Combining SCIAMACHY limb and nadir aerosol measurements

Sulfate aerosols from Nabro volcano
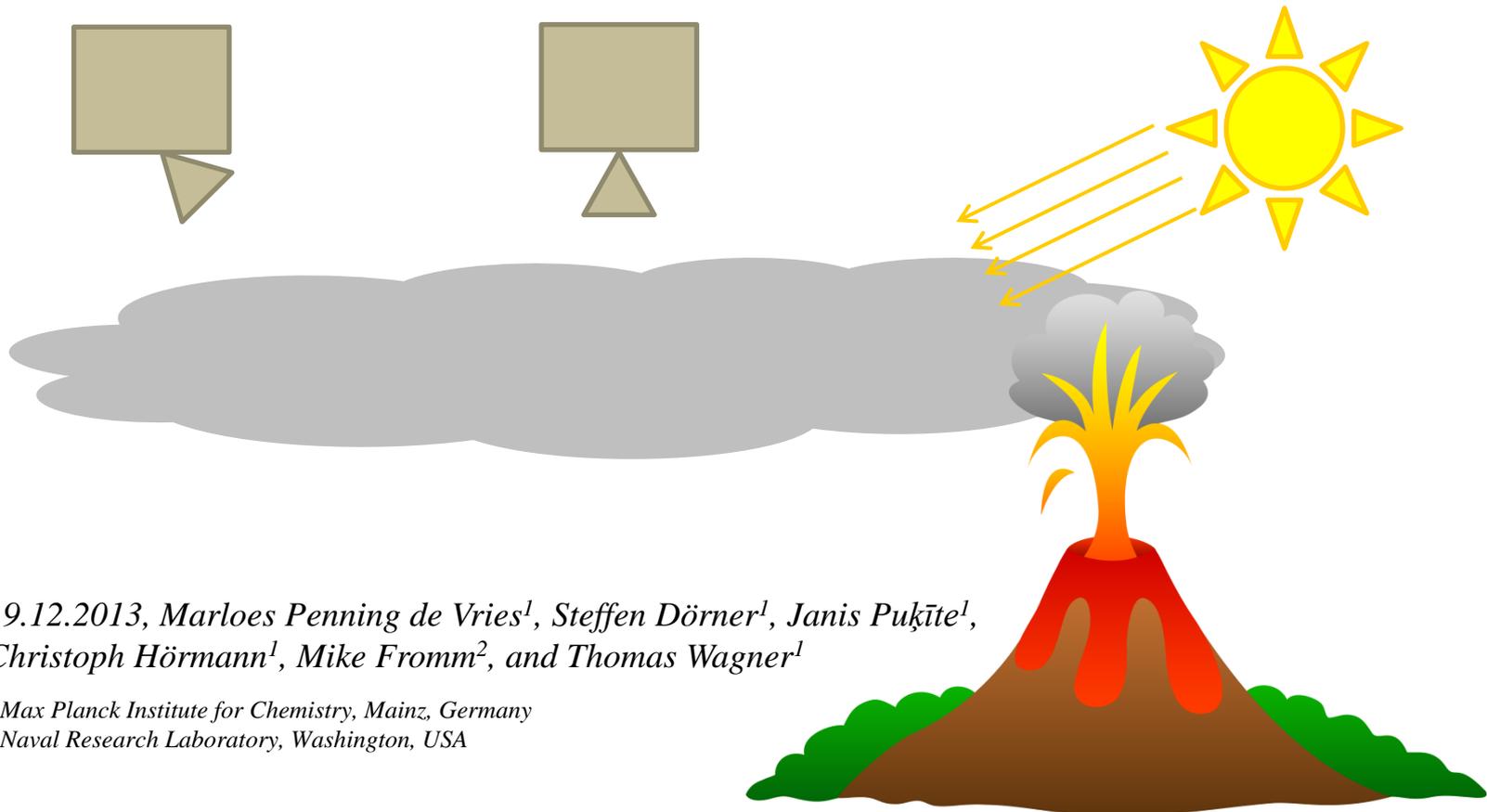
19.12.2013, Marloes Penning de Vries[1], Steffen Dörner[1], Janis Puķīte[1], Christoph Hörmann[1], Mike Fromm[2], and Thomas Wagner[1]

[1] *Max Planck Institute for Chemistry, Mainz, Germany*
[2] *Naval Research Laboratory, Washington, USA*

Eruption of Nabro (June 2011)

- Nabro volcano (13°N / 42°E, Eritrea) was assumed extinct
- First explosive eruption in late evening of June 12, 2011; more in following weeks
- Large amount of SO_2 emitted: 4-5 Tg in first 15 days[1] (Pinatubo: 20 Tg)
- Total stratospheric AOT was highest measured by OSIRIS since its launch in 2001 [2]
- Eruption observed by many different satellites; GOME-2 and SCIAMACHY among first instruments to detect plume
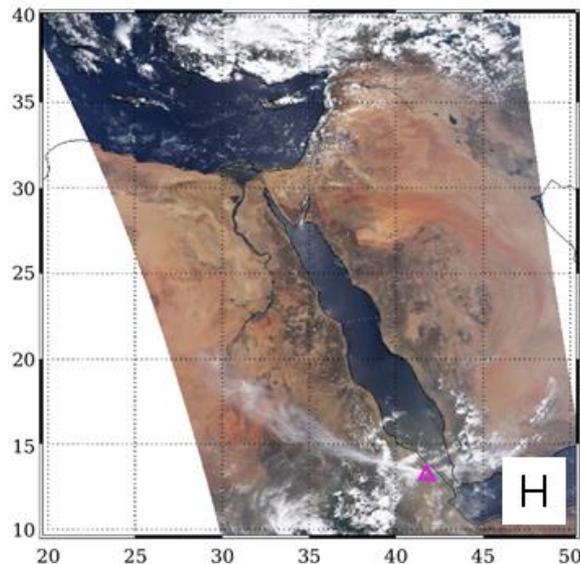
MODIS-AQUA
On June 13, 2011

Manuscript soon to be submitted:
Penning de Vries et al., Characterisation of a stratospheric sulphate plume
from the Nabro volcano by combination of passive satellite measurements in nadir and limb geometry

[1]Theys et al., ACP, 2013; [2]Bourassa et al., Science, 2013

Nadir measurements

- View of the total atmospheric column
- Satellite instruments: passive, polar orbiting
  UV-Vis spectrometers
- SCIAMACHY (ENVISAT)
  - Nadir & limb
  - Daytime descending orbit, overpass at 10:30 local
  - Nadir pixel size 30x60 km^2
- GOME-2 (METOP-A)
  - Nadir only
  - Descending orbit, overpass at 9:30
  - Pixel size 40x80 km^2
  - 1x per month in narrow-swath mode (pixel size ~40x10 km^2)
- OMI (AURA)
  - Nadir only
  - Ascending orbit, overpass at 13:30
  - Pixel size at nadir 13x24 km^2
  - Row anomaly since June 2007

iup.physik.uni-bremen.de

ENVISAT

dutchspace.nl

METOP-A

ESA

AURA

A-Train

CNES
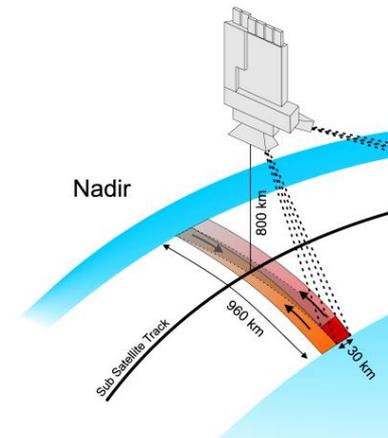
Nadir measurements – UV Aerosol Indices

- UV Aerosol Indices (UVAI)
  - Measure of aerosols, especially sensitive to elevated UV-absorbing aerosols[1,2]
  - Differentiation between UV-absorbing (UVAI>0) and non-absorbing aerosols (UVAI<0)[3]
  - Can be meaningfully interpreted even in presence of clouds
  - Dependent on solar and viewing geometry!

Clouds

Non-absorbing aerosols: sulfate

Absorbing aerosols: dust, volcanic ash?

[1]Torres et al., JGR 1998; [2]de Graaf et al., JGR 2005; [3]Penning de Vries et al., ACP, 2009
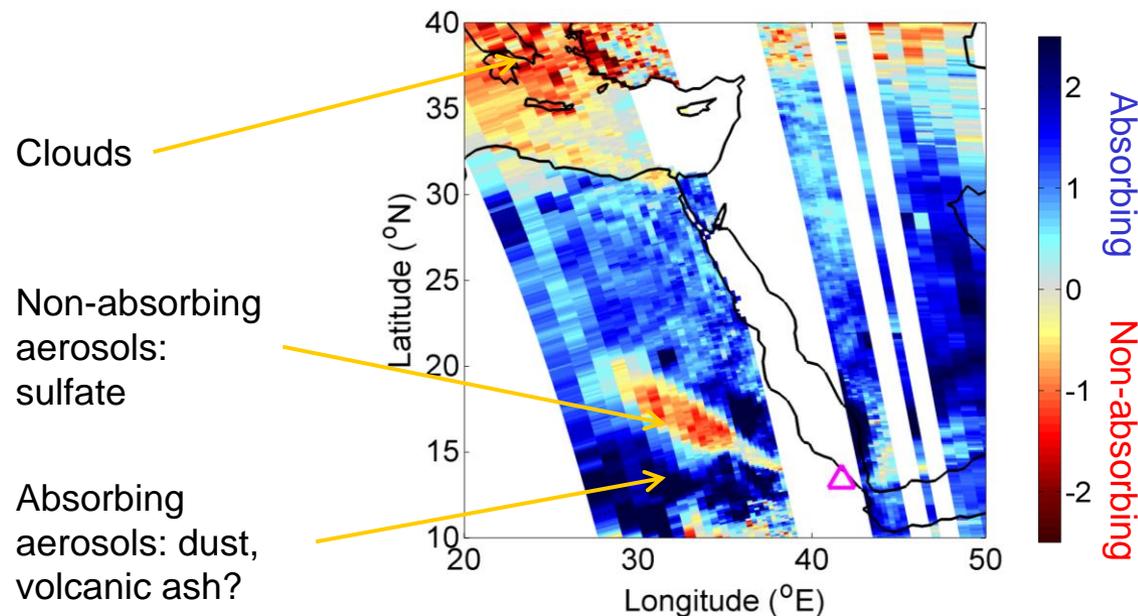
Nadir results – June 13

- Good spatial agreement between SO$_2$ and neg. UVAI
  - best agreement for OMI
- No strong ash signal (pos. UVAI) visible
- UVAI also detects clouds and desert dust
- MODIS shows presence of ice cloud
- UVAI probably influenced by ice cloud

OMI pixels affected by row anomaly removed

SO$_2$ VCD   UVAI   RGB

GOME-2   SCIAMACHY   OMI

MODIS-TERRA   MODIS-AQUA
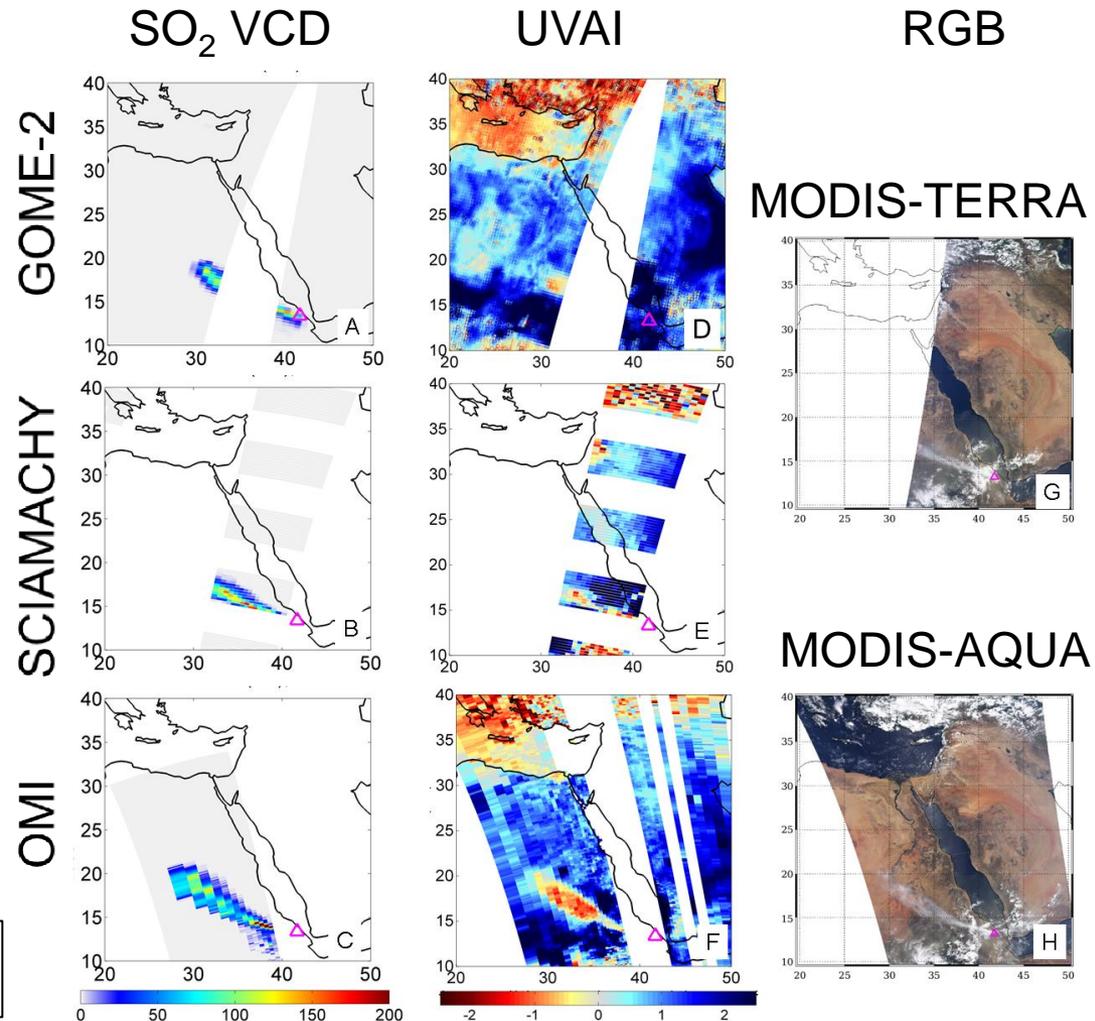
Nadir results – June 14

- GOME-2 in narrow swath mode; no aerosol signal visible
- SCIAMACHY caught tail end of plume; visible in SO_2 and UVAI
- OMI detected volcanic plume in two consecutive, partially overlapping orbits
- Aerosol plume visible in both OMI orbits, but... (see next slide)
- Plume disappeared from MODIS' view

GOME-2 in narrow-swath mode

OMI pixels affected by row anomaly removed

SO$_2$ VCD   UVAI   RGB

MODIS-TERRA

MODIS-AQUA
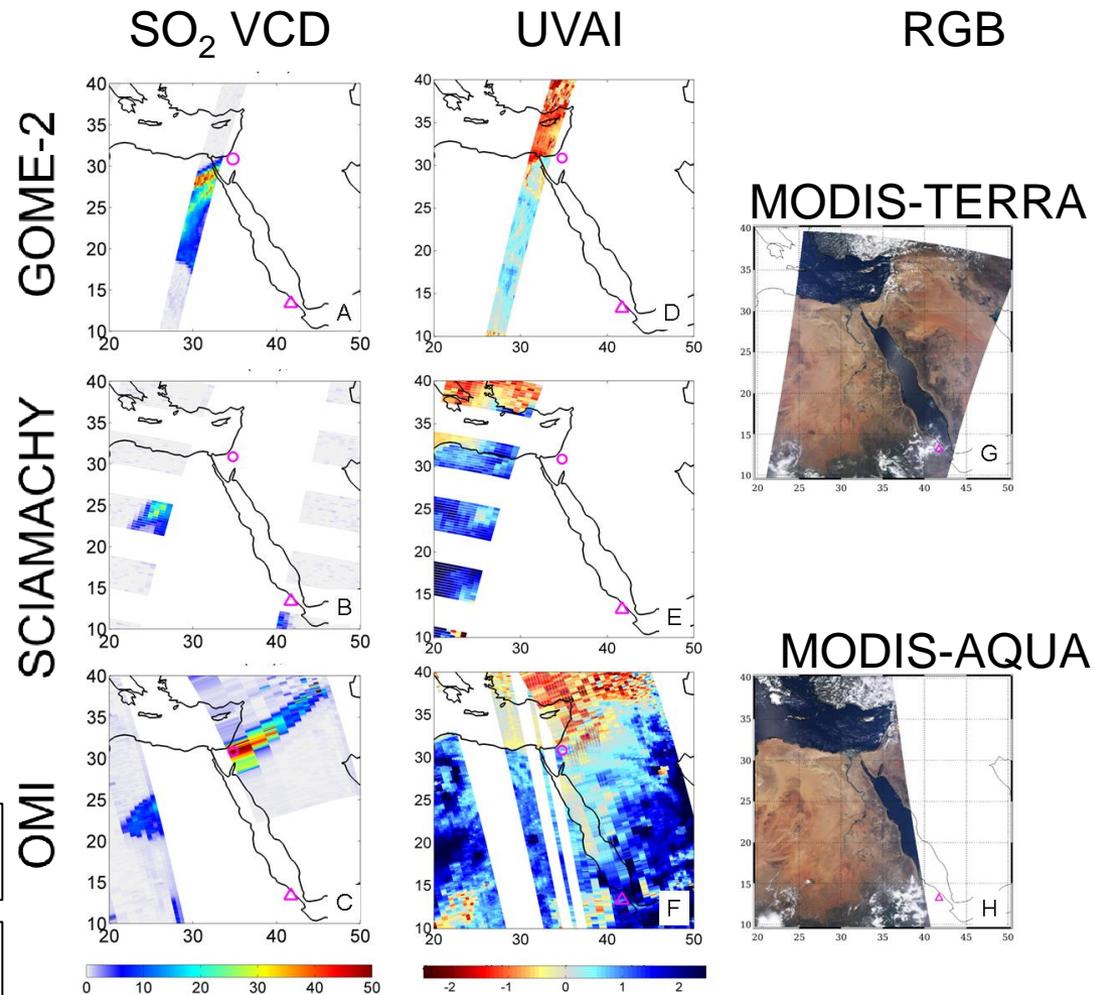
OMI UVAI results – June 14

- Same section of plume measured twice within 100 minutes but from opposing sides
- Pixels selected with SO_2 VCD>1DU to pick out volcanic plume
- First overpass: negative UVAI; second overpass: positive UVAI?!

OMI

OMI strat. SO2 (max. 50DU), orbit 36772

OMI strat. SO2 (max. 50DU), orbit 36773

SO_2 VCD (NASA)

OMAERUV UVAI, orbit 36772

OMAERUV UVAI, orbit 36773

Only plume pixels selected (SO_2>1DU)

OMAERUV UVAI, orbit 36772, SO2>1DU

OMAERUV UVAI, orbit 36773, SO2>1DU

OMAERUV UVAI (NASA)
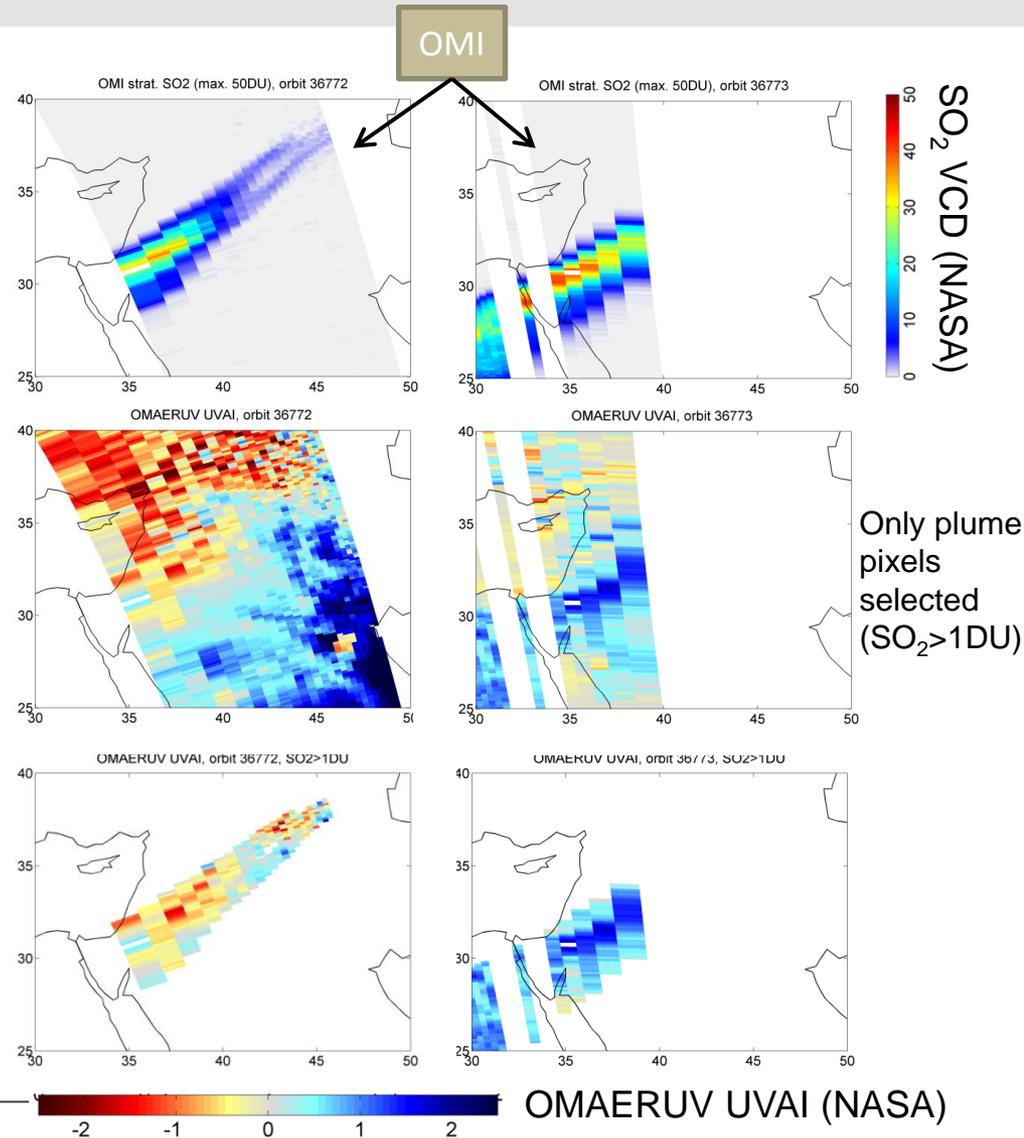
Angle dependence of UVAI

- Angle dependence was studied theoretically in de Graaf et al., JGR 2005:
  - Model calculations using DAK
  - Aerosol layer (SSA = 0.9, AOT = 1, g = 0.7) at 3-4 km, surface albedo 0.05

Rel. azimuth angle 0

Rel. azimuth angle 180

(TROP)OMI

GOME-2

SCIAMACHY

ΔUVAI = 0.5
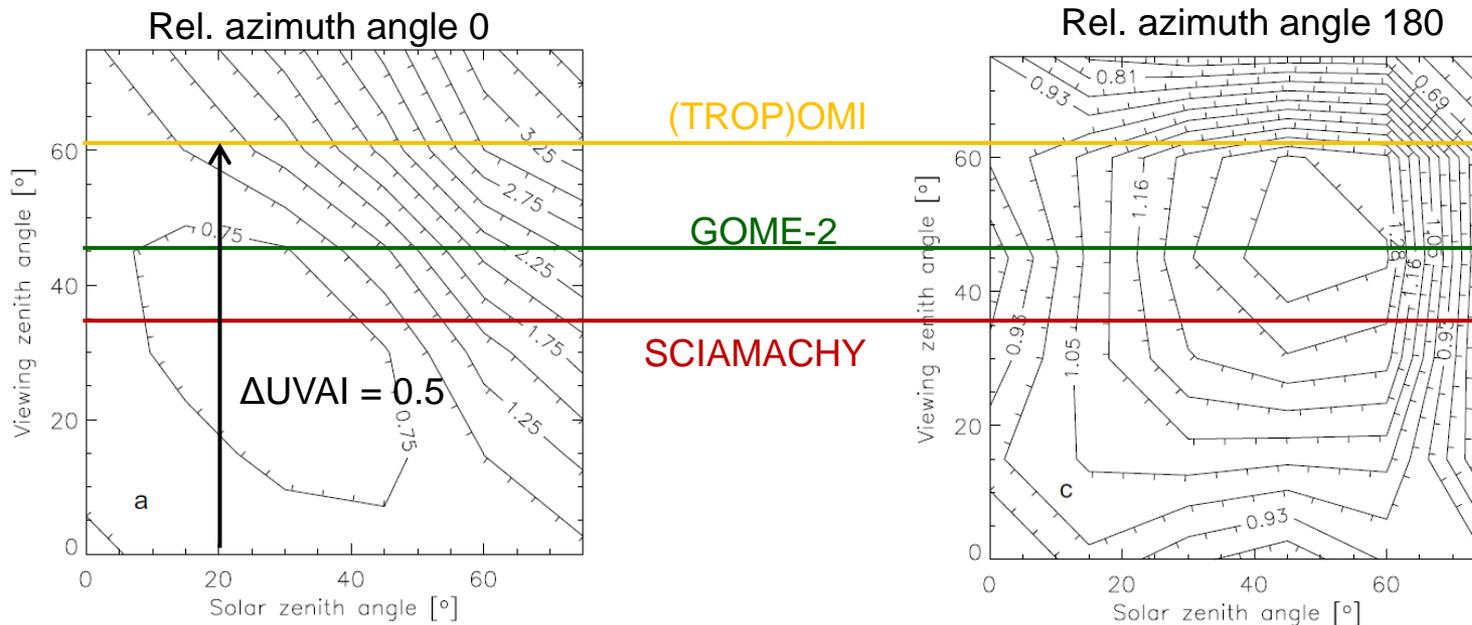
- Viewing angle dependence is moderate for GOME(-2) and SCIAMACHY viewing geometries, but is substantial for (TROP)OMI

MAX-PLANCK-INSTITUT
FÜR CHEMIE

- RTM calculations with Monte Carlo model McArtim[1]
- We did simulations with an aerosol layer:
  - Aerosols with g=0.6 and Angstrom coefficient 1.5
  - Layer thickness: 1 km, surface albedo 0.1
  - SZA 20
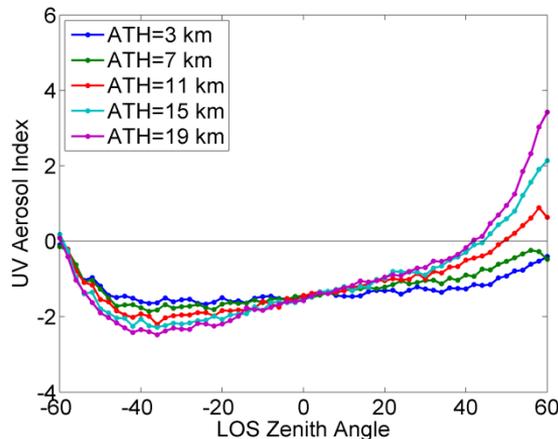
AOT_{380} = 0.4, SSA=1.0   SSA=1.0, ATH=19 km AOT_{380}=0.4, ATH=19 km
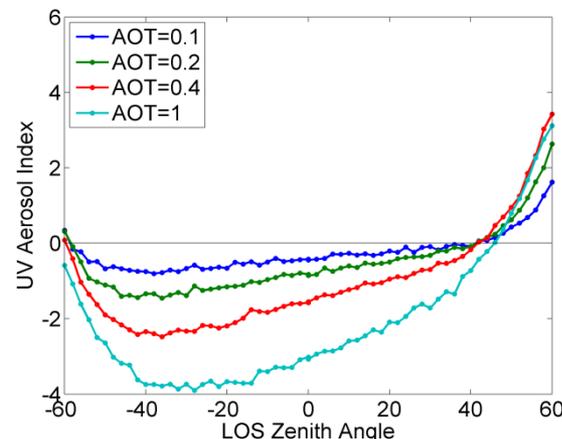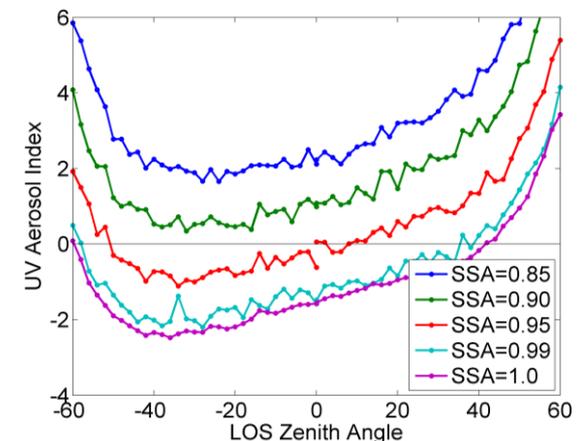
- Viewing angle dependence causes UVAI<0 in west and UVAI>0 in east of swath!
- Magnitude of effect dependent on AOT, not on SSA

[1]Deutschmann et al., JQSRT 2011

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UVAI viewing angle dependence – simulations 2

- We also did simulations with a cloud layer:
  - Cloud with g=0.87 and COT 1-50
  - Cloud thickness: 1 km, surface albedo 0.1
  - SZA 20
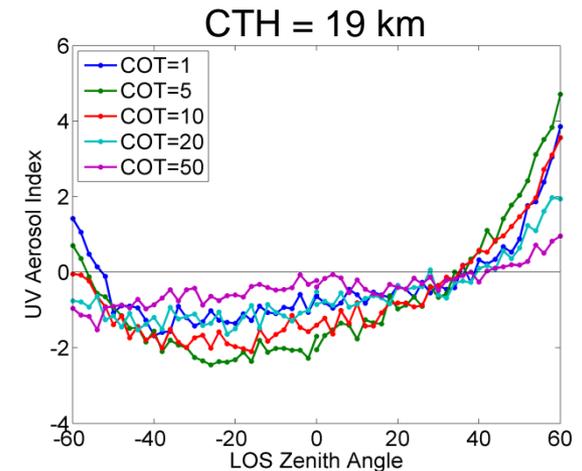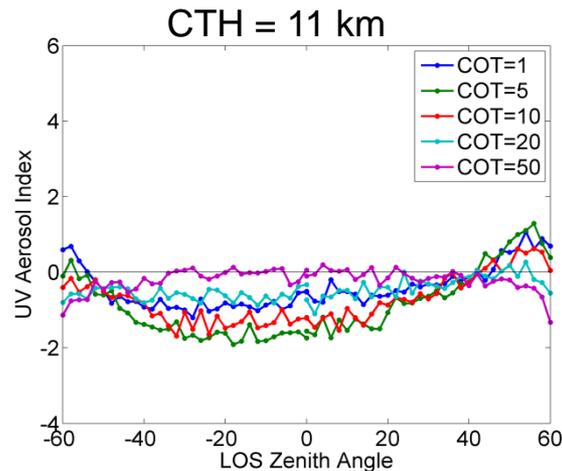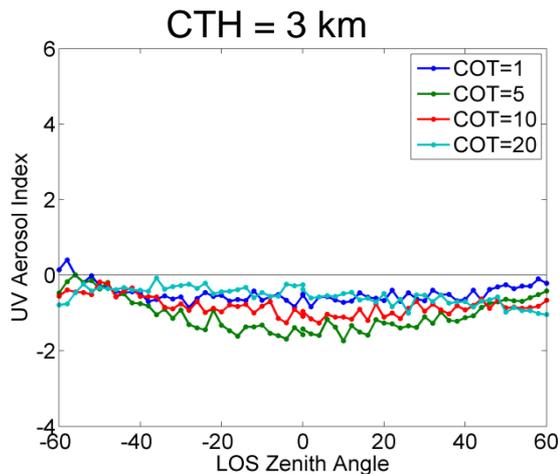
- Viewing angle dependence less pronounced than for aerosols, but apparent for CTH=19
- Clouds are not normally found at such altitudes!

- Radiative transfer modeling of UVAI of elevated sulfate plume
  - Plume at 18-19 km
  - Non-absorbing aerosols with AOT 0.1-0.4 (depending on SO_2)
- Viewing angle effect well reproduced by simulations
  - Agreement not perfect due to simple parameterization of aerosols and contamination (clouds, surface, dust)
- Evidence for high-altitude aerosol layer with high single-scattering albedo (>0.95)

Only plume pixels selected (SO_2>1DU)
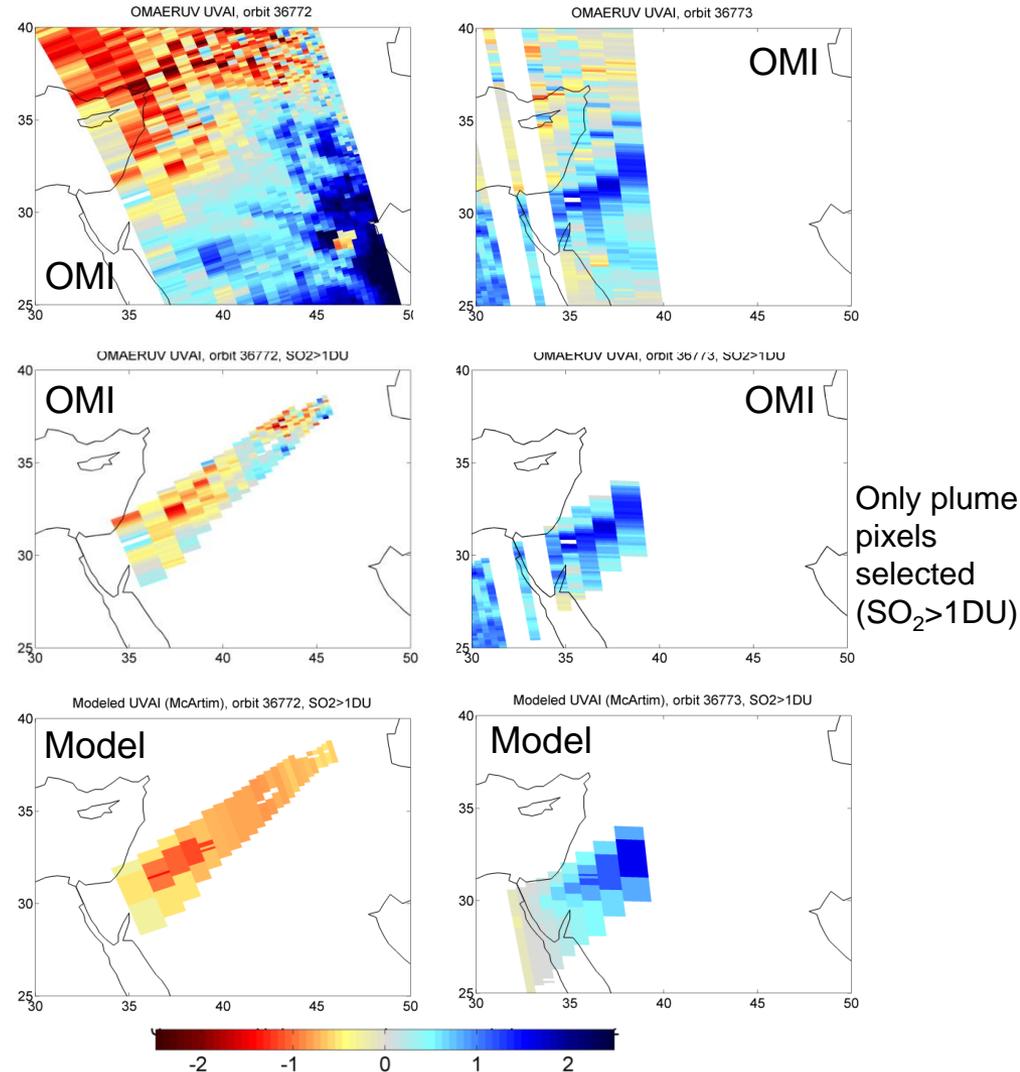
Limb measurements

- Scans through the atmosphere
- Pixel size ~240x30 km^2
- Vertical resolution: ~3 km

- Onion-peeling method:
  - Reference tangent height (TH) at 34.5 km
  - For each lower TH in sequence, retrieve extinction at 750 nm from measured intensity using RTM calculations in an iterative process
  - Aerosol model: sulfate with size dist. centered at 0.2 µm (g = 0.6)

iup.physik.uni-bremen.de/sciamachy
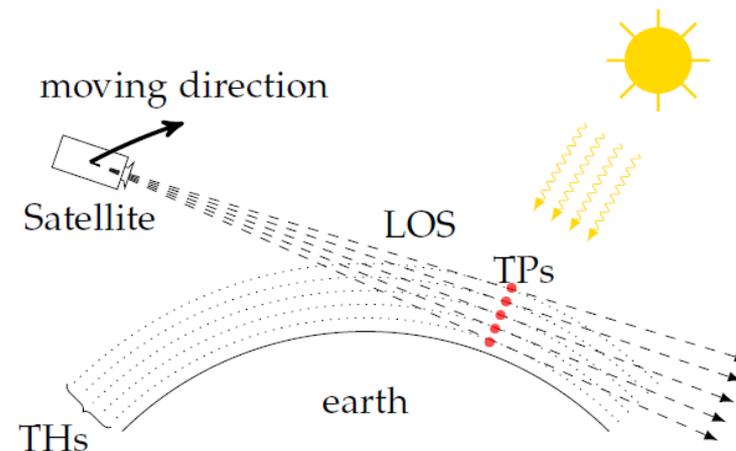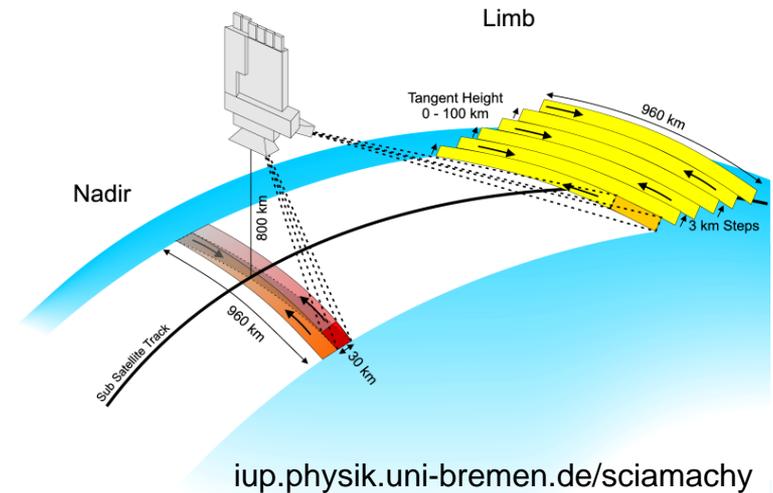
Extinction profiles from limb measurements

- Extinction profiles retrieved from all four limb pixels containing volcanic plume
- June 14:
  - Plume covers pixels 3-4
  - 1-2 have background conditions
  - Clearly defined maximum at 16.5 km
  - Aerosols visible up to 19.5 km
- June 13:
  - Plume covers all pixels
  - Extinction higher
  - Plume altitude lower
  - Effect of localized plume (next slides)

June 13

June 14
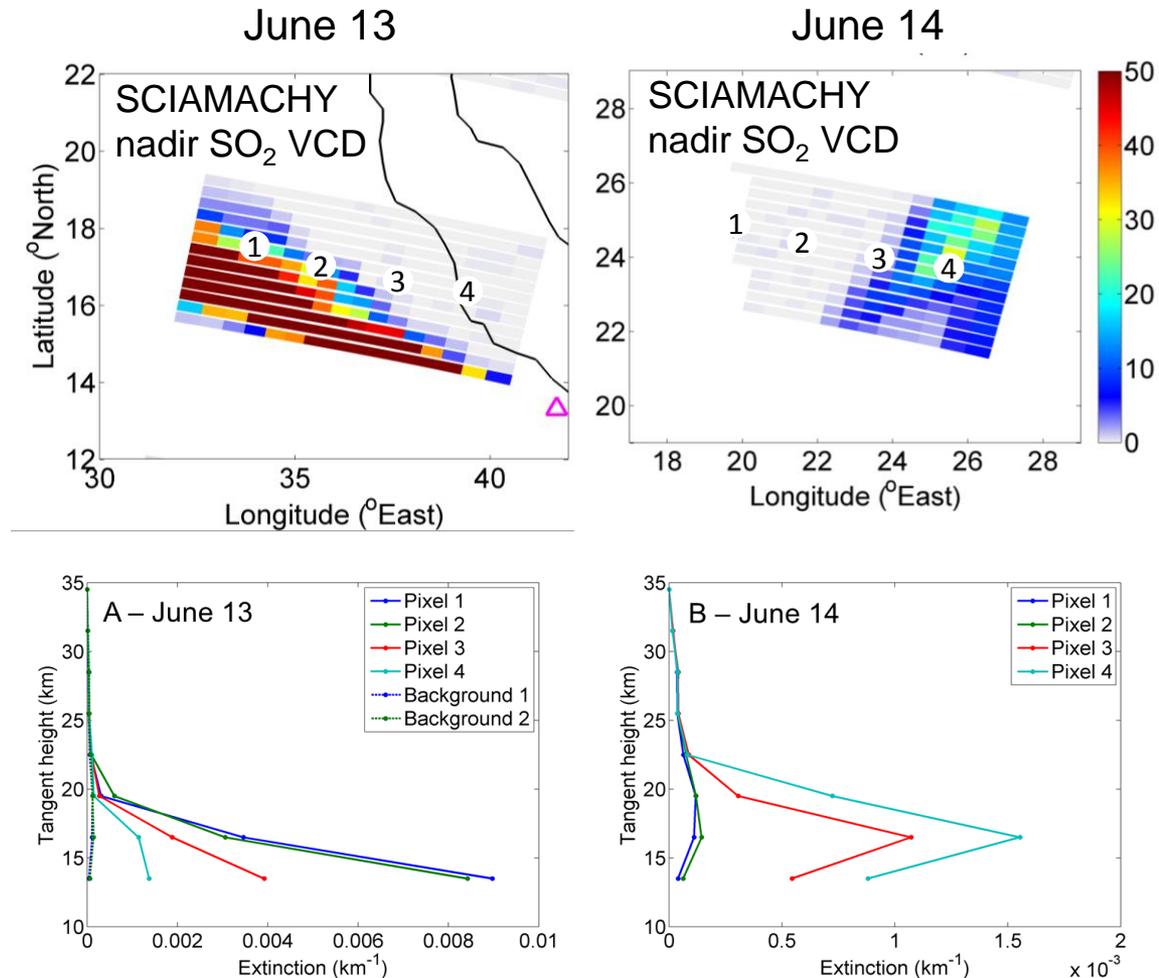
3D effects - theory

- Limb retrieval assumes homogeneous aerosol layer, infinite in the horizontal plane (A)
    - Valid for background, NOT for some volcanic (or smoke) plumes and clouds (e.g. PSCs)
- If plume is localized (B), extinction is underestimated
- If plume is additionally not centered at TP (C), extinction and altitude are underestimated
- No overestimation possible!
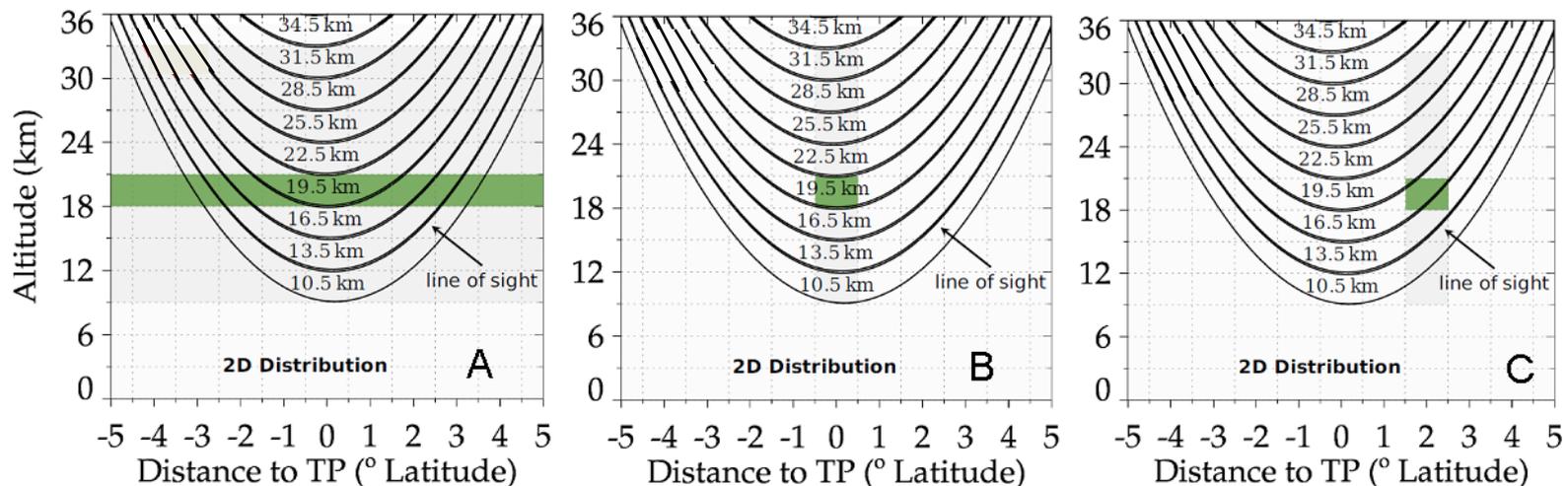
SCIAMACHY limb lines-of-sight for THs 10.5-34.5 km
Aerosol layer depicted in green

3D effects - practice

- Limb sensitivity regions: for finite plume at 18-21 km
  - If plume restricted to blue boxes, correct TH (19.5 km) is retrieved
  - If plume only in green boxes, retrieval finds (wrong) TH=16.5 km
  - If plume in red boxes, TH=13.5 km is retrieved

- Effects of plume position and size visible in data
  - Plume ± at TP of pixels 3 and 4 of June 14
  - Plume south of TPs on June 13, so (progressively) smaller extinctions at lower altitudes retrieved
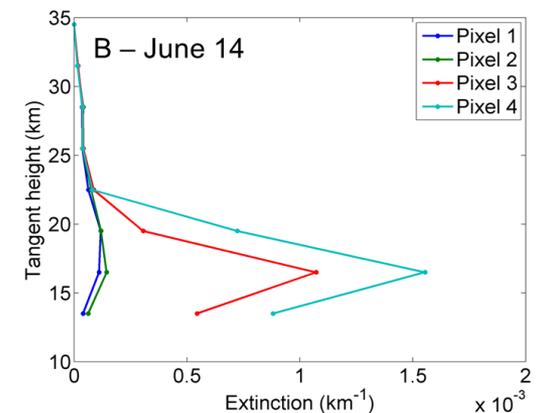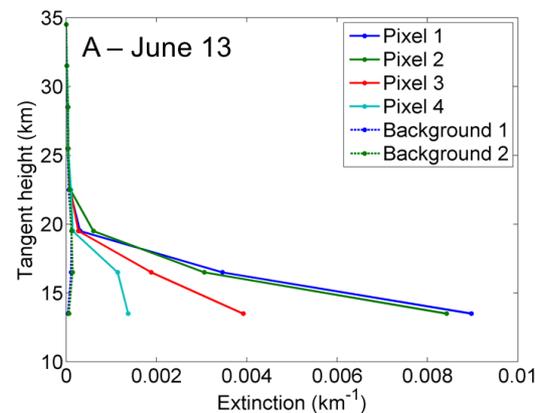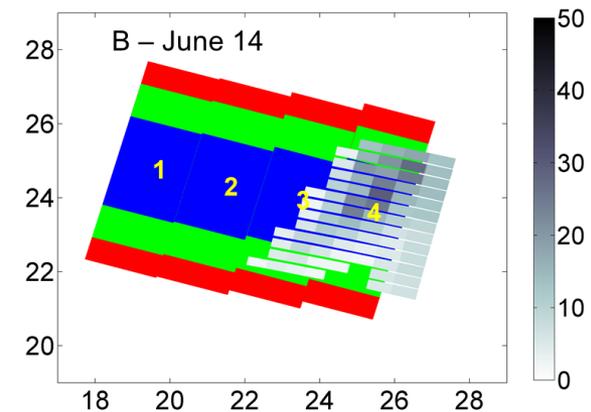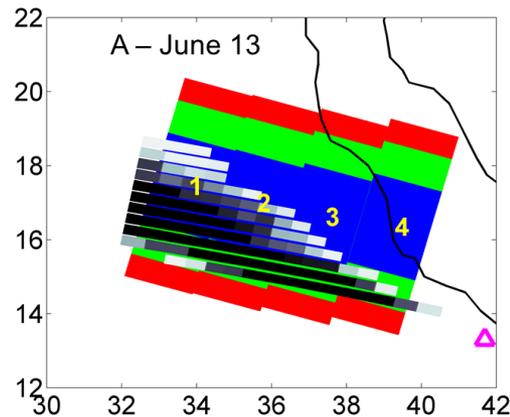
- Stratospheric plume takes more northerly route than lower-altitude plumes
  - Confirmed by CALIPSO lidar during 5 overpasses on June 16 [1]
- After June 17, nadir SO_2 plumes overlap too much
- Extinction profiles retrieved for all states in pink boxes

[1]Vernier et al., Science, 2013
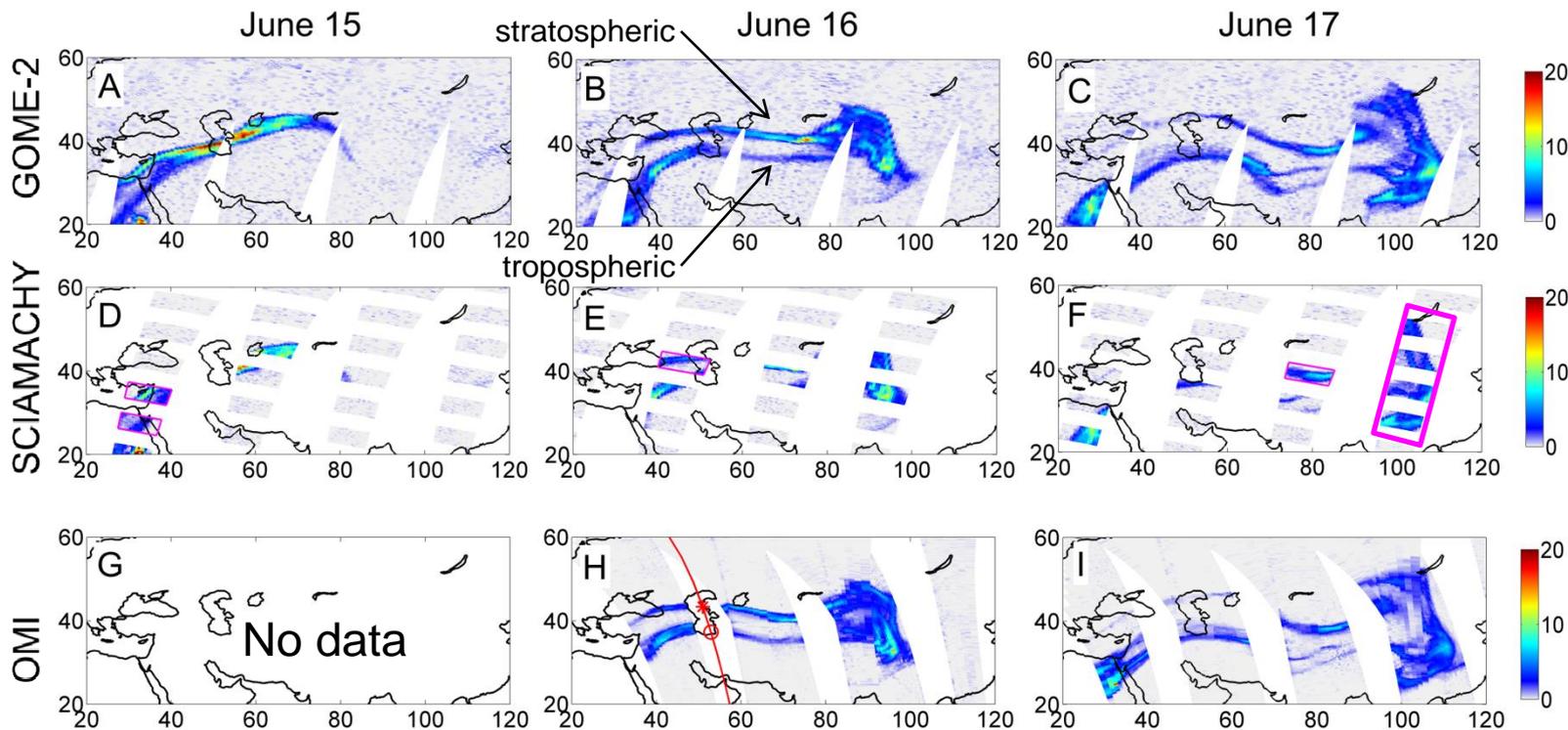
Extinction profiles June 15

- **State 17:**
  - Pixel 1 sees nearly only background, possibly plume at large distance (not seen in nadir)
  - Plume closest to TP in pixel 3, hence highest extinction and altitude
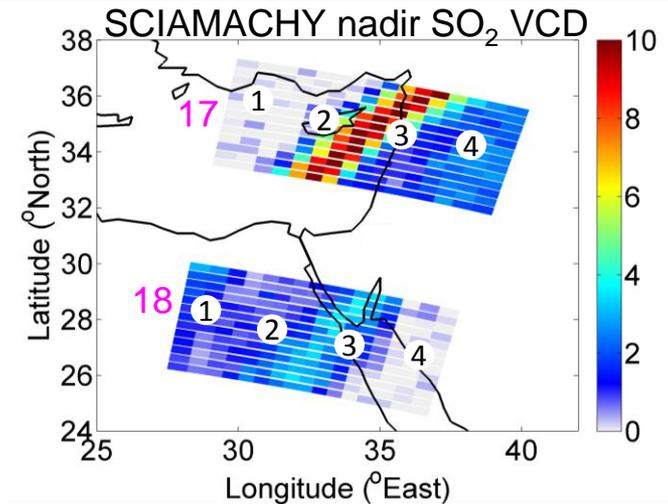
- **State 18:**
  - Pixel 1 sees tail end of plume
  - Pixel 3 probably sees only tropospheric plume
  - Pixel 4 has background conditions

SCIAMACHY nadir SO$_2$ VCD

A – June 15, state 17

B – June 15, state 18
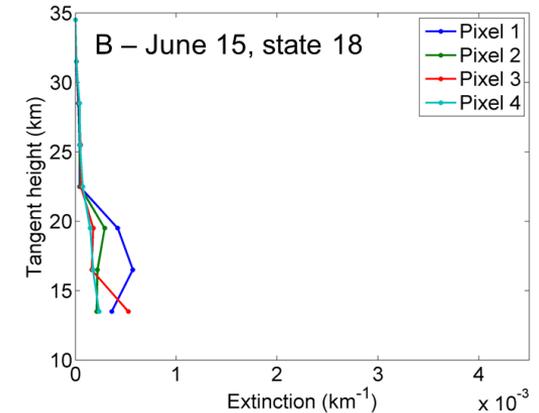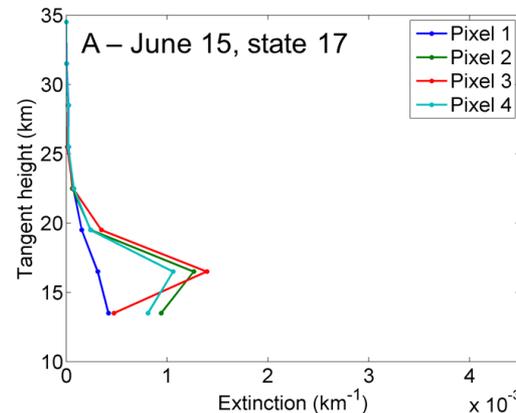
Extinction profiles 16-17 June

- June 16:
  - Plume close to TPs of all pixels
  - Largest altitudes found for pixels 2-3
  - Aerosol plume different from SO_2 plume?

- June 17:
  - Plume visible in all pixels
  - High extinctions at high altitudes (19.5 km) retrieved
  - Relatively large extinction at lowest TH may be due to clouds
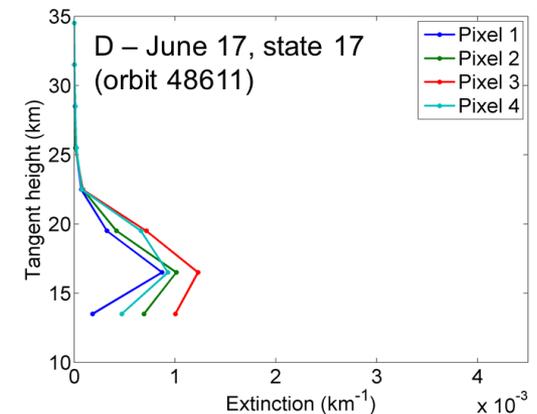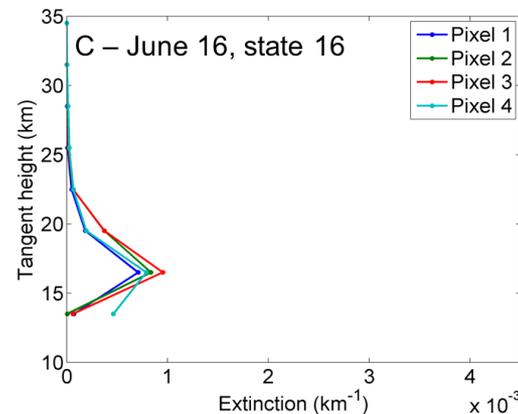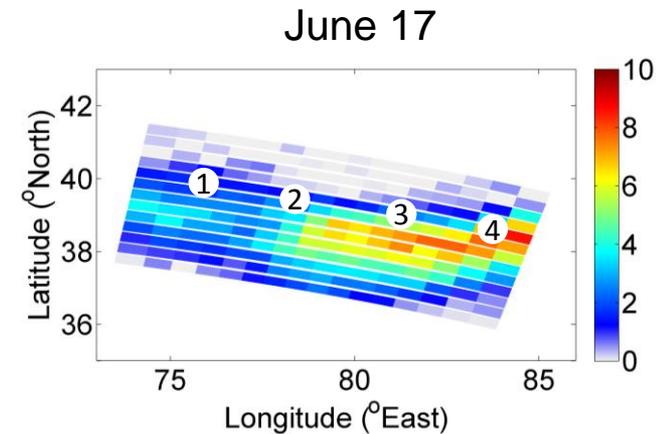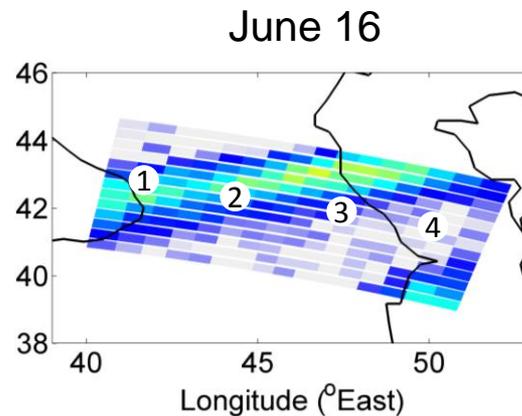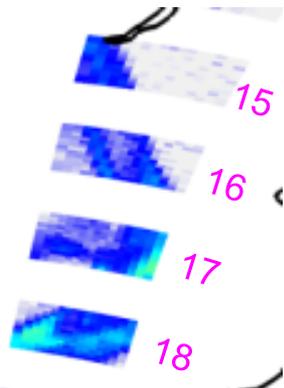
June 16

June 17

June 17

- • State 15:
  - – Pixel 1 sees plume
  - – Other pixels see lower-lying cloud
- • State 16:
  - – Plume seen by pixels 1-3, best by 2 and 3

State 17:

  - – Only pixel 4 sees plume
  - – Lower-lying SO_2 in other limb pixels?

State 18:

  - – Plume seen in all pixels
  - – Most in pixels 3 and 4
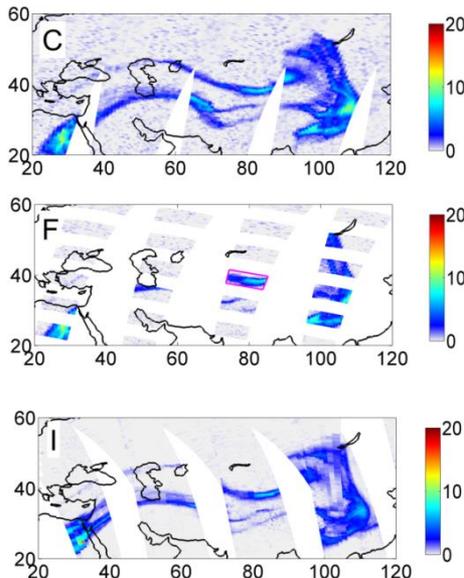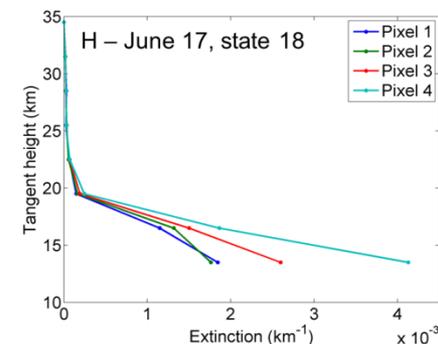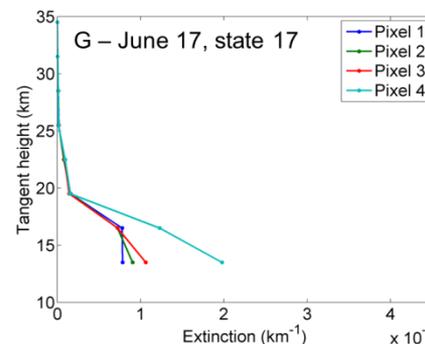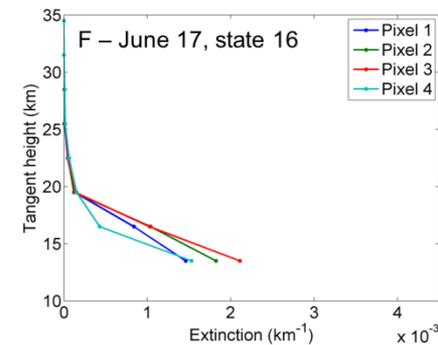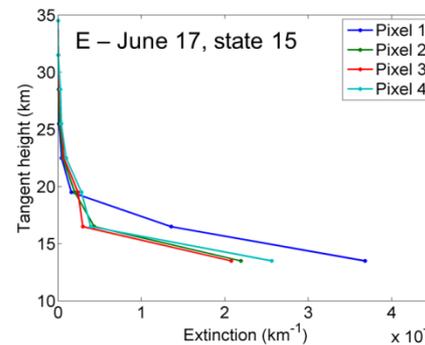
Conclusions

- Using nadir and limb measurements from SCIAMACHY, GOME-2 and OMI we detected a sulfate aerosol plume in the stratosphere on the five days (June 13-17, 2011) following the eruption of Nabro

- Viewing angle dependence of UVAI from high-altitude plumes can be large enough to change the sign of UVAI
  - This complicates the interpretation of UVAI, but:
  - also provides opportunity to determine aerosol properties within large aerosol plumes

- If dimensions and position of an aerosol plume are not taken into account into limb aerosol retrieval, retrieved extinction and layer height may be affected appreciably
  - This should also be kept in mind when color index (ratio) profiles from limb-viewing instruments like SCIAMACHY are used

- Combination of nadir trace gas and aerosol data with limb measurements provide excellent opportunity to study characteristics of a high-altitude volcanic plume
  - Although SCIAMACHY is now lost, this type of analysis (at least for volcanic plumes) could be continued using an instrument like the Ozone Mapping and Profiling Suite instrument (OMPS) on NPP, which also measures SO_2 and UVAI in nadir, and has limb-viewing capabilities

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- **For discussions:**
  - S. Kühl, L. Clarisse, N. Theys, C. Brühl, M. von Hobe

- **For data:**
  - O3M-SAF and TEMIS (SCIAMACHY and GOME-2 UVAI); special thanks to O. Tuinder (for UVAI from PMDs)
  - NASA – OMI (SO_2 and UVAI) and MODIS teams (calibrated radiances); special thanks to K. Yang (for SO_2 using LF)
  - ESA/EUMETSAT for level-1 data from GOME-2 and SCIAMACHY

- DFG for funding J. Puķīte

Nadir measurements – SO_2

- SO$_2$ retrieval
    - SCIAMACHY and GOME-2: DOAS in 2 wavelength ranges to account for "saturation" effects within explosive volcanic plumes with high SO_2 columns[1,2]

<u>SO$_2$ Vertical column densities (VCDs)</u>
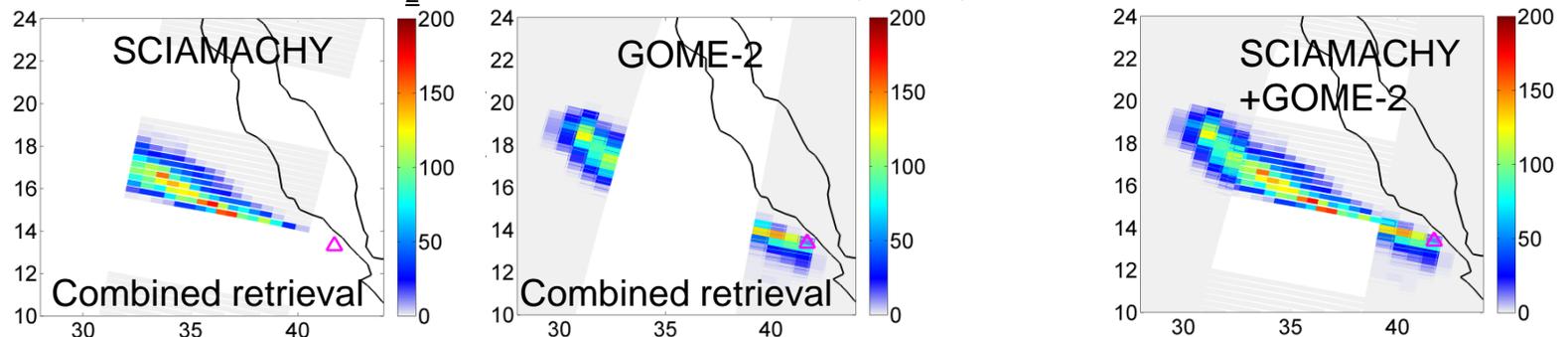
- OMI: Band Residual Difference[3] algorithm for small SO_2 columns;
- Linear Fit[4] algorithm for large columns

[1]Bobrowski et al., AMT, 2010; [2]Hörmann et al., ACP, 2013; [3]Krotkov et al., IEEE TGRS, 2006; [4]Yang et al., JGR, 2007