Source term determination for volcanic eruptions (and other point-source releases)

Andreas Stohl, with the help of many others

Volcanic ash

- Threat to aviation
- Potential health hazard
- Quantitative predictions of ash dispersion notoriously difficult

ESA-funded projects SAVAA and VAST

Goal: Objective use of satellite data for quantitative source term determination and dispersion modeling

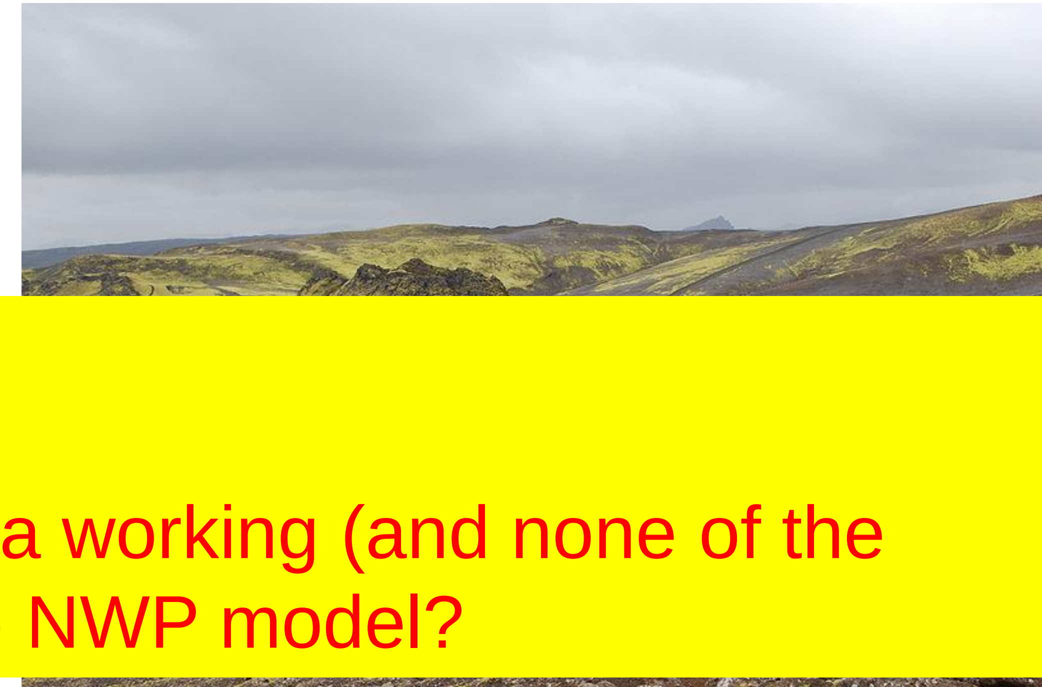
Strong sulfur emissions into stratosphere climate- (and NWP-) relevant

- Strong eruption ”statistically overdue”
- Super-eruption would threaten modern society (and humankind)
  - Toba 73000 years ago: maybe 100 times more sulfur than Pinatubo
- Regional weather/climate effects from ash deposition also for smaller eruptions

Pinatubo, 1991

Laki 1783-84 eruption

- Killed > 6 million people globally (mainly in Europe)
- Gases and haze killed people in Iceland and even in U.K.
- In Europe, ships could not navigate for ½ year (too dense haze)
- Heatwaves and draughts in summer
- Extremely cold winter
- Floodings in spring



Imagine the same today!

Can we afford not having a working (and none of the existing ones would work) NWP model?

The unknown source term (that’s why we need inverse modeling)

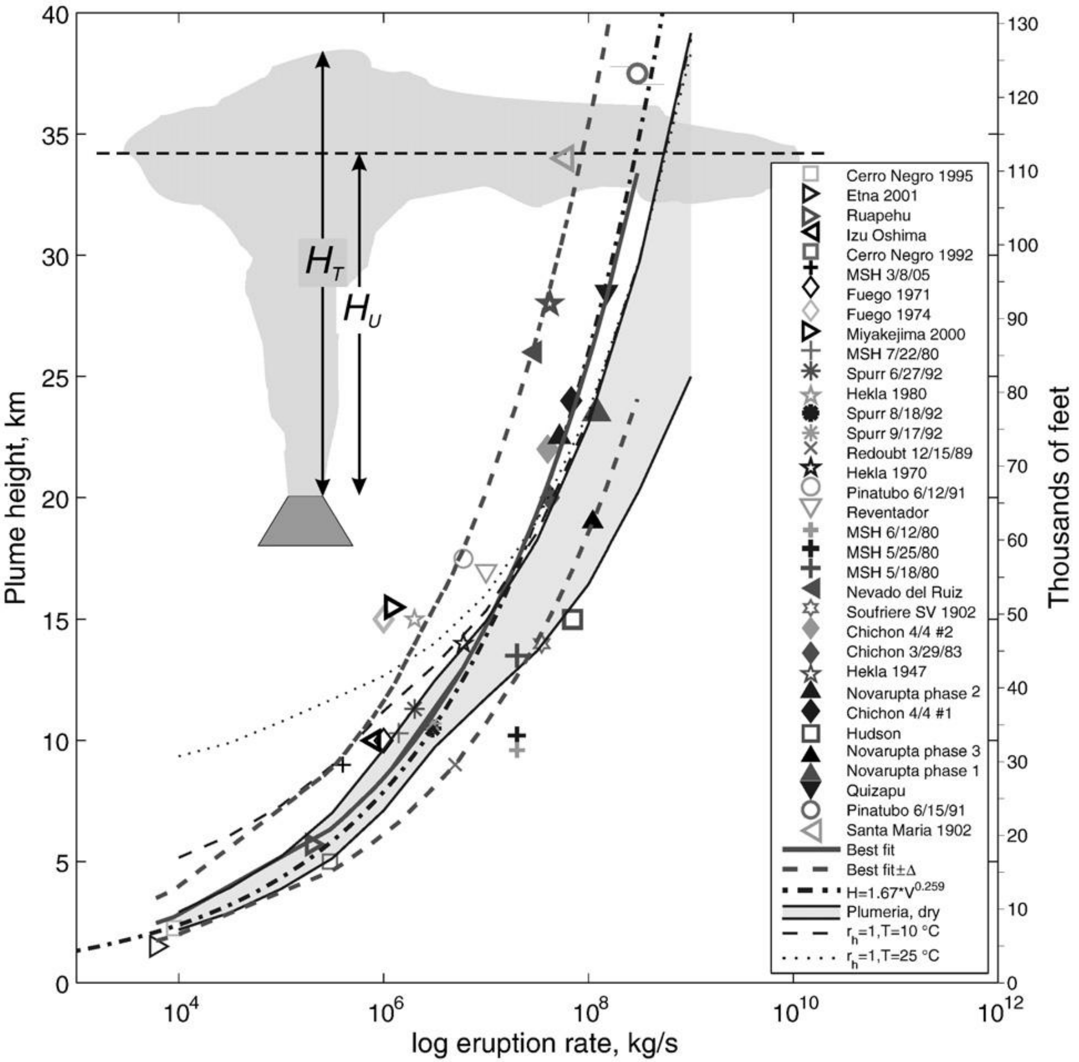
Highly uncertain, difficult to determine from volcanological data

Sparks’ relationship:

$H=1.67\ V^{0.259}$

- Height distribution of emissions unknown
- Fraction of ”fine” ash unknown
- Sulfur dioxide emissions even more uncertain

Mastin et al., 2009



Determination of the vertical ash or SO_2 source distribution

Eckhardt et al. (2008), Kristiansen et al. (2010)

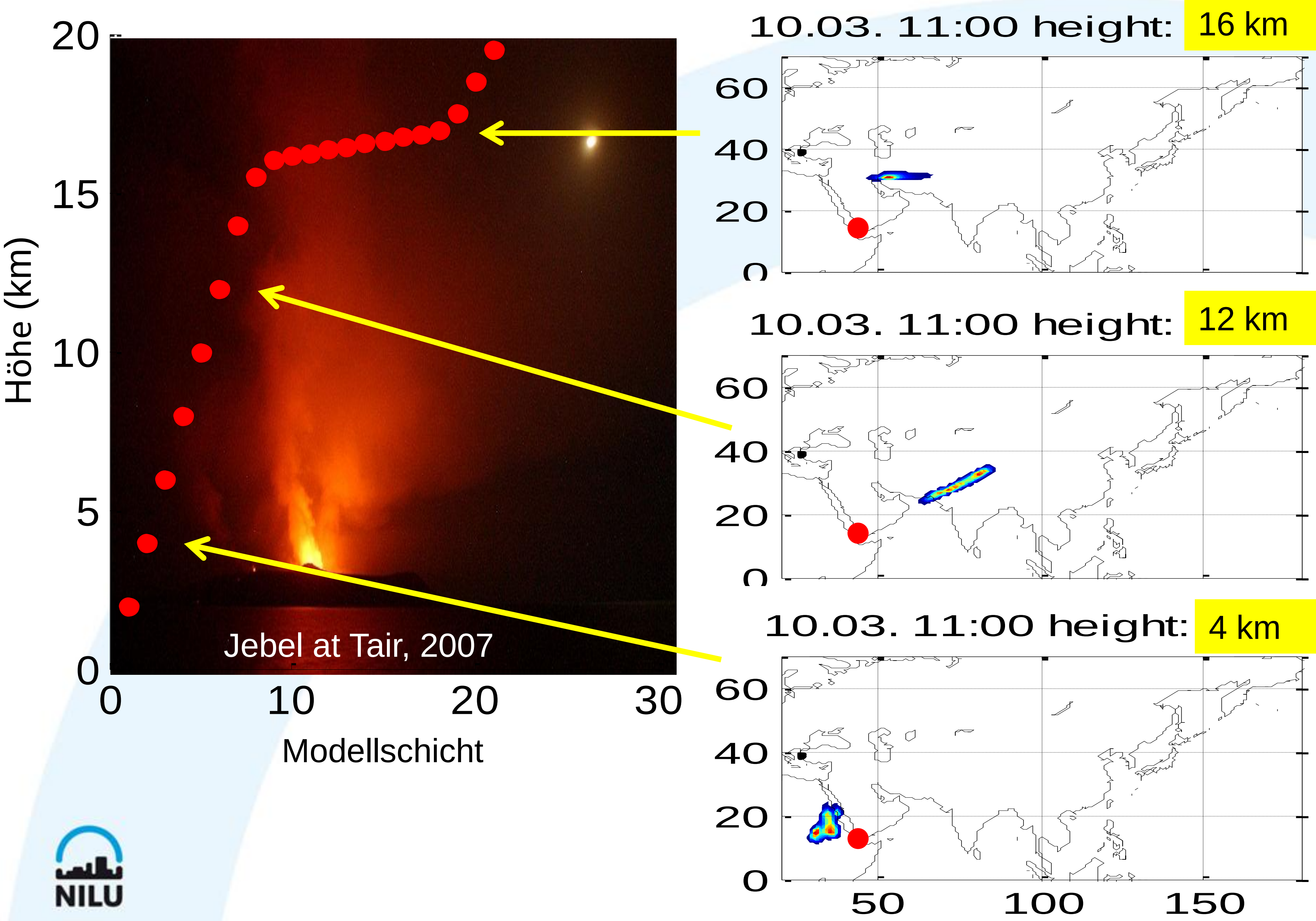
Volcanic eruptions are only important for aviation if substantial amounts of ash reach flight altitudes

Problem: Source strength and its vertical distribution unknown

Solution: Combination of

1. Satellite measurements of SO_2 total columns (no height information)
2. Transport model: Lagrangian particle dispersion model FLEXPART
3. Algorithm for optimization of agreement between measurement and model ("inverse modeling")

Transport in atmosphere depends on height of eruption



The FLEXPART model

Model descriptions in Atmospheric Environment,
Boundary Layer Meteorology, Atmospheric Chemistry and Physics,
Geoscientific Model Development

Lagrangian particle dispersion model
Turbulence and convection parameterizations
Dry and wet deposition
Inverse modeling
Data input from ECMWF, GFS, MM5, WRF,…

Used at probably >>100 institutes

NILU

Bayesian inversion method used

Aim: Determination of the emission sources from air concentration measurements

$$M\tilde{x} \approx \tilde{y}.$$

M ... *M* x *N* matrix of emission sensitivities from transport model calculations
… often called source-receptor relationship
x ... Emission vector (*N* emission values)
y ... Observation vector (*M* observations)

Difficulty: poorly constrained problem; large spurious emissions possible as there is no penalty to unrealistic emissions

Solution: Tikhonov regularization: $||x||^2$ is small

Bayesian inversion method used

Slight reformulation if a priori information is available

$$M(x - x^a) \approx y^o - Mx^a$$

y^o ... Observation vector (M observations)
x^a ... A priori emission vector (N emission values)

Tikhonov regularization: $||x-x^a||^2$ is small

We are seeking a solution that has both minimal deviation from the a priori, and also minimizes the model error (difference model minus observation)

Bayesian inversion method used

Minimization of the **cost function**

$$J = (M\tilde{x} - \tilde{y})^T \, \mathrm{diag}({\boldsymbol{\sigma}_o}^{-2}) \, (M\tilde{x} - \tilde{y}) + \tilde{x}^T \, \mathrm{diag}({\boldsymbol{\sigma}_x}^{-2}) \, \tilde{x}$$

1 2

1. Term: minimizes squared errors (model – observation)
2. Term: Regularization term

σ_x, σ_o ... Uncertainties in the a priori emissions and the observations
diag(a) … diagonal matrix with elements of a in the diagonal

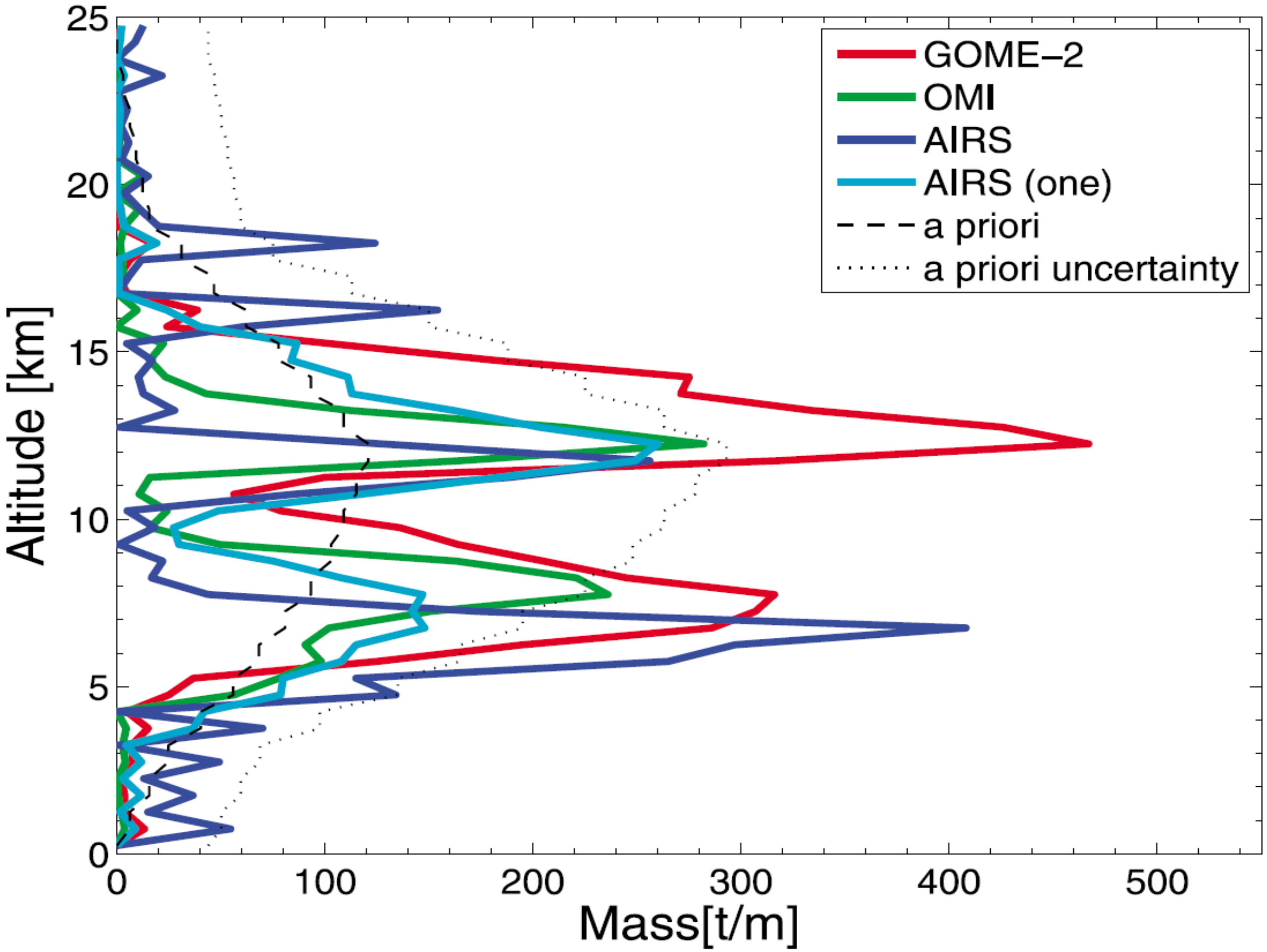
The uncertainties of the emissions and of the „observations“ (actual mismatch between model and observations) give appropriate weights to the two terms

Kasatochi eruption, 8 August 2008

Kristiansen et al. (2010)

Aleutian island volcano, 3 eruptions within 6 hours

Vertical profiles determined by inverse modeling of SO_2 satellite measurements during first two days



Kasatochi eruption, 2008: Model evaluation with satellite lidar data (CALIOP)

Kristiansen et al. (2010)

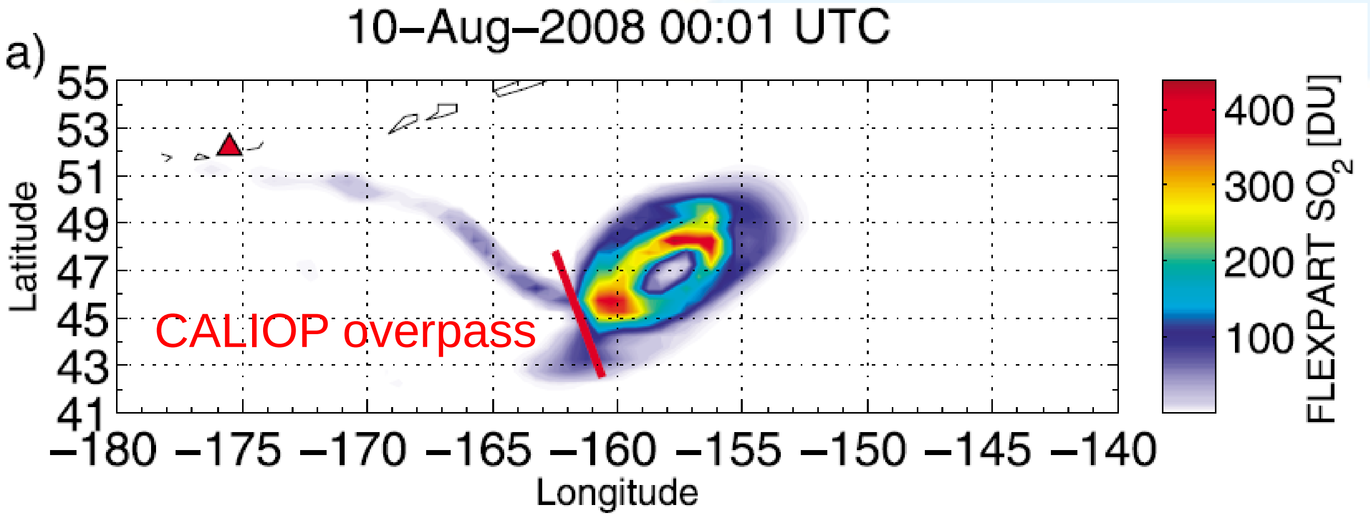
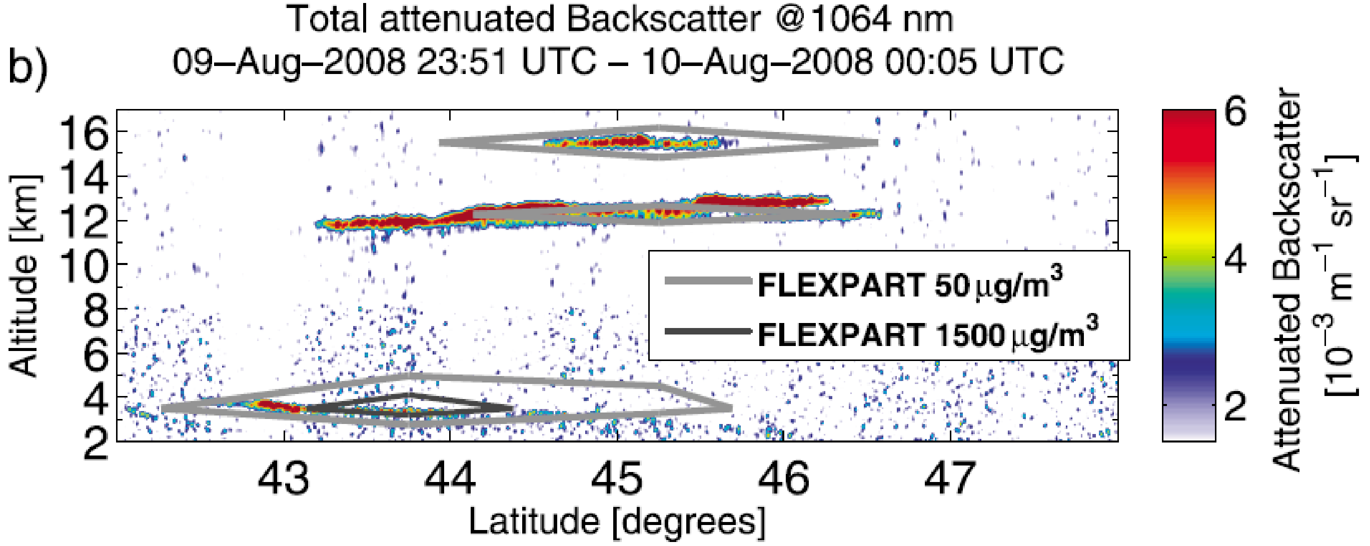


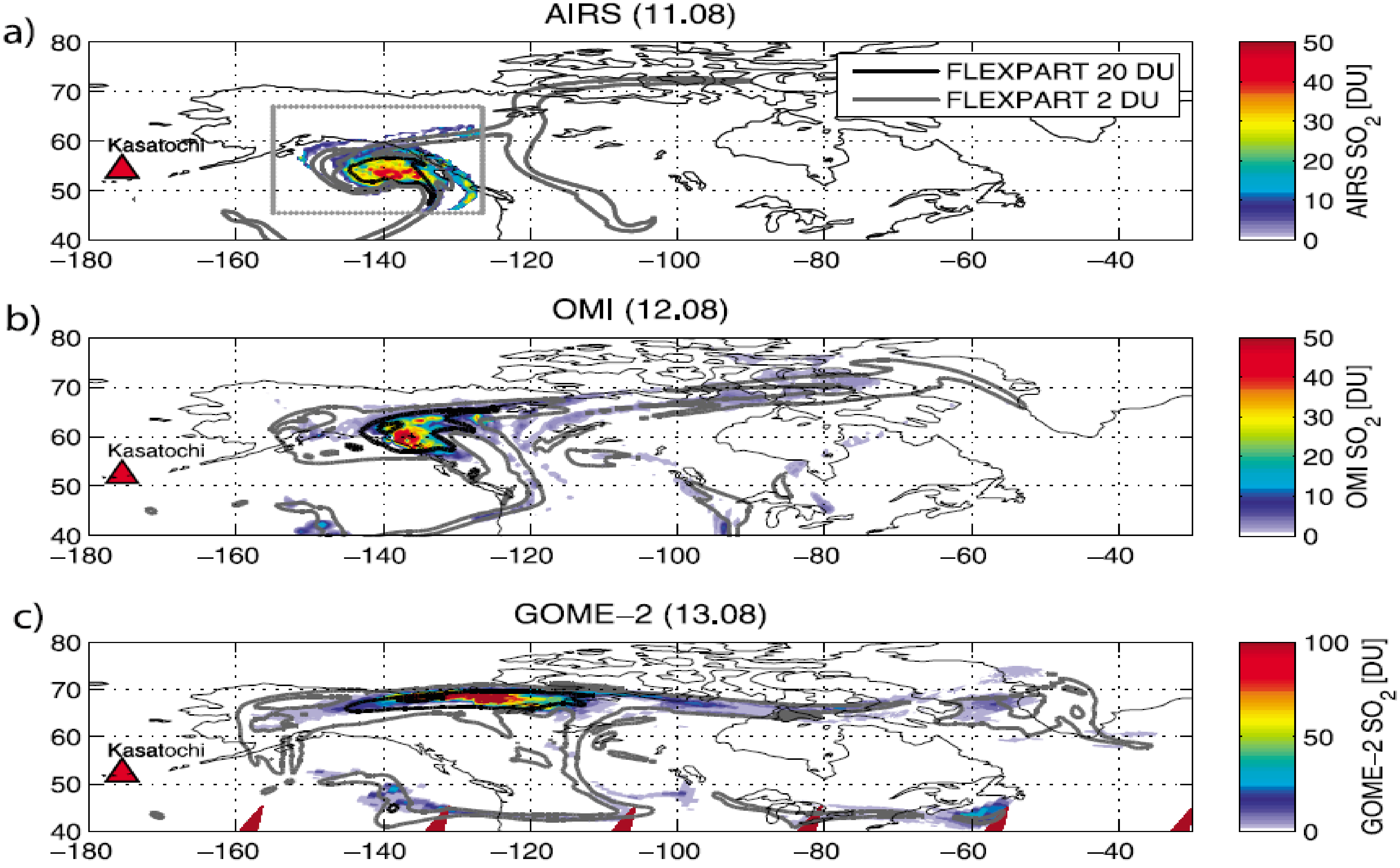
Chart showing simulated SO_2 column concentrations



CALIOP: Lidar measurements along red line in (a)

Kasatochi eruption, 2008: Model evaluation

Kristiansen et al. (2010)



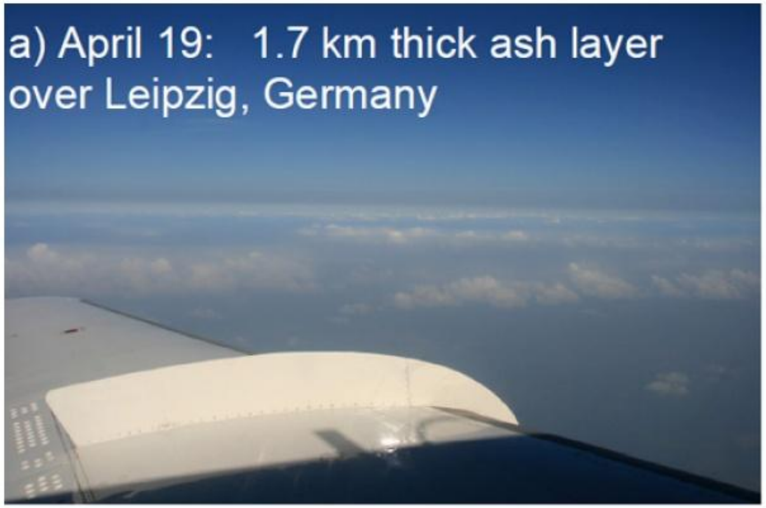
Eruption of Eyjafjallajökull, 2010

Stohl et al. (2011), Kristiansen et al. (2012)

Opportunity to apply our algorithm to volcanic ash

Use of SEVIRI and IASI IR-Retrievals (Ash total columns)

Challenge: Ash emissions had to be determined as a function of height and time



a) April 19: 1.7 km thick ash layer over Leipzig, Germany

b) May 1: Ash plume 70 km downstream the Eyjafjallajökull

A priori emissions

1. VAAC plume height reports, 3-hourly radar data

2. Forced PLUMERIA 1-D model (Mastin, 2007) to reproduce plume heights, using 3-hourly vertical profiles of actual meteorological data

3. Assumed that 10% of the ash mass flux was in the observed size range (2.8-28 µm): total of 11.4 Tg

Model simulations

Based alternatively on ECMWF (0.18 deg resolution) and GFS (0.5 deg) meteorological input data

Difference used to quantify model error

6232 forward model simulations used as input for inversion: 19 height levels a 650 m, 328 times (3-hour resolution), output resolution 0.25 deg

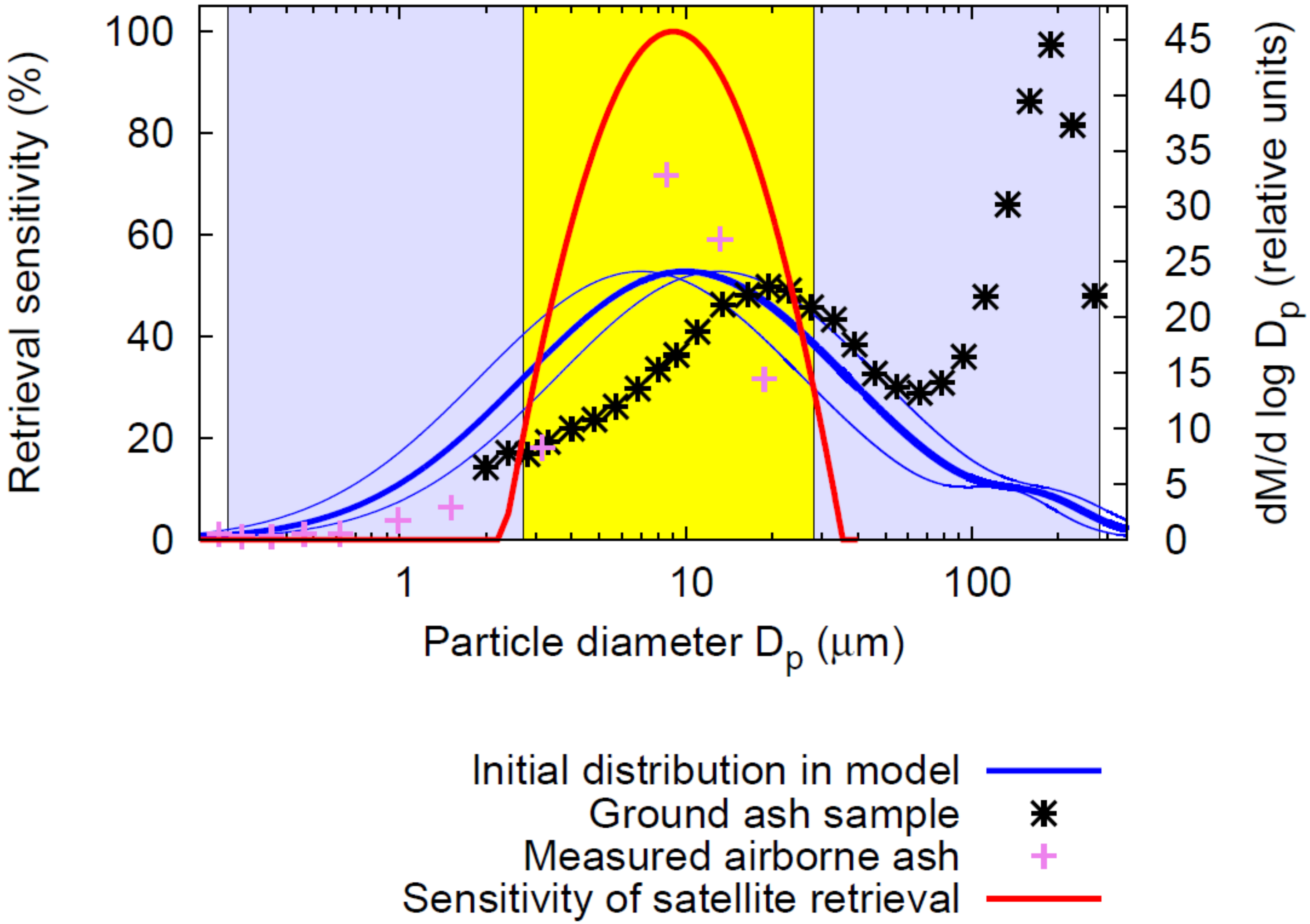
Ash column loadings based on infrared retrievals from SEVIRI (geostationary) and IASI (polar orbiting) were used: 2.3 million observations in total

SEVIRI data were used at 0.25 deg resolution every hour

Ash particle size distribution

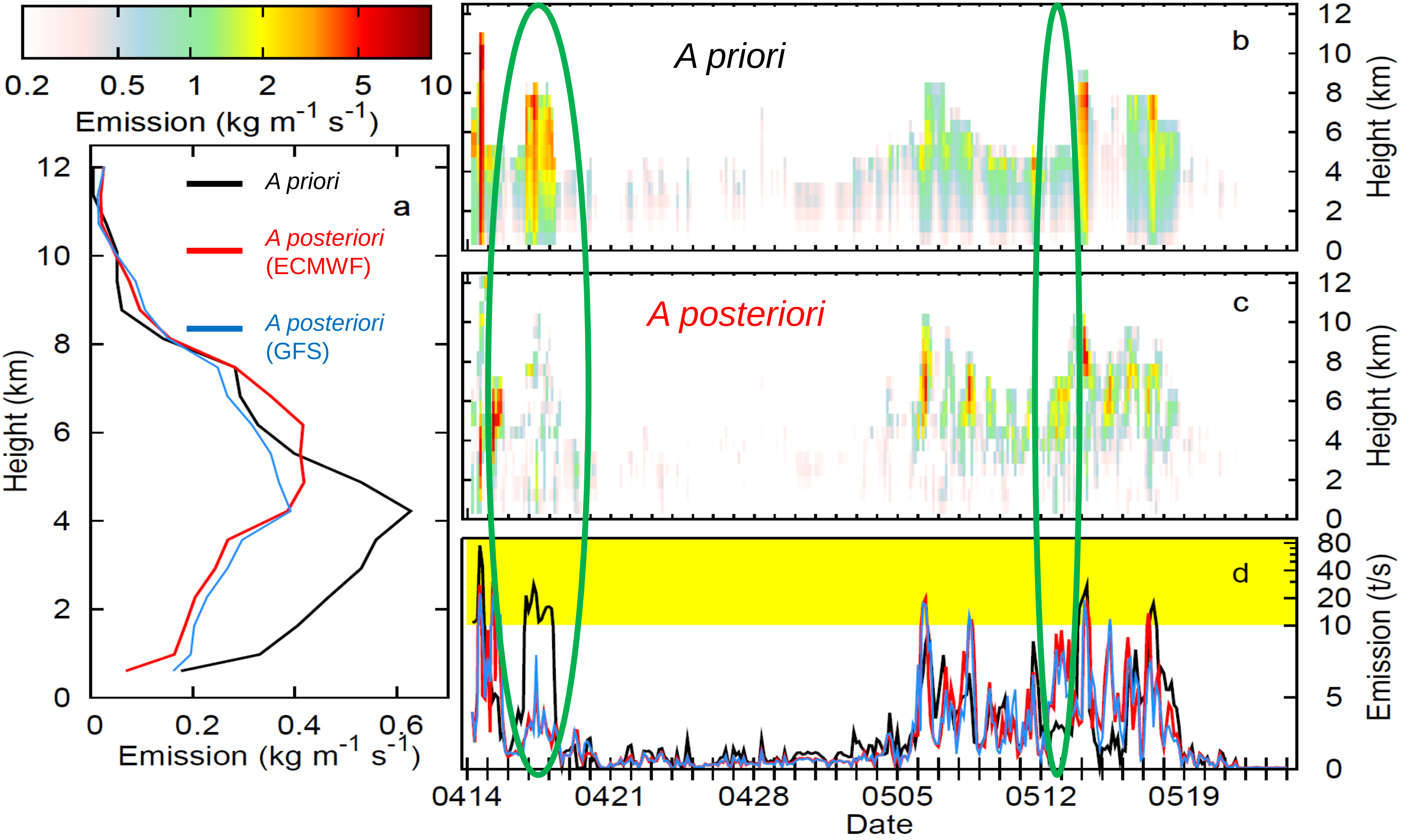
Satellite can constrain only measured size range (yellow) – which, however, is critical for aviation

Need to assume an emitted size distribution within and outside that range

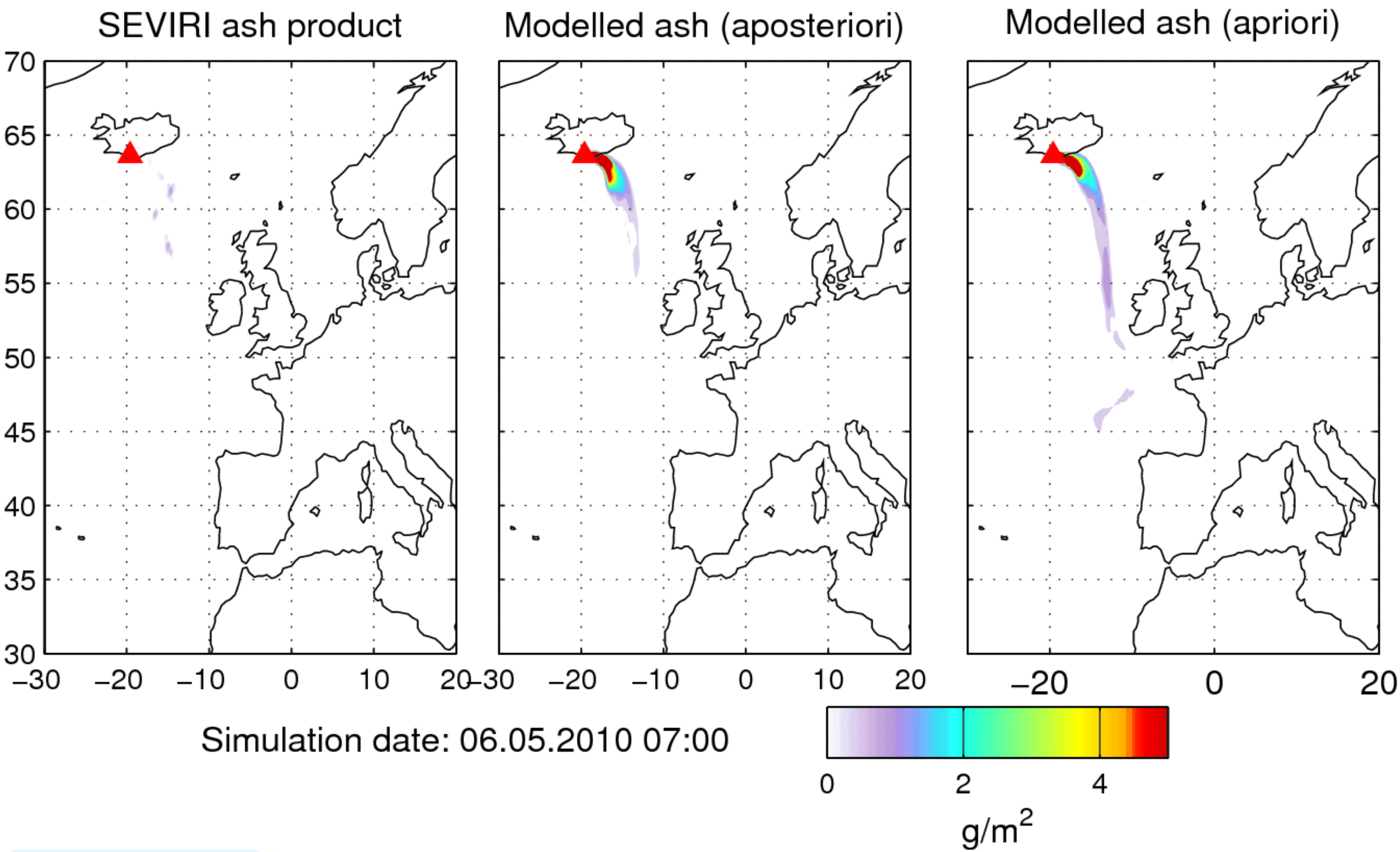


Ash emissions as a function of height and time

Stohl et al. (2011)

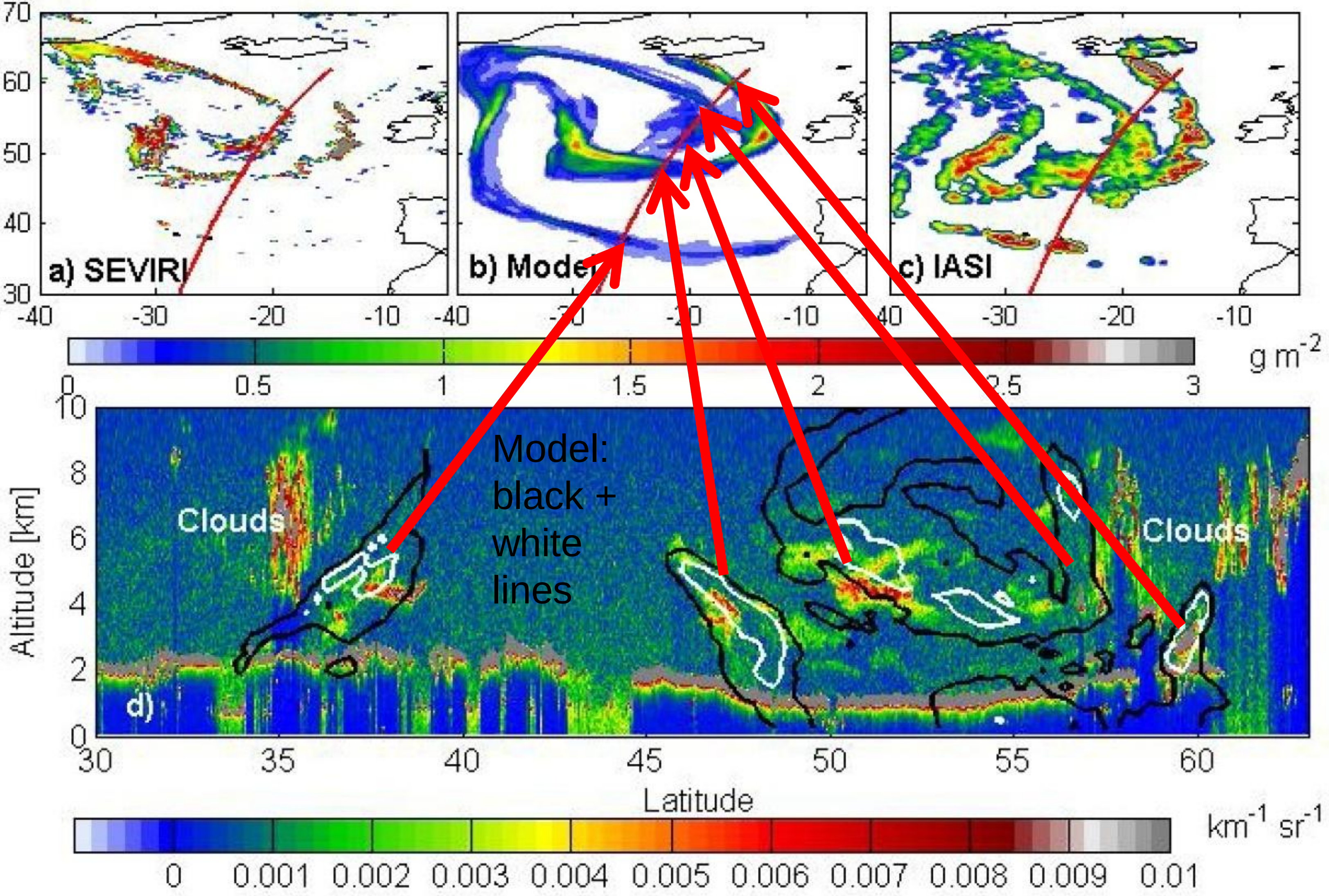


Ash clouds observed and simulated in May 2010



Comparison with satellite ash retrievals and independent satellite lidar data (CALIOP)

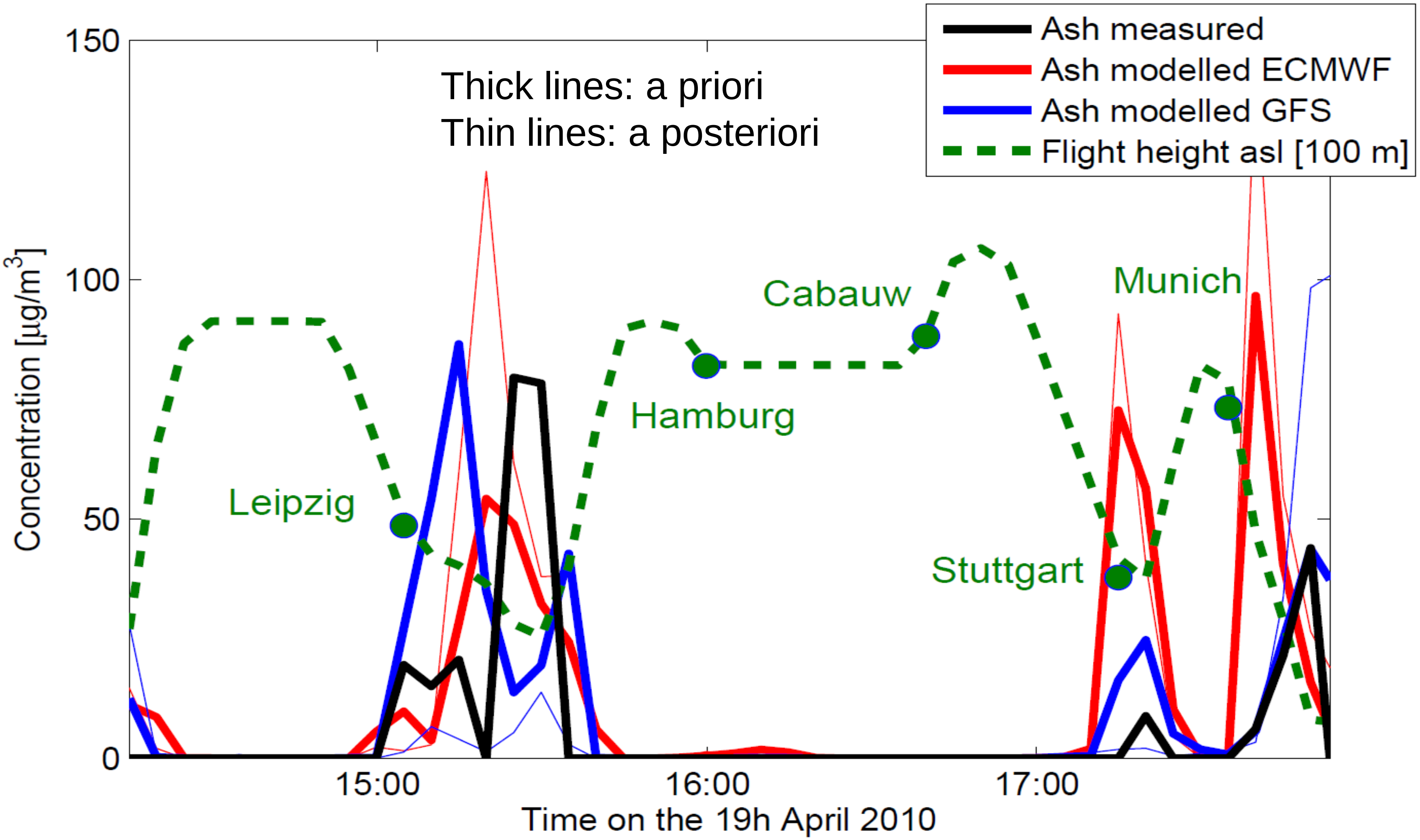
10 May 2010



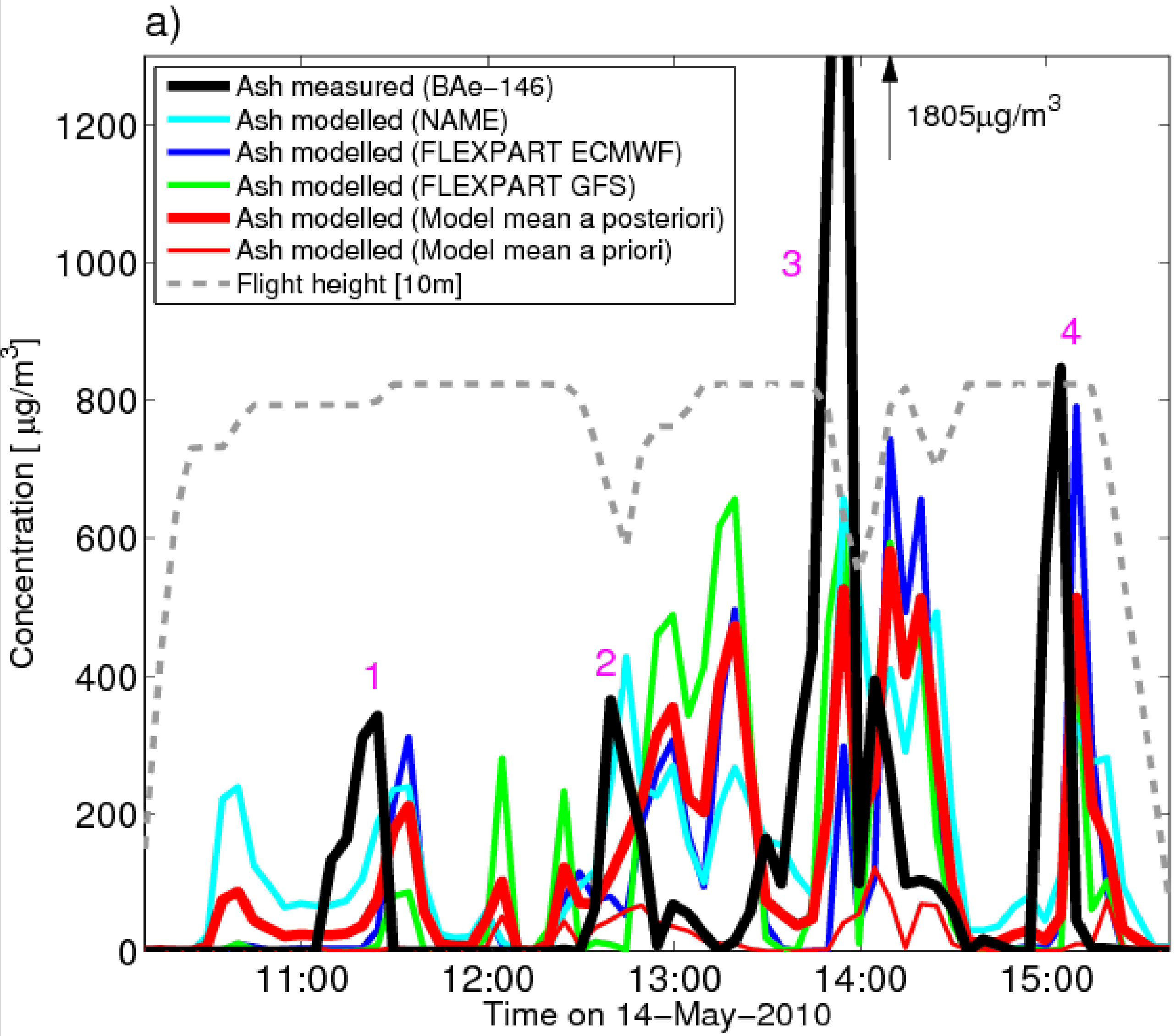
Model: black + white lines

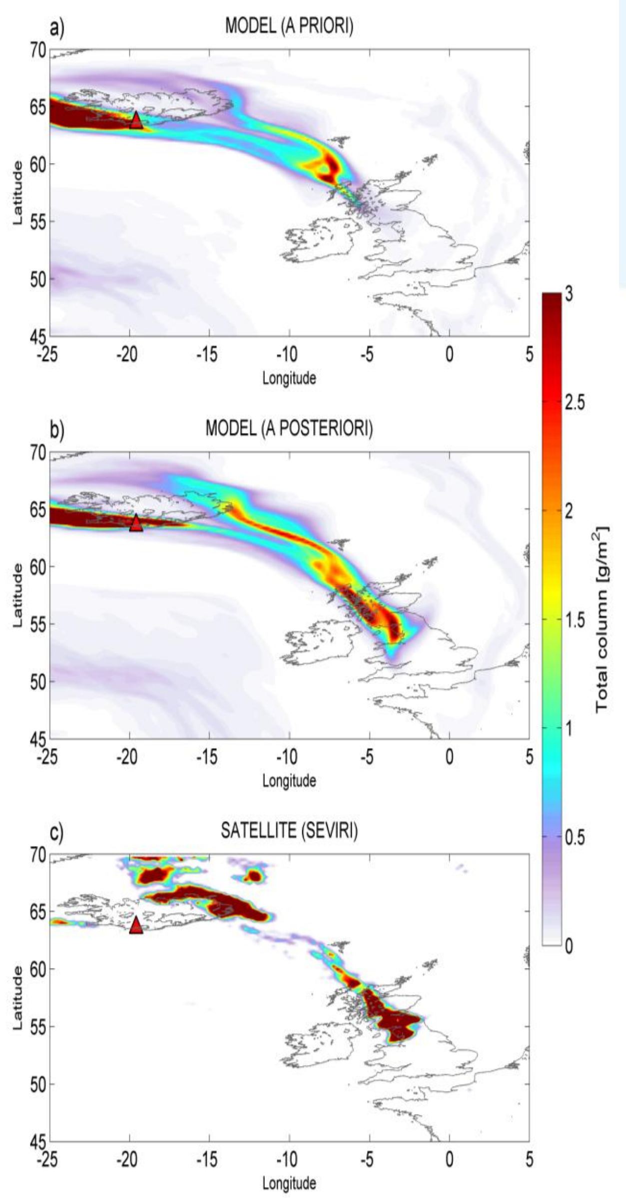
Comparison with airborne measurements of the DLR Falcon

First Falcon flight on 19 April above Germany

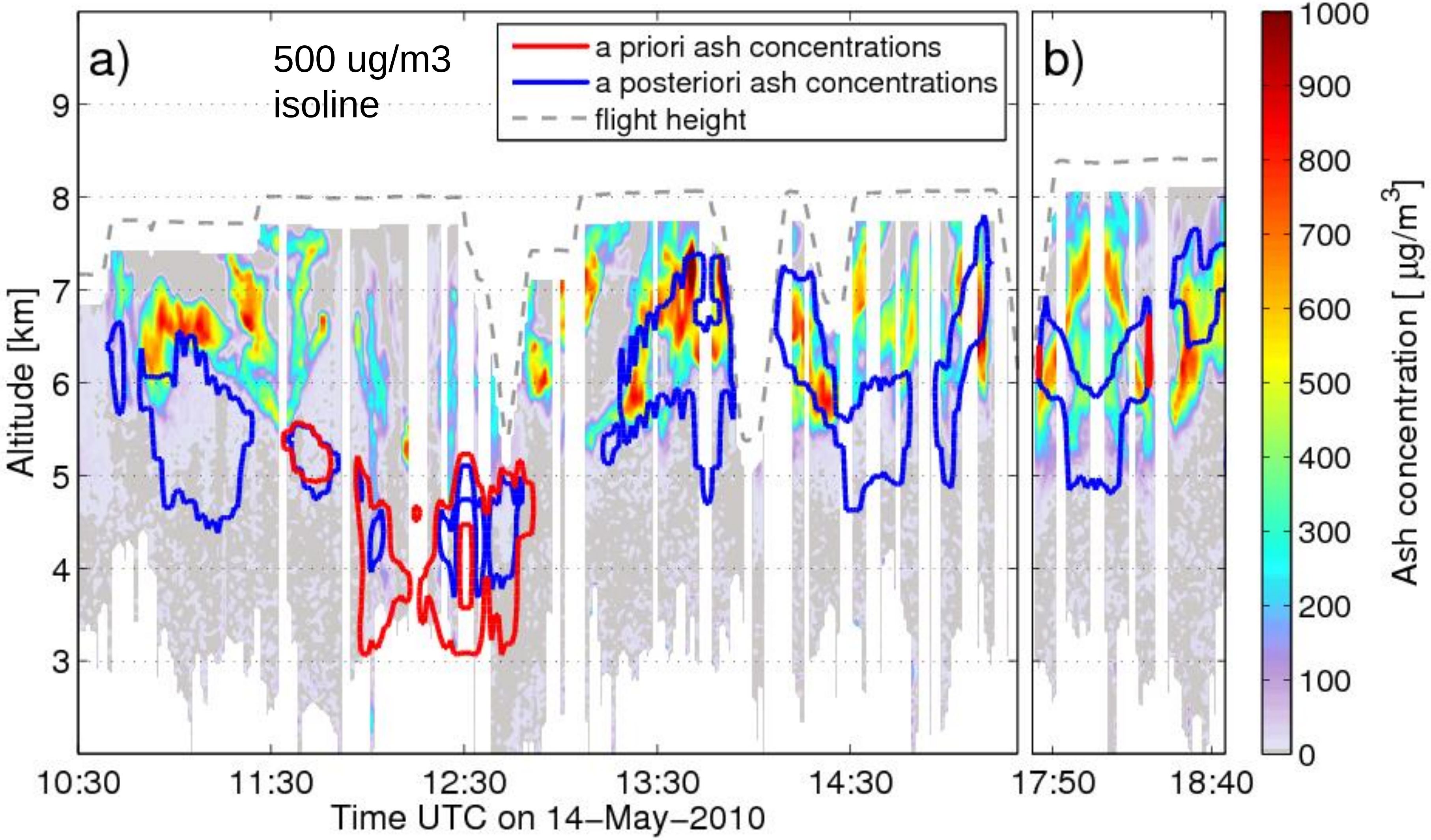


Comparison of 3 models vs. Bae-146 measurement flight on 14 May (Kristiansen et al., JGR)

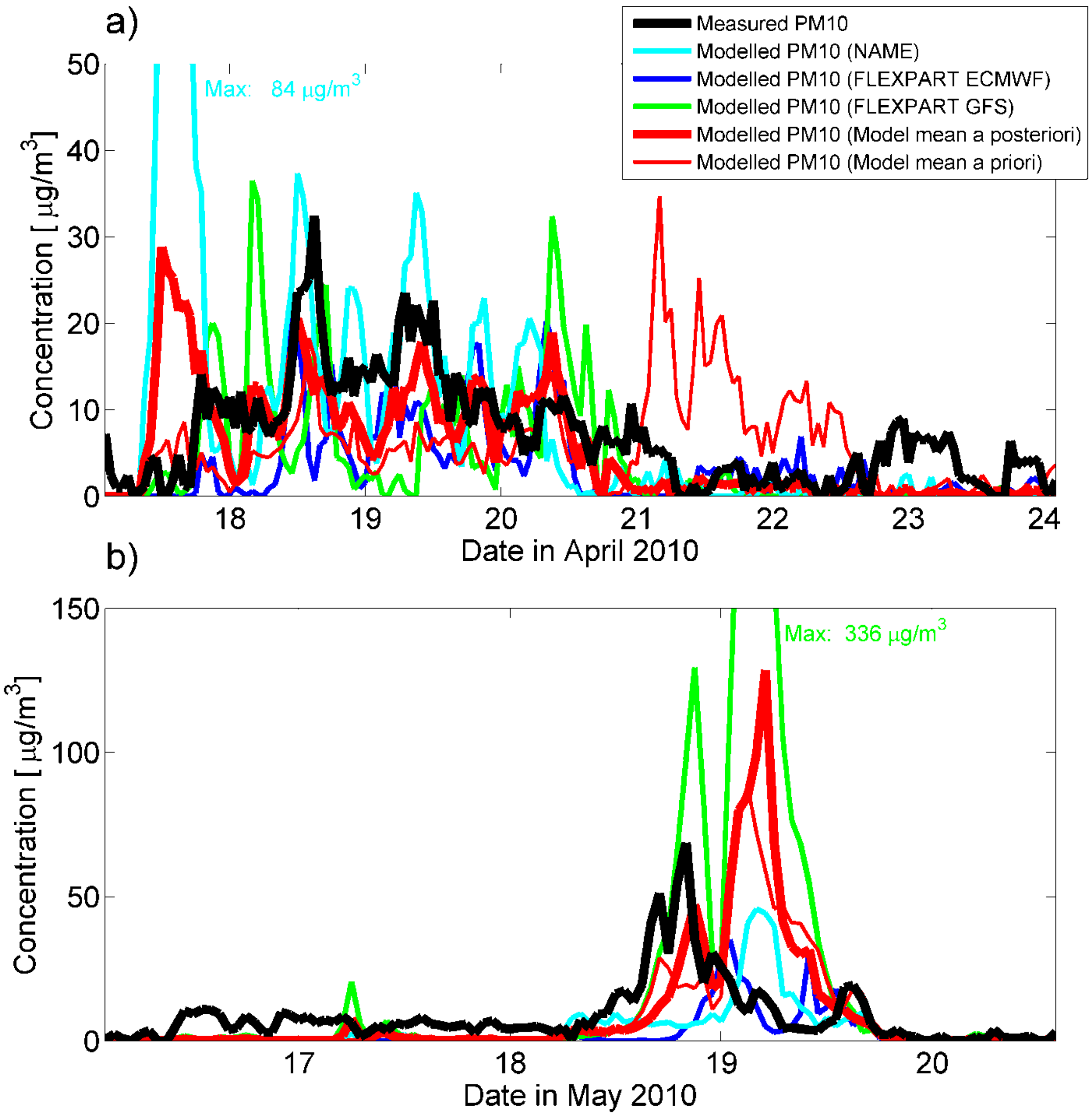




Model-mean vs. Bae-146 lidar measurements on 14 May



Comparison of 3 models vs. Jungfraujoch station measurements



Comparison with airborne measurements (Falcon, Bae-146, DIMO) and Jungfraujoch data

Statistical comparison of all ash plumes measured by three research aircraft, and at Jungfraujoch station, with model

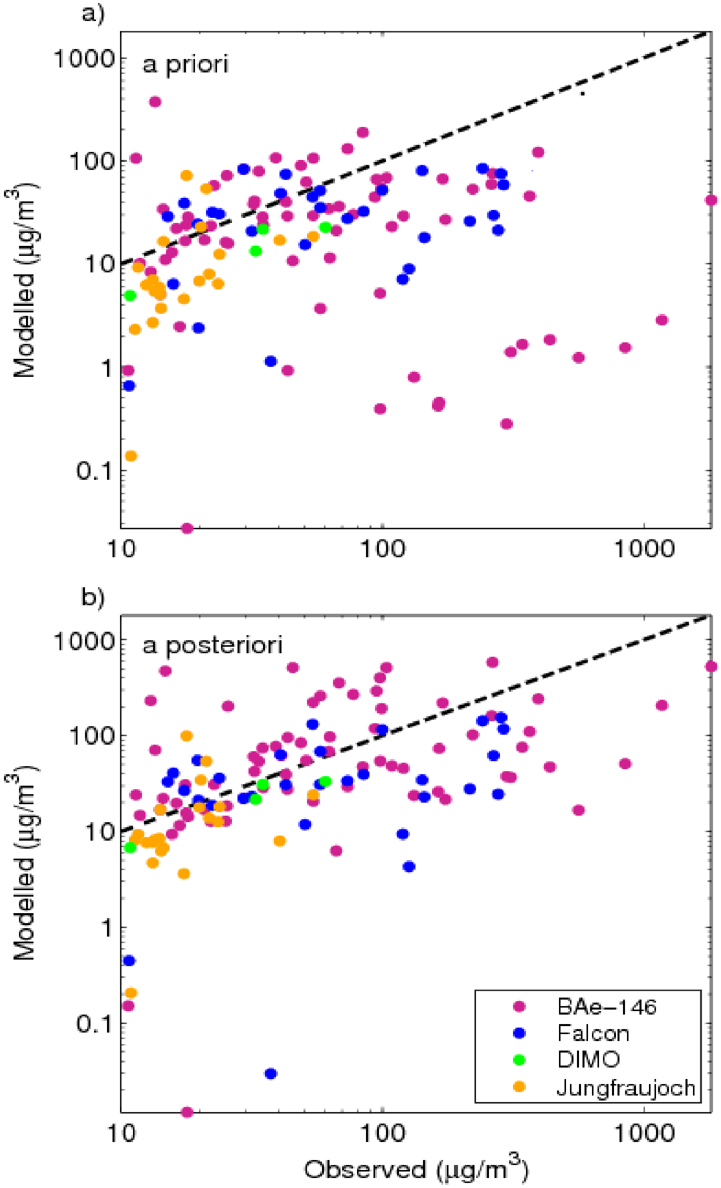
Modeled values are mean of ensemble (FLEXPART-ECMWF, FLEXPART-GFS and NAME)

A posteriori clearly better than a priori:

Rank correlation improves from 0.21 to 0.55

Pearson correlation improves from -0.02 to 0.36

Bias is reduced from -78 to -32 µg/m3



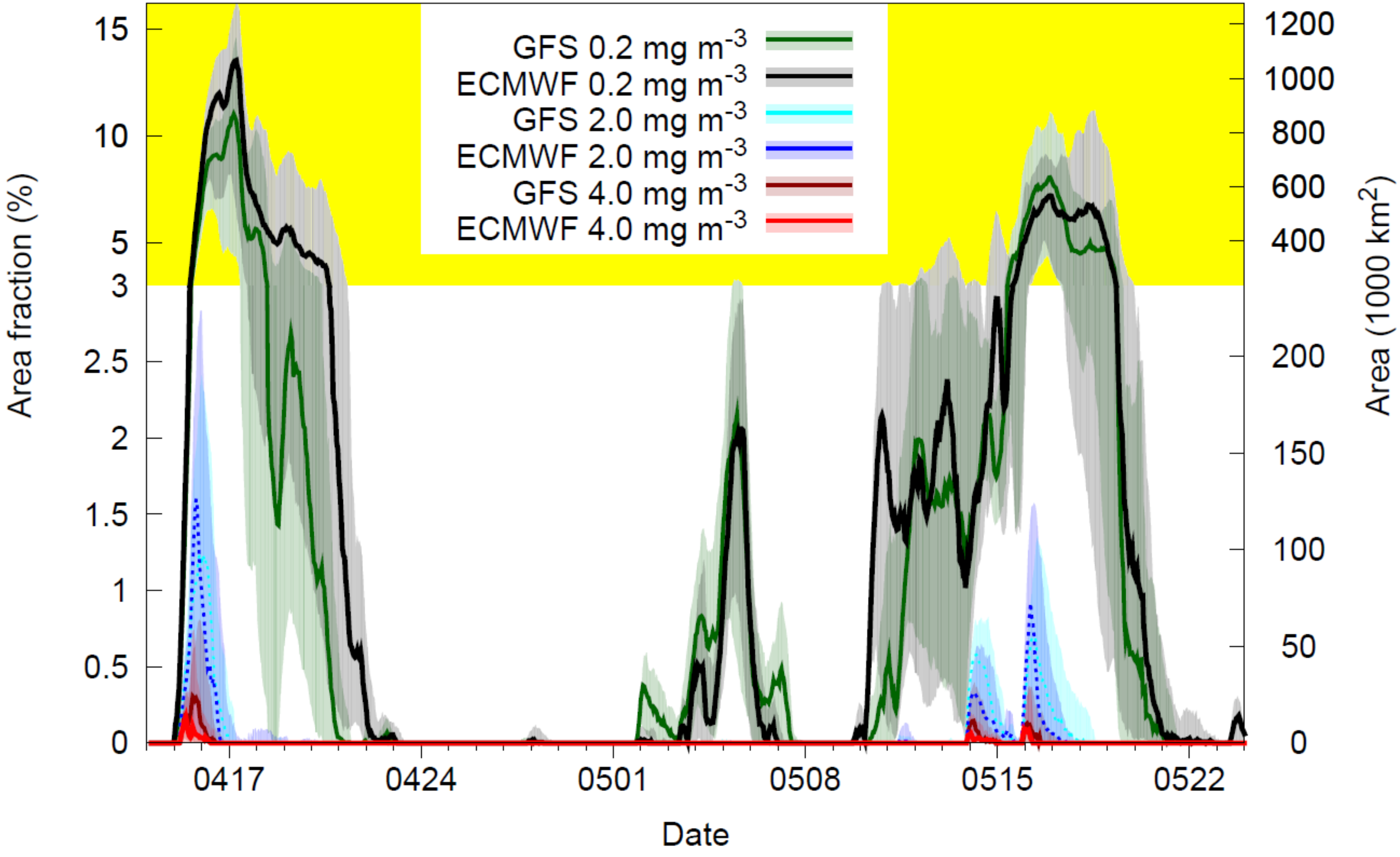
Further statistical comparisons

The ”operational” uniform vertical distribution of ash emissions has a particularly poor performance

Our a priori distribution is better, but further clear improvement by the inversion for all three models

Model (Met data)	**FLEXPART (ECMWF)**			**FLEXPART (GFS)**		**NAME (MetUM)**		**MODEL MEAN**	
Emissions	**uniform**	**a priori**	**a posteriori**	**a priori**	**a posteriori**	**a priori**	**a posteriori**	**a priori**	**a posteriori**
FMT (%) (Figure of Merit)	16	30	46	27	30	31	39	35	43
NMSE (Normal. Mean Sq. Error)	8	3	2	5	3	4	3	3	2
PCC (Pearson corr.)	-0.04	0.17	0.64	0.04	0.19	0.14	0.39	0.11	0.51
SRCC (Spearman rank corr.)	0.22	0.37	0.48	0.34	0.39	0.44	0.51	0.48	0.53

Area over Europe that was affected by ash above certain thresholds (somewhere in the vertical)



Eruption of Grimsvötn in May 2011

Moxnes et al., will be submitted to J. Geophys. Res. this week

Again, disruption to air traffic but not as severe as for the Eyjafjallajökull eruption

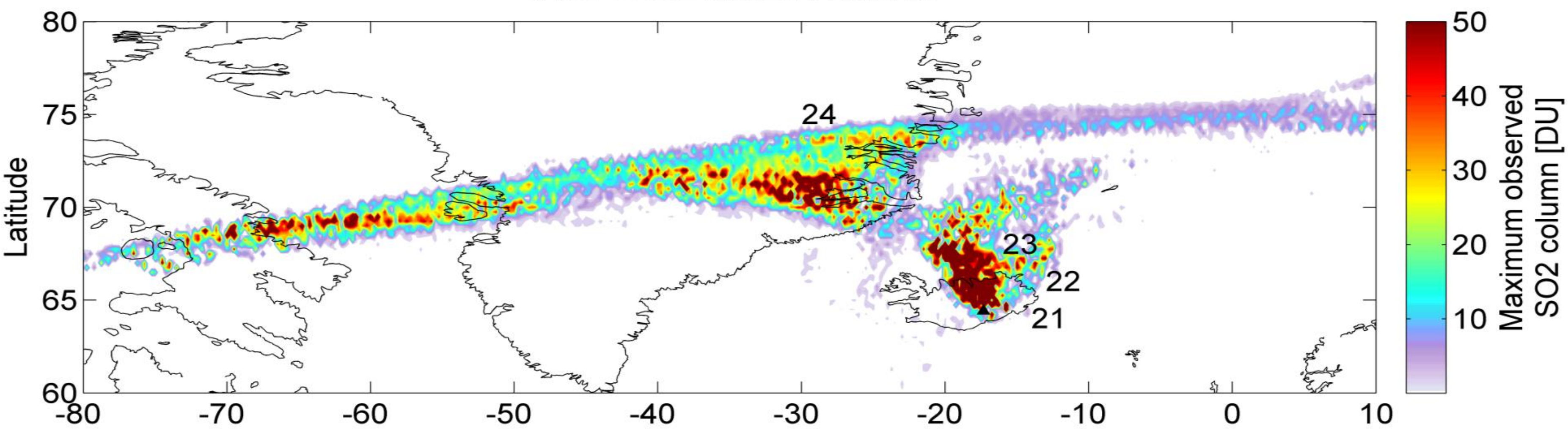
Ash- and sulfur-rich eruption

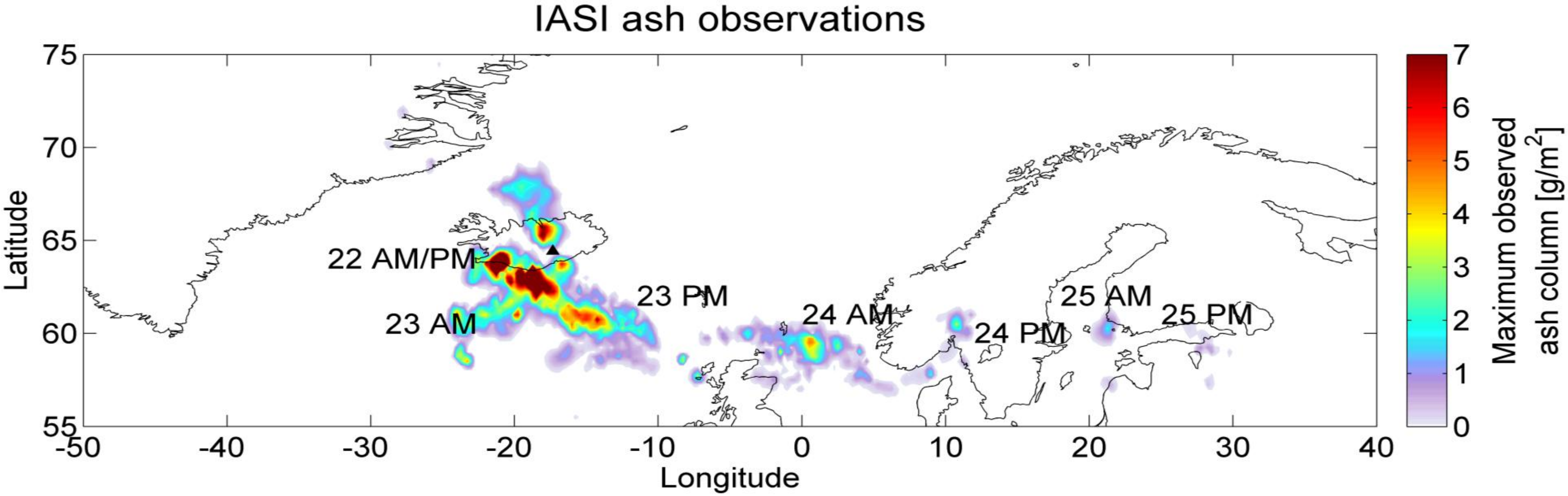
Performed inversions for ash and SO_2 to investigate differences in emission height/time

Input data: IASI satellite retrievals for ash and SO_2

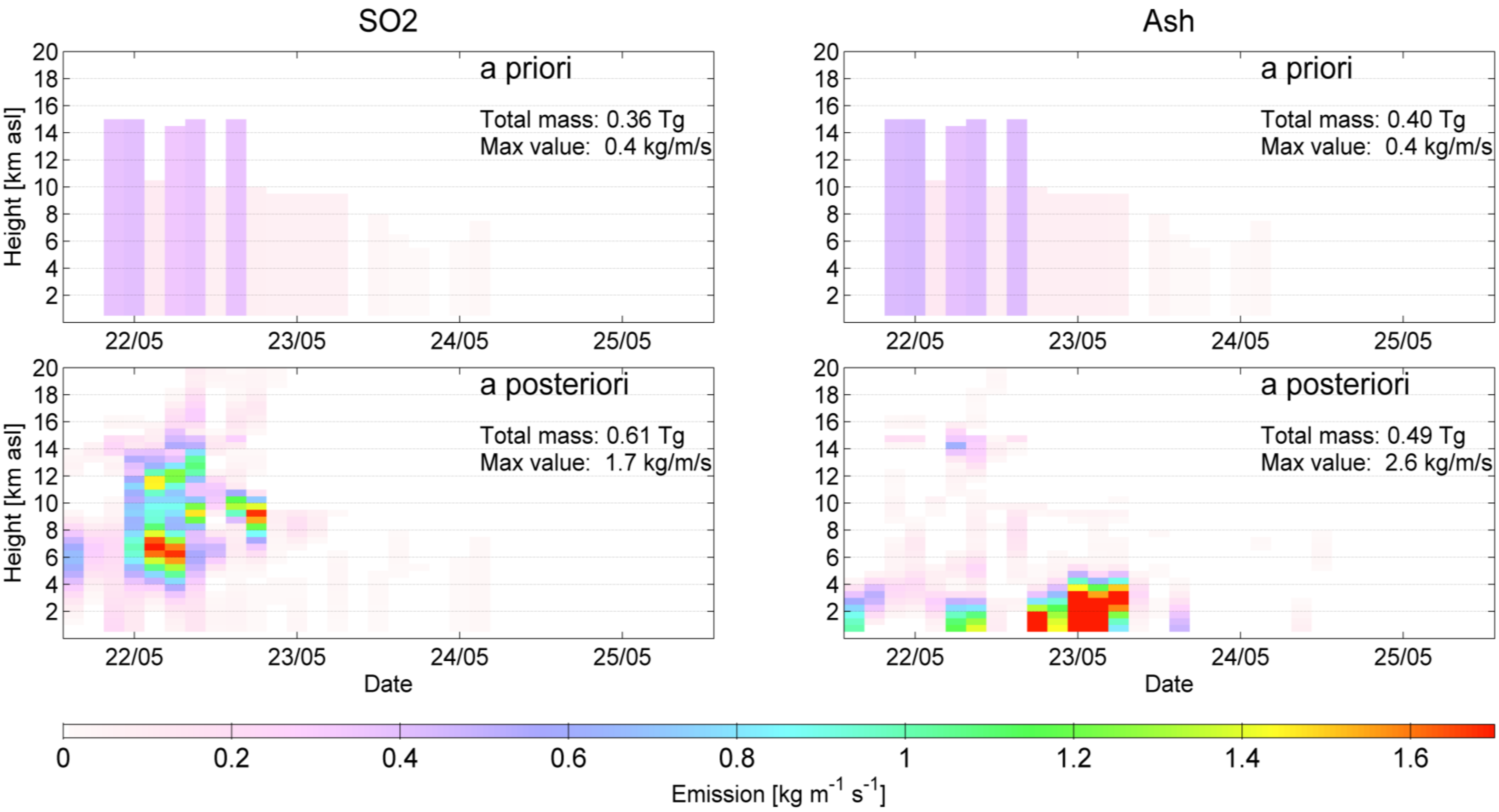
NILU

Different transport routes seen from IASI satellite instrument

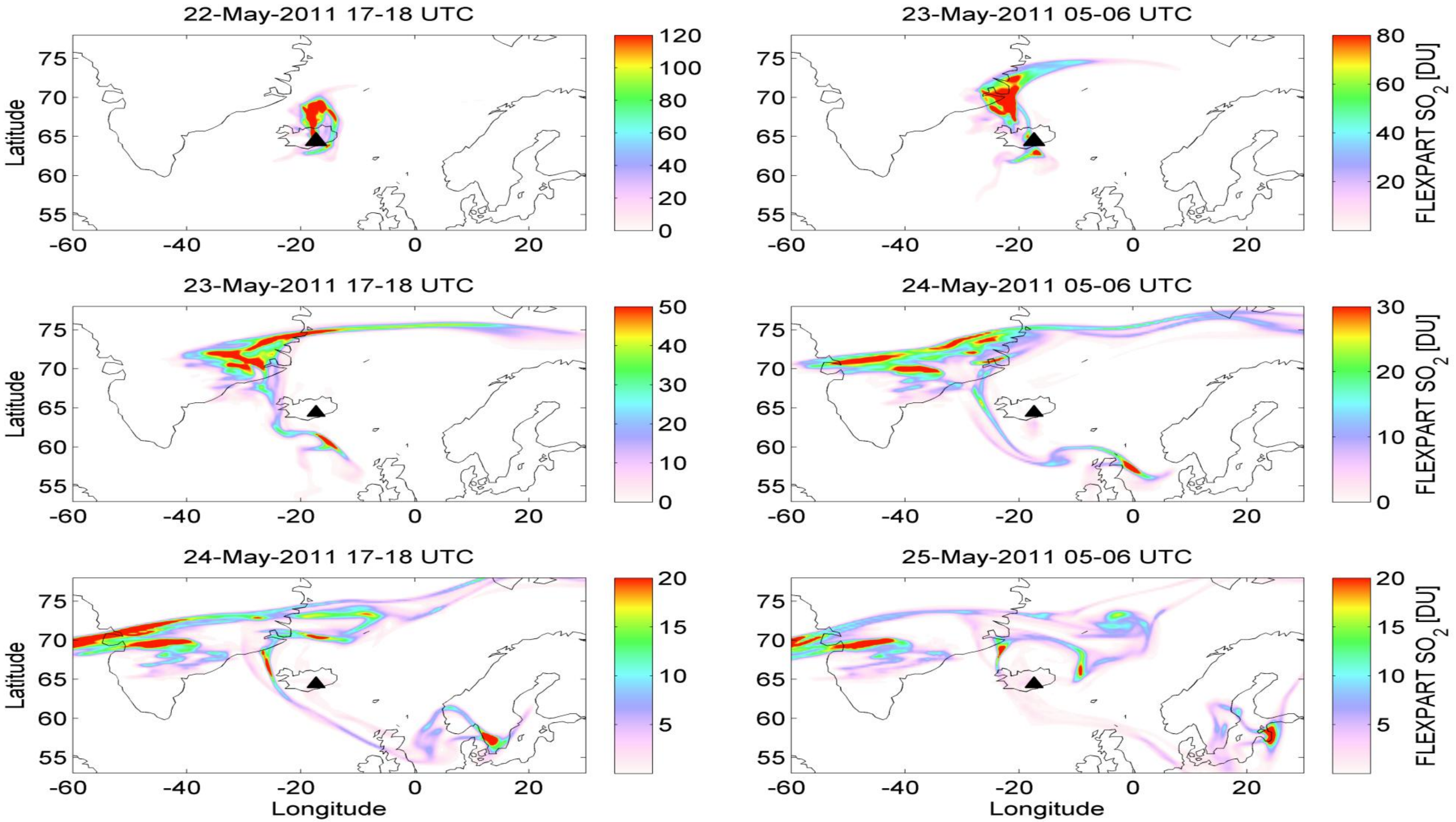

IASI SO2 observations


IASI ash observations

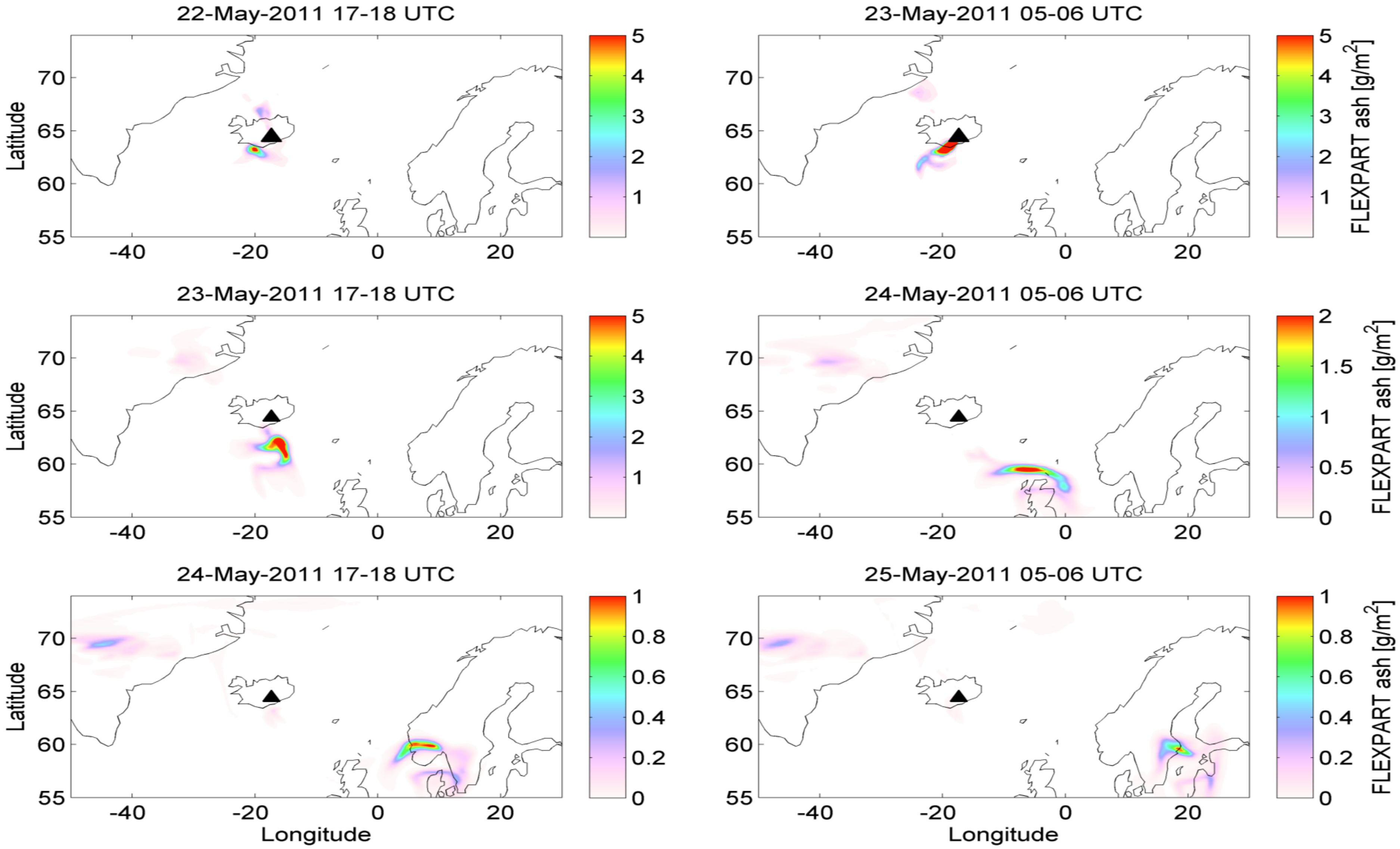
Source terms noisy, but SO_2 was injected high, ash was injected low



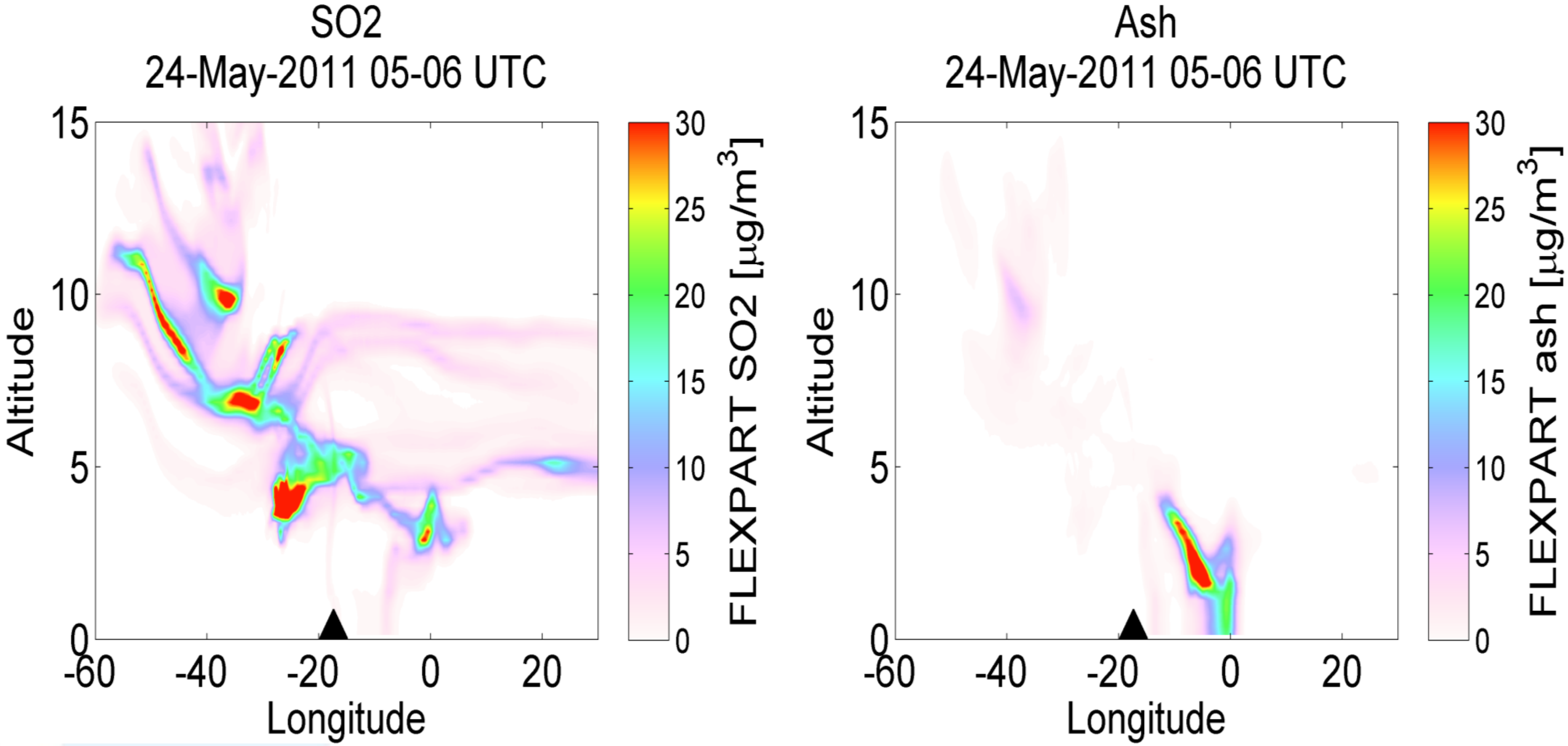
Simulated transport of SO_2



Simulated transport of ash



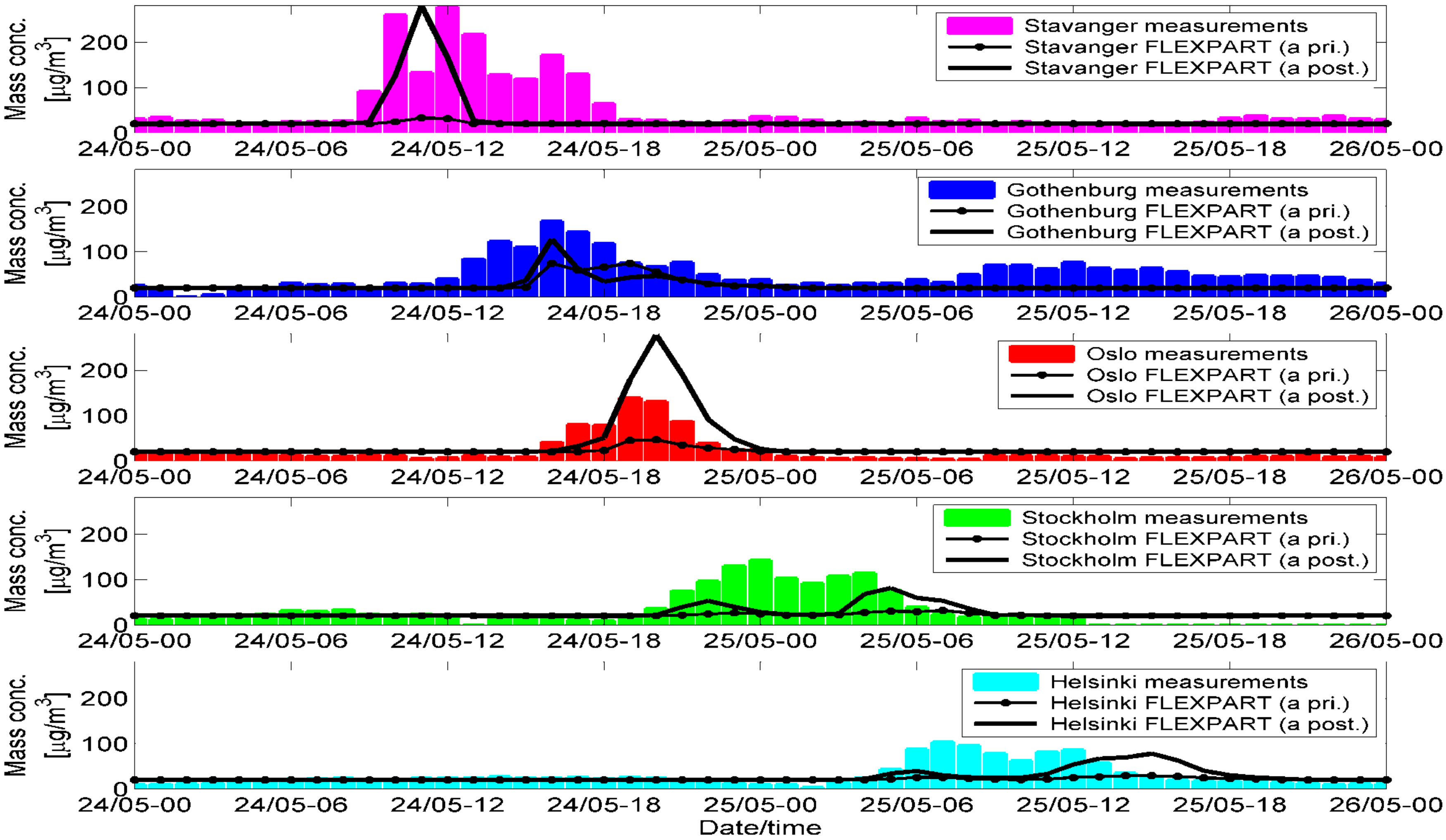
Vertical section through model output



Validation with independent satellite data (SCIAMACHY and GOME)

Fig. 9	**SCIAMACHY**	**A POST (IASI)**	**A POST(AIRS)**	**A PRIORI (IASI)**
Mean	19.8	21.7	12.3	11.0
Bias		2.0	-7.5	-8.8
NMSE		0.7	2.2	3.1
FOEX		-11.1	-17.2	-22.1
PCC conf.int.		0.69 – 0.80	0.40 – 0.58	0.19 - 0.41
Fig.10	**GOME-2**	**A POST (IASI)**	**A POST(AIRS)**	**A PRIORI (IASI)**
Mean	9.3	9.6	5.6	5.0
Bias		0.3	-3.6	-4.3
NMSE		1.2	2.4	3.0
FOEX		0.2	-8.4	-18.0
PCC conf.int.		0.37 – 0.58	0.15 – 0.40	0.13 – 0.38

Comparison of simulated ash to ground-based air quality measurements in Scandinavia



Important remaining issues

Quantification of uncertainties still rather ad-hoc

Need: satellite retrieval uncertainties (clouds, etc.)
Need: model uncertainties (ensemble modeling)

Errors in simulated ash removal will be partly fit into the a posteriori emissions

Need: Model evaluation of ash removal time scales (especially wet removal, but also ash aggregation)

Operationalisation: Artifacts in satellite data create spurious emissions

Need: more ”automatic cleaning” of satellite data

Satellite retrievals use a model, too! They assume a certain ash height distribution

Need: iterative inversion/retrieval or direct assimilation of radiances

Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima nuclear power plant and the global-mean lifetime of accumulation-mode aerosol

A. Stohl, N. I. Kristiansen, P. Seibert, G. Wotawa,
D. Arnold, J. F. Burkhart, S. Eckhardt, C. Tapia,
A. Vargas, and T. J. Yasunari

Based on:

Stohl et al. (2012): *Atmos. Chem. Phys.* **12**, 2313-2343.

Kristiansen et al. (2012): *Atmos. Chem. Phys.* **12**, 10759-10769.

Stohl et al. (2012): *J. Environ. Radioact.* **112**, 155-159.

Halocarbon emissions in China

Example: HFC-23
a by-product of HCFC-22 production

Black dots: 3 measurement stations

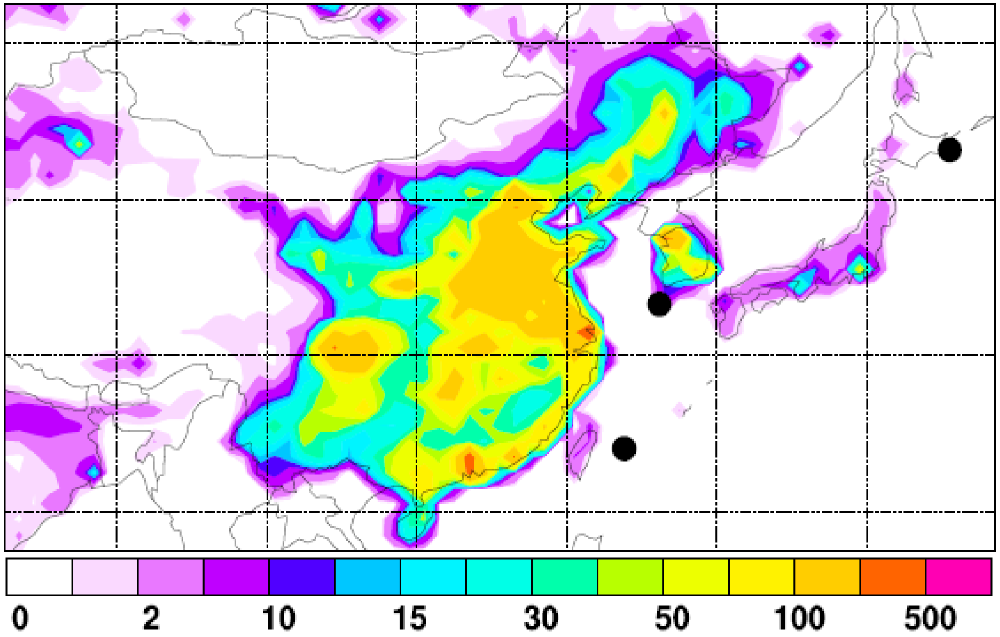
Top panel: emission distribution available a priori

Bottom panel: inversion result

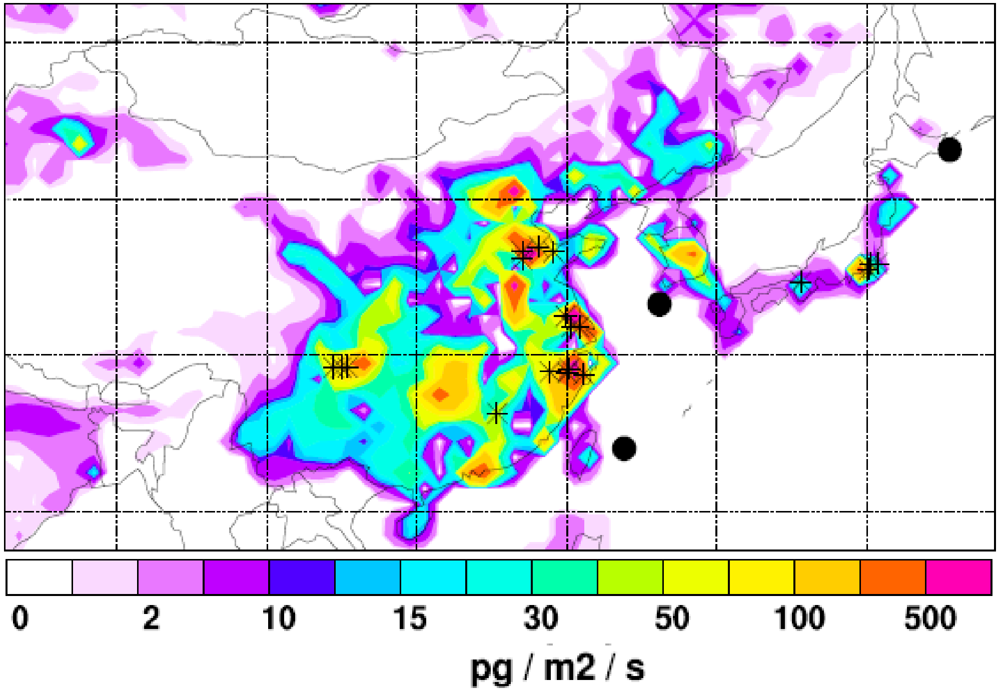
Asterisks: known locations of HCFC-22 factories

New powerful modular open-access code for greenhouse gas emissions in preparation by Rona Thompson et al.

a) A priori emissions



b) A posteriori emissions



Thank you!