Volcanic plume modelling and assimilation with the global MACC system (with emphasis on SO$_2$)

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Introduction

- How can we use timely observations in combination with data assimilation for initial values to improve the MACC forecasts of volcanic eruptions?

- Eyjafjallajökull eruption in 2010 set the agenda
  - The MACC data assimilation system needs to be improved to be able to assimilate plume observations (retrievals)
  - Estimates of injection profile and emission rate are essential for reasonable forecasts

- MACC makes forecast and analyses volcanic aerosol and volcanic SO$_2$ using the Integrated forecasting system (IFS) of ECMWF (4DVAR, NWP forecasting model with a semi-lagrangian advection scheme)
First Attempts …in April 2010

• MODIS AOD north of 60N blacklisted
• No volcanic aerosol tracer
• No assimilation of volcanic SO$_2$ retrievals
• Forecast runs with arbitrary emissions

Figure 1: Sea salt plume off the coast of Iceland on April 19, 2010 at 030UTC.

from Benedetti et al. 2012
Recent Developments: Forecast and Assimilation of volcanic Ash and SO$_2$ Plumes

- Assimilation of MODIS AOD to change proportionally modelled aerosol species
  - Introduce volcanic aerosol model (new)
  - Relax quality criteria to not filter out volcanic signal

- Assimilation of middle-trop to strat UV SO$_2$ retrievals
  - Volcanic SO$_2$ model field and loss terms
  - Optimise DA for plume assimilation (specific background error statistics, variable transformation)

- Method to estimate injection height and emission flux from UV SO$_2$ retrievals
Parameter Estimation and Data Assimilation for SO₂ Plume Forecasts

- What are can be inferred from satellite SO₂ retrievals to make (good) SO₂ plume forecast?
  - Initial conditions (DA)
  - Emissions flux (PE)
  - Injection profile (PE)
  - SO₂ life time (PE)

- Are the SO₂ retrievals providing the required information?

- How important is meteorological forecast error and realism of model transport by the IFS?

- How to represent uncertainty?

- Test cases: 2011 Grímsvötn and 2010 Eyjafjallajökull erruption
Spatial and temporal Coverage – Total Column SO$_2$ retrieval

- **GOME-2**: GOME2 20100507
- **OMI**: OMI 20100507
- **SCIAMACHY**: SCIA 20100507

- Good coverage essential (GOME-2 is best)
- No night time retrievals for UV instruments
- No vertical information
High TCSO2: OMI vs GOME-2 vs SCIA

Gridded observations
OMI tends to have highest maxima

Grimsvoetn 2011
Variability of observed SO$_2$ Burden used to estimate Emissions

SO$_2$ Burden 4000 km around Iceland

2009 SO$_2$ burden

2010 SO$_2$ burden

2011 SO$_2$ burden

2009 SO$_2$ burden delta

2010 SO$_2$ burden delta

2011 SO$_2$ burden delta

Total SO$_2$

Delta SO$_2$

No eruption  Eyjafjallajökull  Grimsvötn
SO$_2$ Lifetime Estimate from SO$_2$ Retrievals

- Use reduction of observed SO$_2$ burden to estimate lifetime after end of eruption

  - “GOME-2 Lifetime” : 15 days
  - “OMI-Lifetime” : 9 days
  - No really exponential loss
  - According to exponential loss obs have too low SO$_2$ in the concentrated plume at the start

\[
\text{SO}_2 \rightarrow \text{SO}_4
\]
\[
d\text{SO}_2/dt = -k \text{ SO}_2
\]
\[
\text{SO}_2(t) = \text{SO}_2(0) \exp(-t/\tau)
\]
Emission and Injection Height Estimate using Ensembles of Tracers

- Simulate test tracers with fixed emission rate (1t/s) injected at different levels up to 24 h before observation
- Find best overlap of test plume with plume observations (1DU)
  - Identify plume height by plume locations (wind shear)
- “scale” fixed emissions to fit observations in “best” test plume
  - Minimise area to calculate burdens (only area covered by test plumes)
- Refine temporal resolution of estimate with test forecast 18/12/6 h before observation time, if possible
Test Tracer Grimsvötn

Eruption start
19 UTC 21.5.11
Emissions Flux and Injection height - Grimsvötn

Reasonable agreement with plume top height observations from radar

Using GOME-2

Estimate after 28.5 is artefact caused by plume returning to Iceland
OMI and SCIA estimates more “jumpy” than GOME-2
Larger differences with IASI based estimate by Heard et al. 2012
Data Assimilation of volcanic SO$_2$ (GOME-2)

- Emissions flux in assimilating model yes – no
  - DA was good in producing plumes but not correcting wrong plumes
- With log-Jb and Normal Jb
  - Log-Jb required existing plume to be amplified
- “External” plume height information needed to locate plume vertically
- Final setup for SO$_2$ plume assimilation
  - Normal Jb
  - minimum > 0.1 DU, no thinning
  - increased background error variance at height of plume – obtained from plume height estimate
  - 100 km horizontal length scale
SO$_2$ Analysis Examples

Log-Analysis not “over dispersive” but too high and dependent on a plume in background
Analysis exaggerate plume extent
Initial Conditions vs. / and Emission Parameters

- SO$_2$ forecasts for 2011 Grímsvötn and 2010 Eyjafjallajökull
- Forecasts configurations:
  - **EMI**: Forecast with SO$_2$ source parameter (also for duration of forecast)
  - **INI**: Forecast with SO$_2$ analysis (GOME-2) as initial conditions only and no SO$_2$ source term (INI)
  - **INIEMI**: Forecast with SO$_2$ analysis as initial conditions and estimated SO$_2$ source terms
- Daily 12 UTC Forecast over 120 h, T511L60, Mass fixer applied
- Evaluated with GOME-2 - How good can we forecast tomorrow TCSO2 plume using today's TCSO2 retrievals?
- *(NOTE: EMI is not a NRT scenario because we don’t know future emissions!)*
Eye-ball Plume Forecast Evaluation 2010
24 FC SO_{2} Plume Forecast Evaluation – 2011

Evaluation w.r.t to gridded observations (0.5x 0.25)

- Threshold based exceedance hits/miss/false alarm
- Plume size (w.r.t to threshold) independent of overlap
Forecast Lead Time  24, 72 & 120 hours

Quality of meteo forecast was very important for plume forecast
Meteorological Ensemble Forecast (T639L91 20 Members)

This diversity is specific of 2011 Grimsvoetn

120 h Forecast
6 of 20
Members
Same emissions

Parameter Estimation Workshop 2013
Different mass fixers

Model transport has difficulties to maintain the high observed values after the end of eruption.
## Current Status of Response to Volcanic Eruptions with MACC system

<table>
<thead>
<tr>
<th>Automated, no intervention</th>
<th>NRT intervention (working hours)</th>
<th>1-2 day delay intervention</th>
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</thead>
<tbody>
<tr>
<td>• Assimilation of OMI SO₂ retrievals prescribed heights</td>
<td>• Emit SO₂ and ash in model at volcano location using ad-hoc emission estimate</td>
<td>• Estimate SO₂ emission rate and injection height based on UV-VIS satellite retrievals</td>
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<tr>
<td>• Assimilation of MODIS AOD in existing aerosols</td>
<td>• Relax QC and reduce thinning for assimilated MODIS observations</td>
<td>• Rerun MACC system for eruption period with improved settings and emission estimates</td>
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<td>• Active assimilation of TRM SO₂ retrieval (GOME-2, OMI)</td>
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*MACC has no mandate to volcano forecast but the MACC products might be useful for VAAC etc.*
Summary

- MACC Data assimilation system picks up automatically volcanic ash and SO$_2$ plumes if they are observed.
- The DA assimilation requires emission rate and injection height estimates (ash) or only injection height (SO$_2$) estimate.
- A method to estimate injection height and emission rate from SO$_2$ retrievals using an ensemble of test plumes has been developed.
- Combining emission estimate and initial value data assimilation provided best results for SO$_2$ plume forecasts.
- Uncertainty of meteorological forecast and SO$_2$ lifetime is less important than emission parameters but still influential.
- Ensembles of forecasts might be useful to express uncertainty of emission estimates, in particular after forecast start time.
References:

SO$_2$:


AOD:

Benedetti, A., J. W. Kaiser, J-J. Morcrette, R. Eresmaa and S. Lu (2011), Simulations of volcanic plumes with the ECMWF/MACC aerosol system, December 2011, ECMWF Technical Memorandum, 653,
MACC system – A global-to-regional forecasting system for atmospheric composition
Grimsvötn (21-24.5.2011 eruption) – well sustained plume for over two weeks