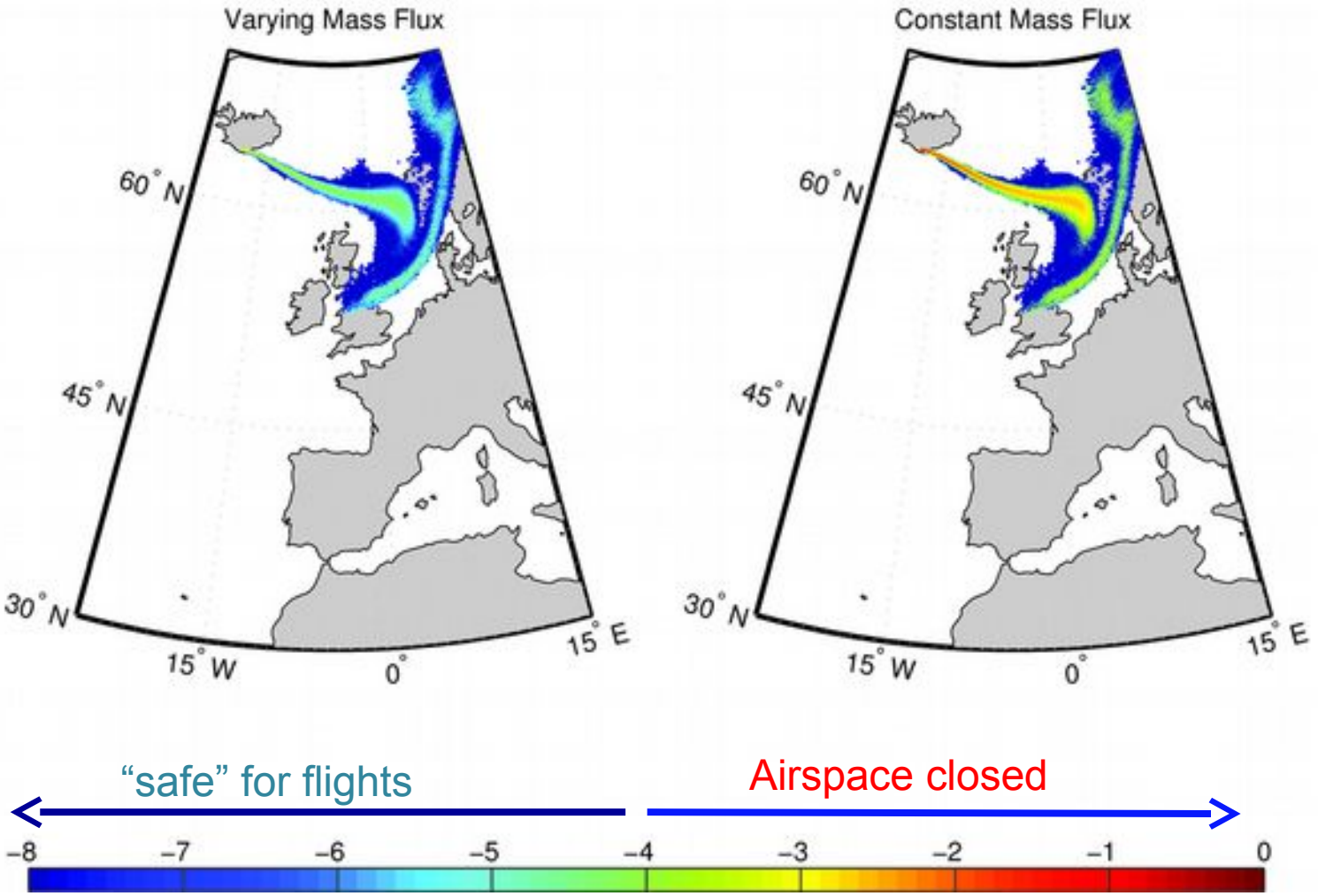
We've extended these models to include the effects of wind.

Mathematical modelling of bent over plumes

Ash dispersion 25 hours after start of eruption.

Source flux estimated from curve fit (no wind effect)

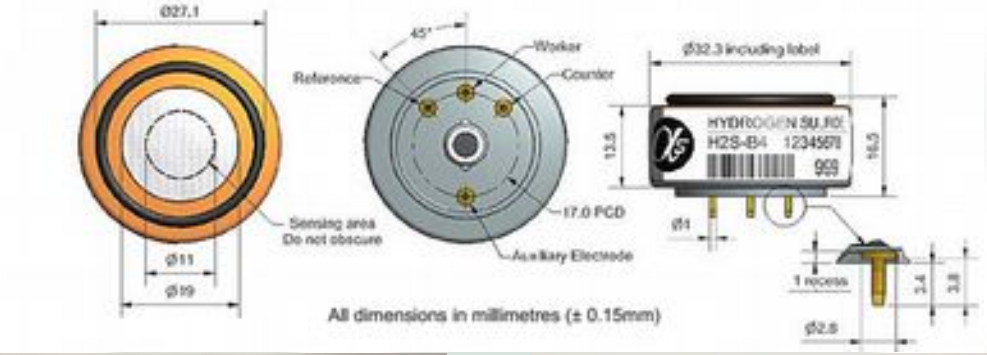
Estimate from our model with wind

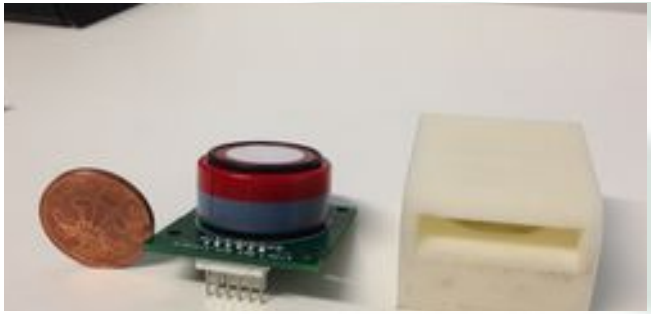


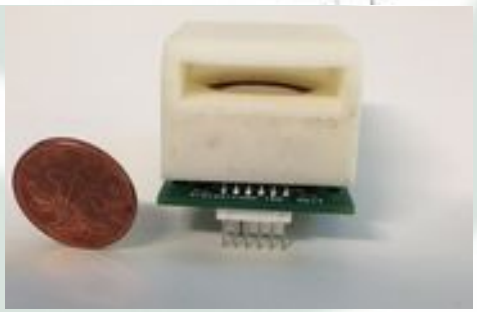
Gas detection using UAVs and sensors

Ally Lewis, Richard Lidster and colleagues, York

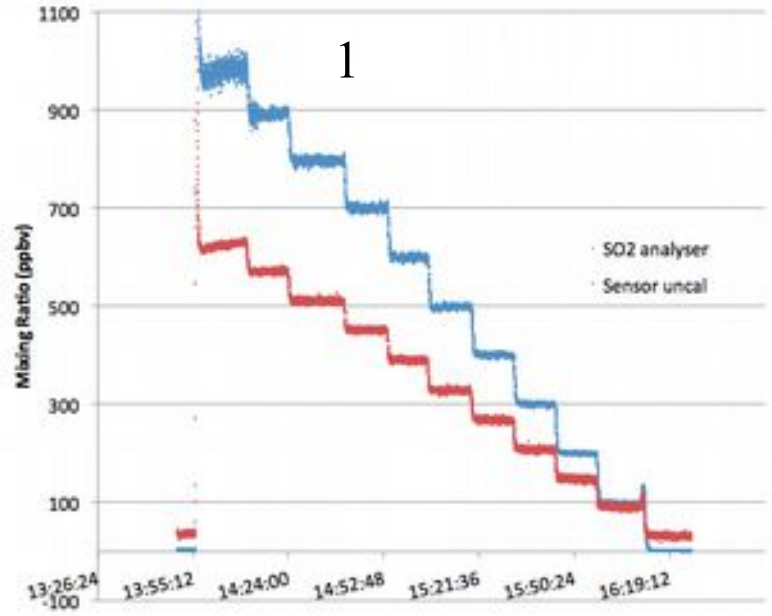
- Aims: To study the quantitative emission of SO_2 close to source using miniaturised electrochemical sensors carried by a UAV.
- Primary sensor is SO_2 but the sensor package is interchangeable for CO and H_2S if required.
- Key laboratory work is to investigate sensor performance and calibration under real-world conditions (e.g. variable T, P, H_2O etc)



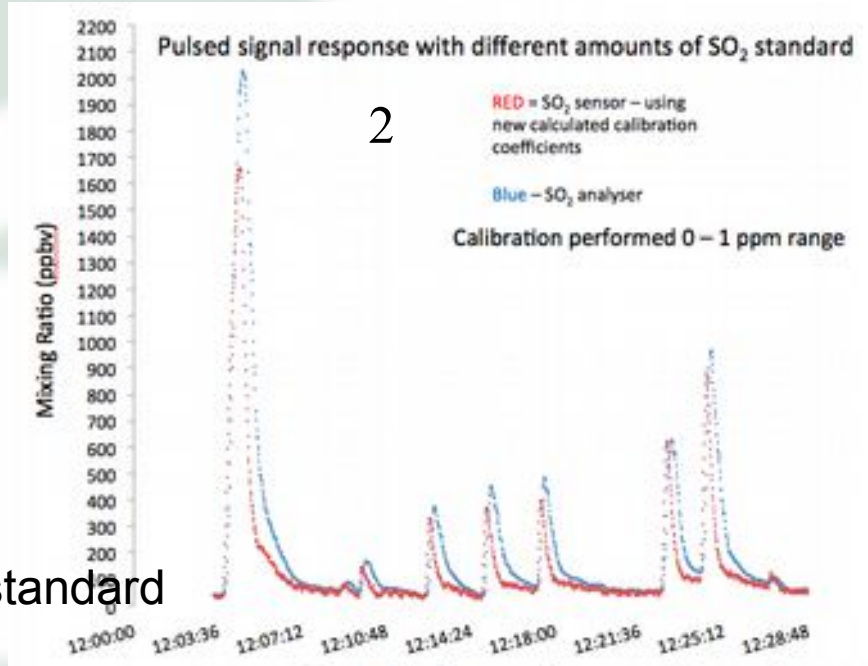




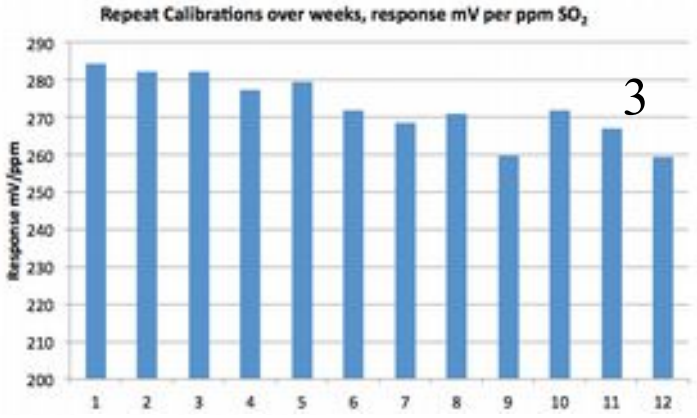
Gas detection using UAVs and sensors



Sensor calibration



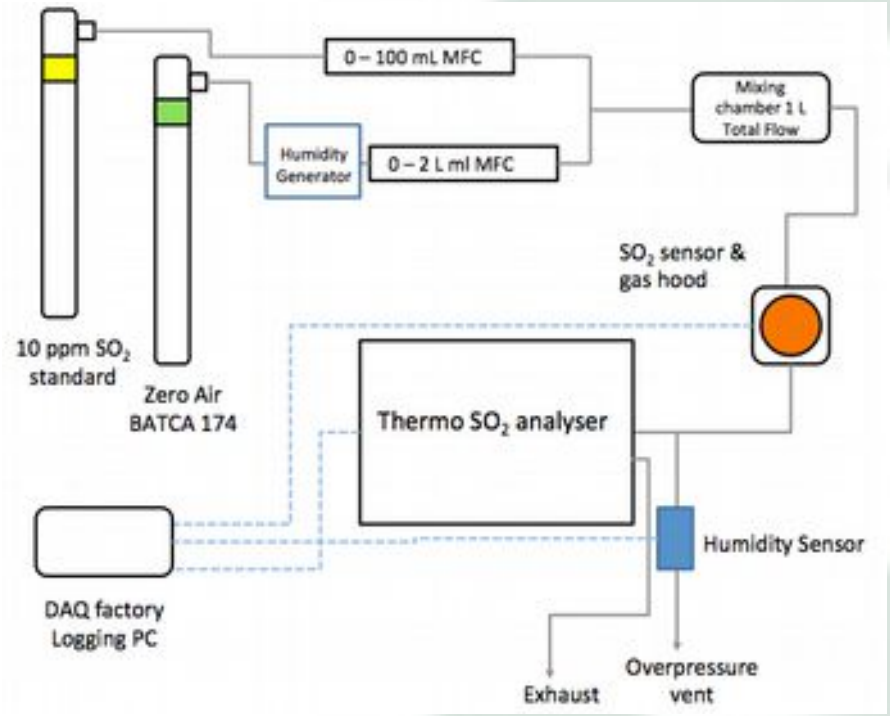
1. Calibration against Thermo SO_2 / NPL standard
2. Test of fast sensor response vs Thermo
3. Repeat calibrations over weeks

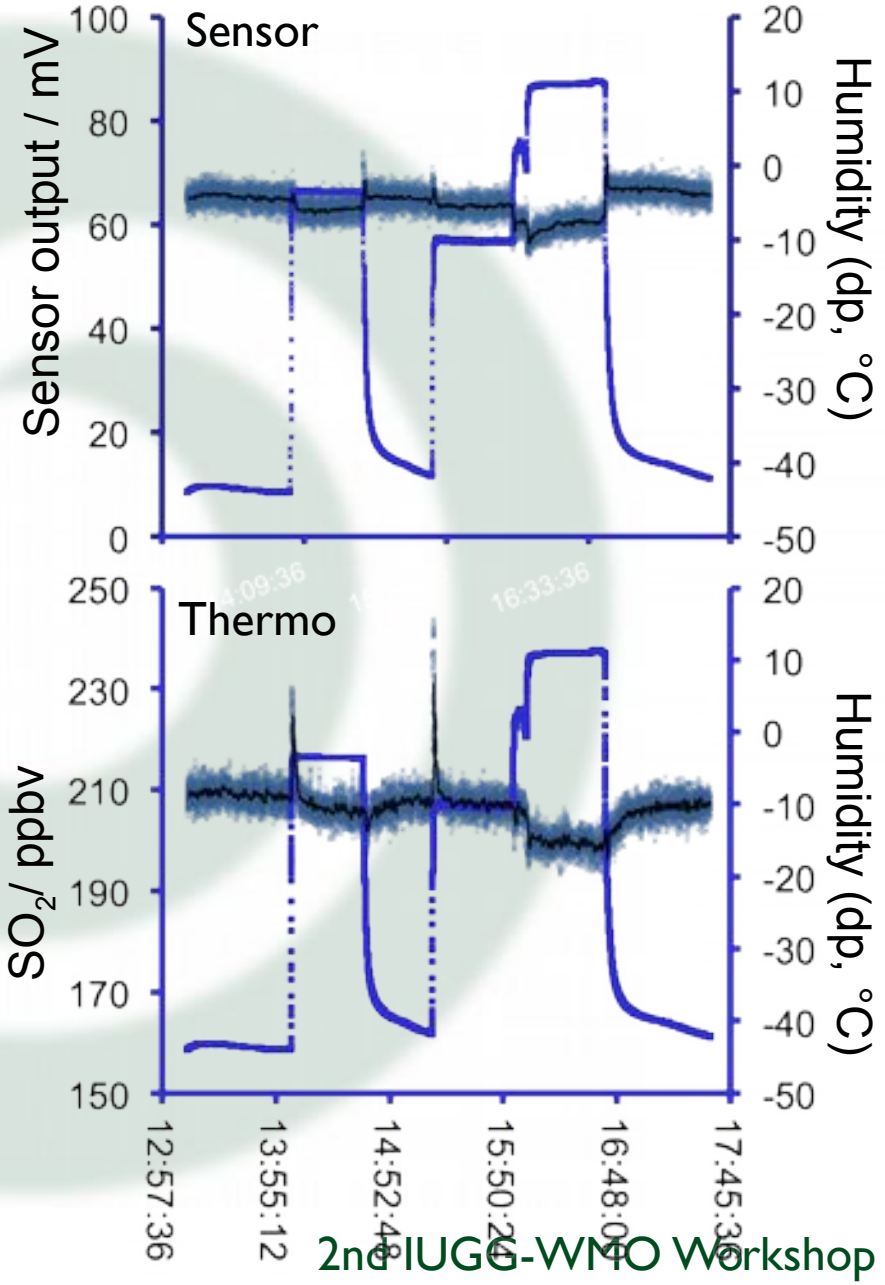


Key message: Calibration essential! Similar basic performance over 10-1000 ppb range as bench-top instrument, but regular in-field calibration will be required.

Gas detection using UAVs and sensors

Water corrections

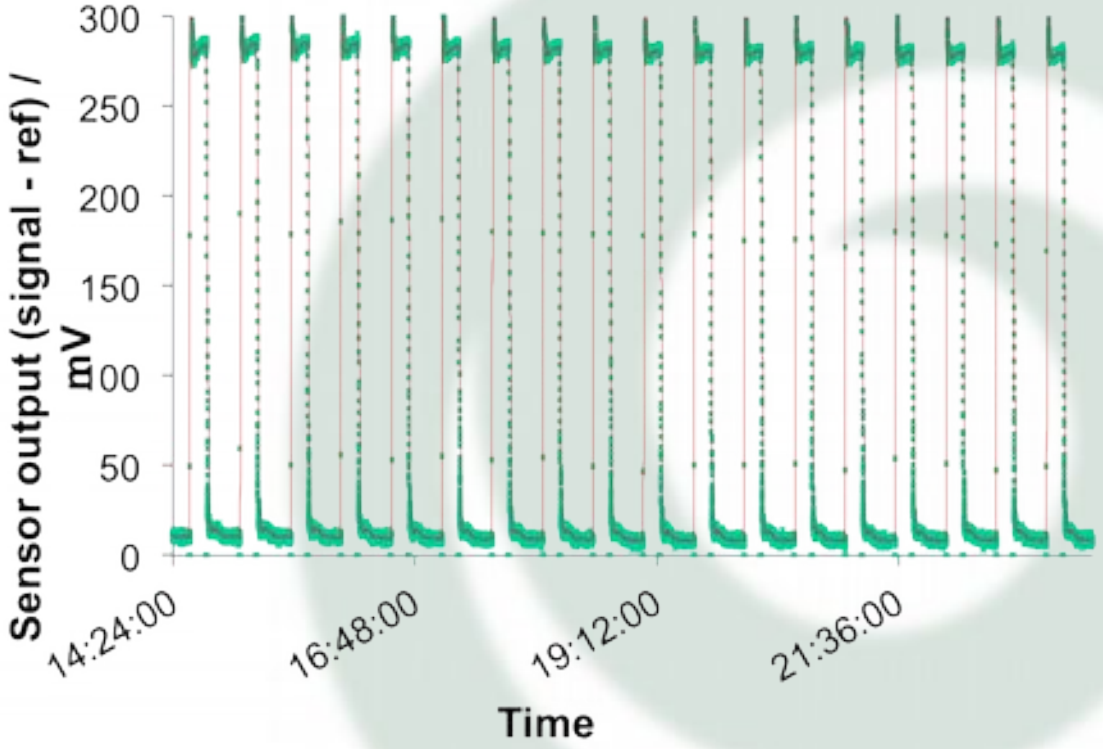


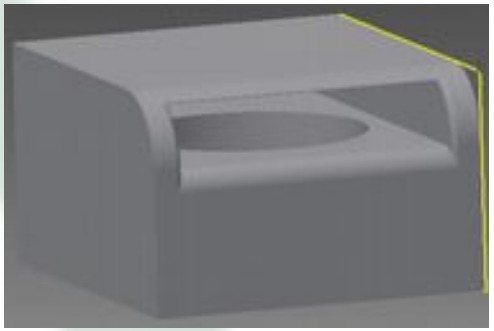


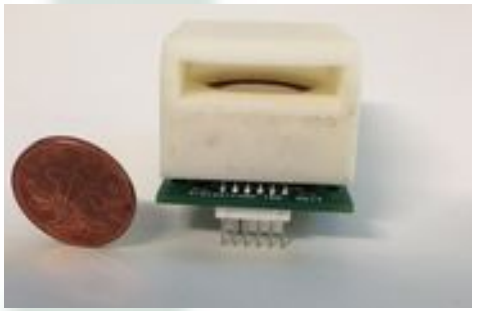
Key message: small sensitivity to ambient water vapour, but no worse than Thermo instrument. Most noticeable at higher humidity.

Gas detection using UAVs and sensors

Flight readiness issues





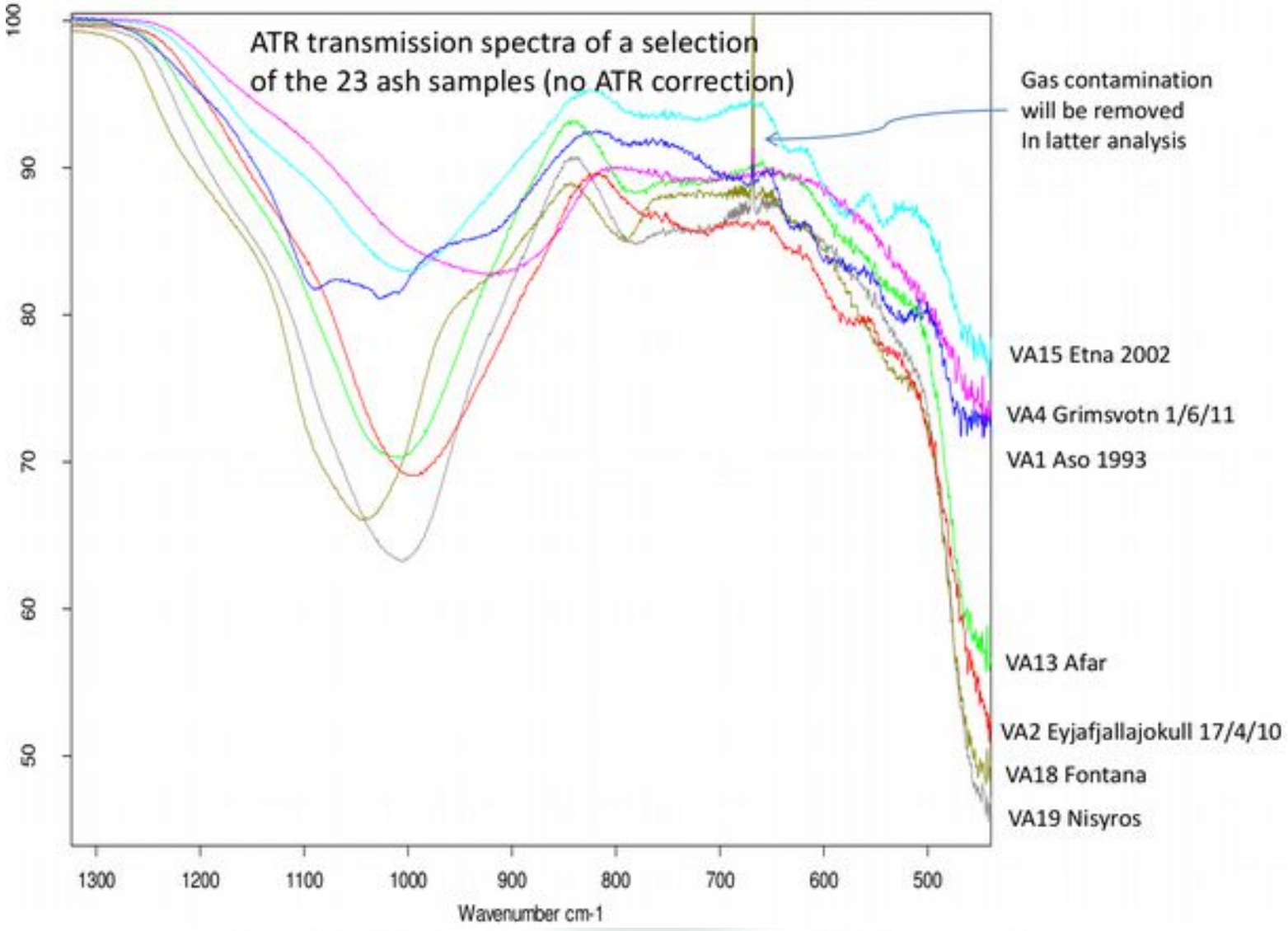


Battery life tests: signal output minus reference voltage used as test of supply V sensitivity.
<1% drift over 8 hours, plenty for UAV flight.

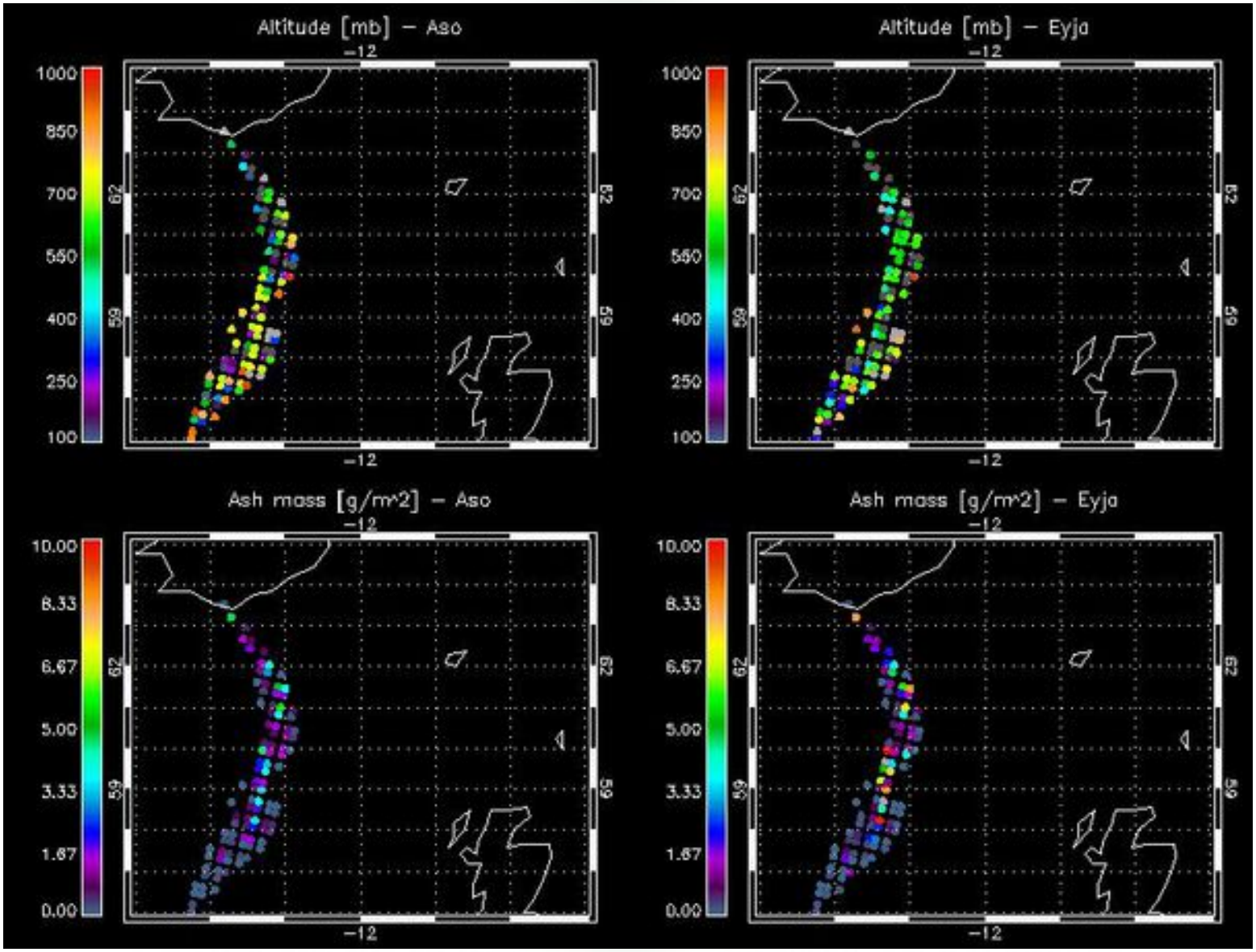
Inlets: Sensor is passive so requires a custom inlet. Ram-air design 'letterbox' facing direction of UAV travel. 3D printed.

Ash retrieval from satellite data

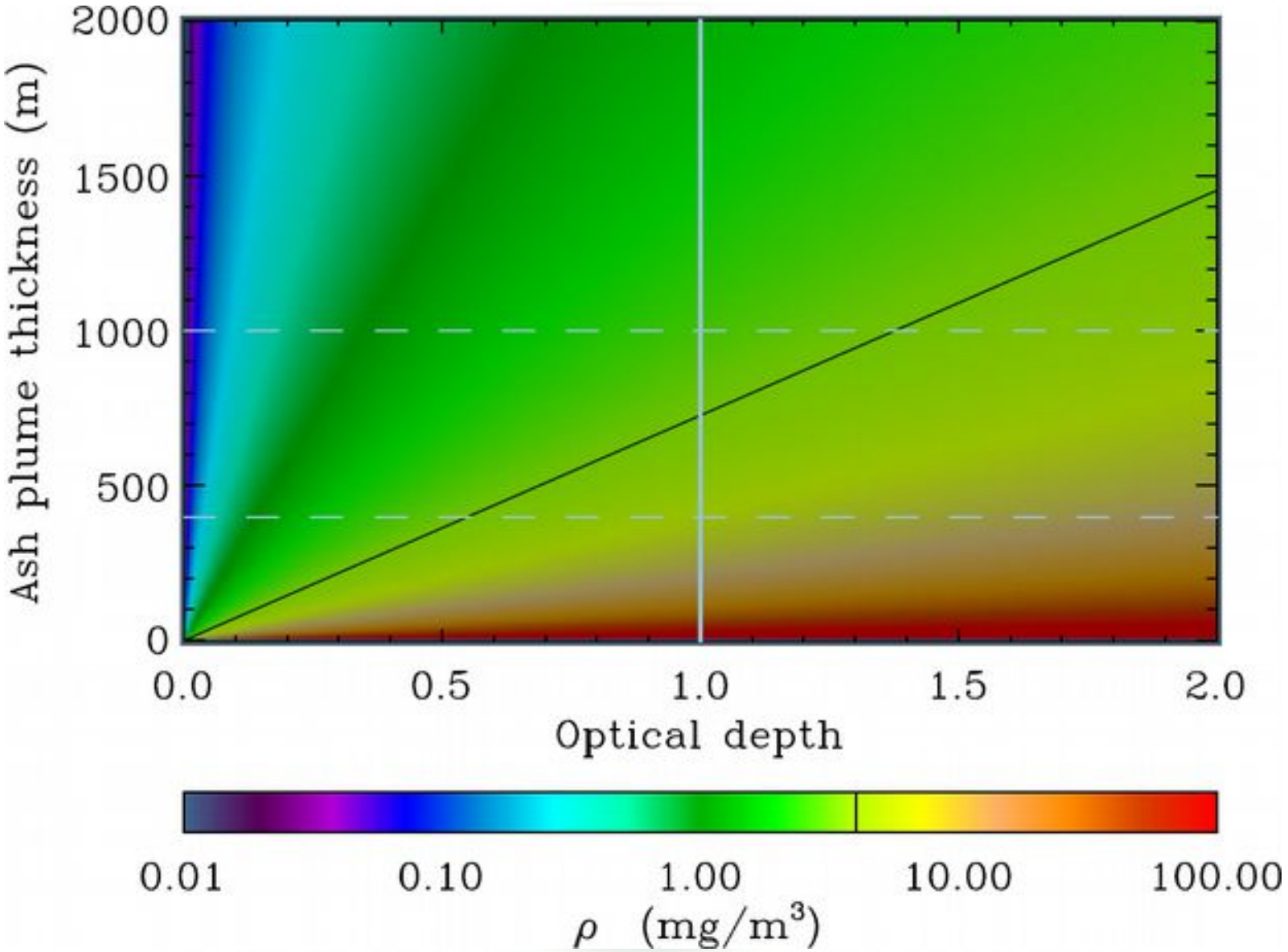
Don Grainger & Colleagues, Oxford



Ash retrieval from satellite data



Ash retrieval from satellite data



Lidar observations of ash

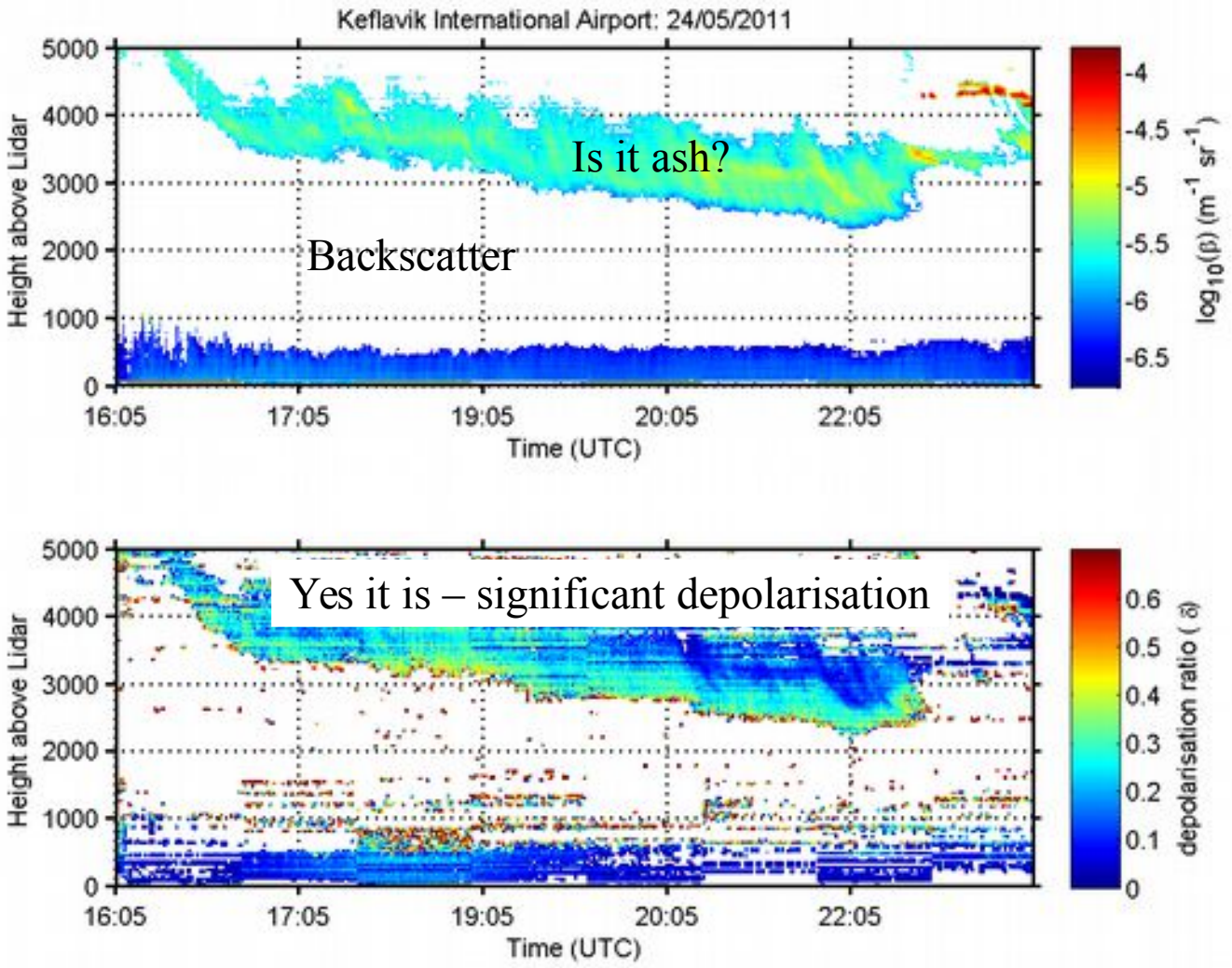
Barbara Brooks & colleagues, NCAS

Doppler Lidar

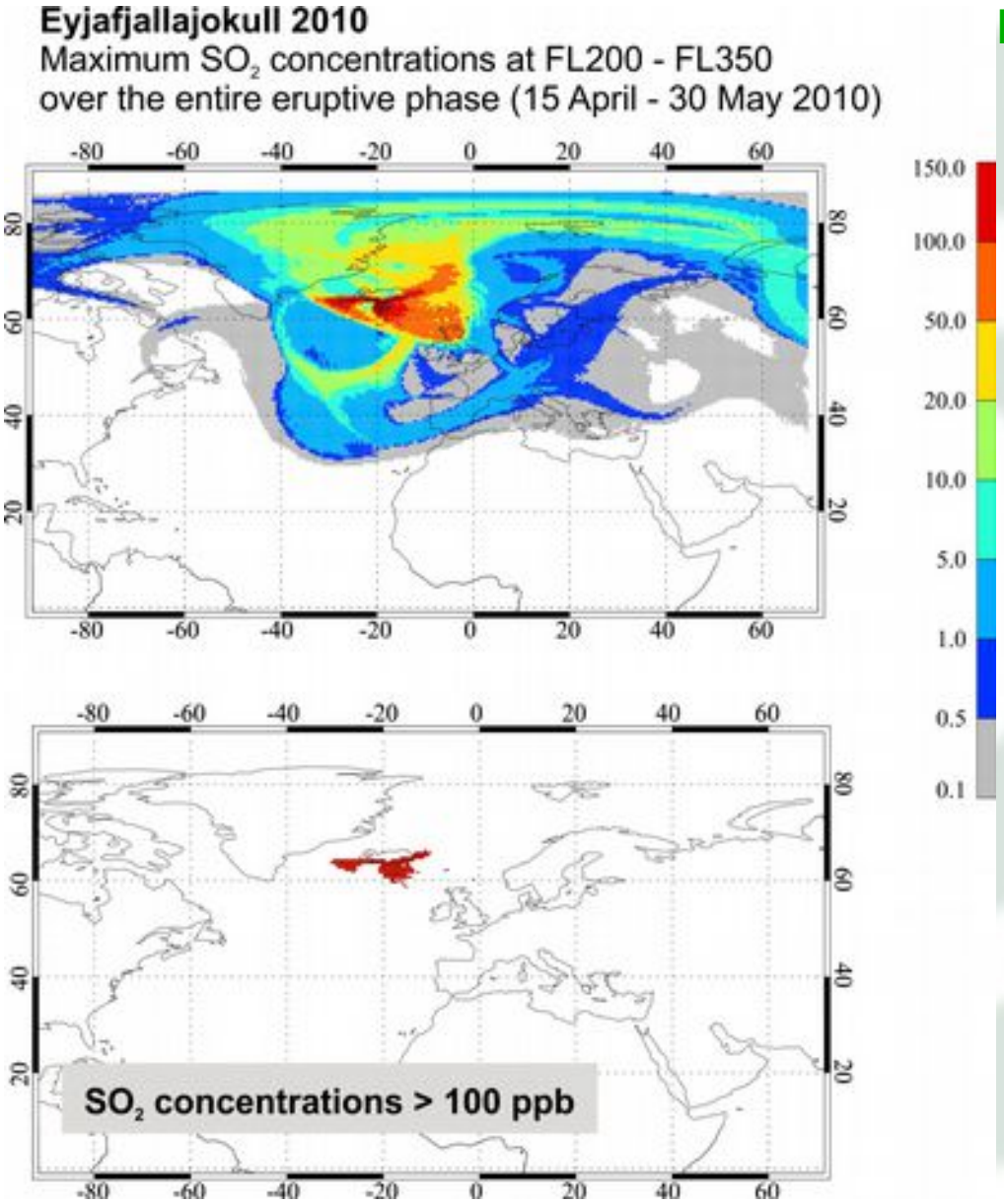
- λ = 1.55μm
  - insensitive to molecular scatter
- Doppler - along beam velocity
  - speed & direction profiles
- Steerable
  - 0 - 359° Az, 0 – 180° EL
- Polarised
  - particle shape

Lidar observations of ash

Grimsvötn Eruption May 2011



Modelling sulphur dioxide transport



Ken Carslaw and Anja Schmidt, Leeds

- SO_2 scheme from UKCA model added to Met Office NAME dispersion model
- E2010 released about 0.4 million tons of SO_2 in total
- Near-source concentrations exceeded 100 ppb but not considered a major concern as number of exceedances are low and peak concentrations still 'moderate' on air quality index
- But emissions from larger eruptions could easily be 10 times larger leading to aviation hazards