Stratospheric aerosol size reduction after volcanic eruptions

Authors: Felix Wrana (speaker)¹, Ulrike Niemeier², Larry W. Thomason³, Sandra Wallis¹, Christian von Savigny¹

¹ Institute of Physics, University of Greifswald, Germany
² Max Planck Institute for Meteorology, Hamburg, Germany
³ NASA Langley Research Center, Hampton, Virginia, USA

Correspondence: felix.wrana@uni-greifswald.de
1. Overview VollImpact research group

2. Aerosol size retrieval method

3. Aerosol size reduction after smaller volcanic eruptions

4. Model simulations of Raikoke/Ulawun

5. Short look at Hunga Tonga – Hunga Ha’apai
1. Overview: DFG Research unit VolImpact

The VOLIMPACT projects

- **Phase I:** 2019 – 2022
- **Phase II:** 2022 – 2025

**Important:** Synergy between global modelling (ICON-Family & MA-ECHAM) and satellite observations (Algorithm development & usage of other data products)
1. VollImpact: Some results from recent eruptions

**Ambae 2018 eruption**

OMPS-LP | ECHAM-HAM
---|---
18.5 km | 18.5 km
20.5 km | 20.5 km

**Raikoke 2019 eruption**

(a) Accumulation mode

- AERODYN, rad
- no AERODYN, rad
- AERODYN, no rad
- no AERODYN, no rad
- OMPS

(b) Coarse mode

- time after start of eruption [h]
- height [km]

**Malinina et al., ACP (2021)**

- Important for good agreement: Good knowledge of the injected $SO_2$ amount, injection height & also dynamics

**Muser et al., ACP (2020)**

- Essential roles of the ash and aerosol aging in self-lofting
1. VolImpact publications on optical phenomena

On the phenomenon of the blue Sun

- Wullenweber et al., Clim. Past (2021)

On the colour of noctilucent clouds

- von Savigny et al., Clim. Past (2022)

- Is it possible to estimate aerosol optical depth from historic colour paintings?
- Revisiting the question "Why is the sky blue?"
1. Faces of VollImpact

People associated with VollImpact phase I:
1. Overview VollImpact research group

2. Aerosol size retrieval method

3. Aerosol size reduction after smaller volcanic eruptions

4. Model simulations of Raikoke/Ulauwun

5. Short look at Hunga Tonga – Hunga Ha’apai
2. Stratospheric aerosol retrieval method

- Retrieval of stratospheric aerosol size from SAGE III/ISS (solar occultation)
- Latitudinal coverage ~ between 70°N and 70°S
- Limited spatial and temporal coverage
- Retrieval uses aerosol extinction coefficients at 3 wavelengths

Latitudinal coverage of SAGE III/ISS solar occultation measurements, exemplary for 2018.

SAGE III on the International space station.
Source: NASA (https://go.nasa.gov/3FCGR1J)
Assumption: Monomodal lognormal size distribution

\[
dN(r) \quad dr \quad = \quad \frac{N_0}{\sqrt{2\pi} \cdot r \cdot ln\sigma} \cdot exp\left(-\frac{ln^2(r/r_{med})}{2ln^2\sigma}\right)
\]

Needs to be retrieved:

- Median radius $r_{med}$
- Distribution width $\sigma$
- Number density $N_0$

Exemplary monomodal lognormal particle size distribution. Red line marks the median radius (100 nm).
2. Stratospheric aerosol retrieval method

• Paper on the retrieval method published in Atmospheric Measurement Techniques (AMT)

doi: 10.5194/amt-14-2345-2021
2. Stratospheric aerosol retrieval method

- Lookup table with extinction ratios at 3 wavelengths for many combinations of median radius and mode width
- Calculated with Mie Code
  - Assumed aerosol composition: 75% sulfuric acid and ~25% water
  - Assumed shape of size distribution: monomodal lognormal
2. Stratospheric aerosol retrieval method

- Lookup table with extinction ratios at 3 wavelengths for many combinations of median radius and mode width
- Calculated with Mie Code
  - Assumed aerosol composition: 75% sulfuric acid and ~25% water
  - Assumed shape of size distribution: monomodal lognormal

- Plot measurement data into the lookup table (right plot)
- → Retrieval of \( r_{\text{med}} \) and \( \sigma \) through interpolation
- \( N, r_{\text{eff}}, \) etc. can be calculated afterwards
2. Stratospheric aerosol retrieval method

- Best wavelengths: 449, 756 and 1544 nm
- Bad example: Wavelengths: 384, 449, 520 nm

- The broad wavelength spectrum of SAGE III instruments is important for this method!
2. Using three vs two wavelengths

- The 3-wavelength retrieval approach is important to learn how stratospheric aerosol size evolves over time because:

- if only 2 wavelengths (like it was necessary for e.g. SAGE II) were to be used:
  → \( \sigma \) would have to be assumed, often at \( \sim 1.5 - 1.6 \)

- However, \( \sigma \) is very variable (e.g. \( \sim 1.25 \) for Hunga Tonga)

- Wrong \( \sigma \) assumption can lead to very different PSDs! → see plots to the right

Different PSDs, but each one is consistent with the same extinction ratio at 449 nm / 756 nm of 2.0.

Same plot, but PSDs scaled to same number density for visual clarity.
2. Using three vs two wavelengths

- The 3-wavelength retrieval approach is important to learn how stratospheric aerosol size evolves over time **because**:
  - if only 2 wavelengths (like it was necessary for e.g. SAGE II) were to be used:
    \[ \sigma \] would have to be assumed, often at \(~1.5 - 1.6\)
  - However, \( \sigma \) is very variable (e.g. \(~1.25\) for Hunga Tonga)
  - Wrong \( \sigma \) assumption can lead to very different PSDs! → see plots to the right

Different PSDs, but each one is consistent with the same extinction ratio at 449 nm / 756 nm of 2.0.

Same plot, but PSDs scaled to same number density for visual clarity.

Wrong \( \sigma \) assumption can lead to very different PSDs! → see plots to the right
2. Why I will show $\omega$ instead of $\sigma$

- Distribution width $\sigma$ often misunderstood → not useful to understand how wide the size distribution is

- Instead absolute distribution width $\omega$ will be shown:

$$\omega = \sqrt{r_{med}^2 \cdot \exp(ln^2(\sigma)) \cdot (\exp(ln^2(\sigma)) - 1)}$$

- $\omega$, as introduced by Malinina et al. (2018), is the standard deviation of the PSD in linear radius space
- Will be shown in results instead of $\sigma$
1. Overview VollImpact research group
2. Aerosol size retrieval method
3. Aerosol size reduction after smaller volcanic eruptions
4. Model simulations of Raikoke/Ulawun
5. Short look at Hunga Tonga – Hunga Ha’apai
3. Strat. aerosol size reduction

Results to be shown are submitted to Atmospheric Chemistry and Physics (ACP):

Stratospheric aerosol size reduction after volcanic eruptions

Felix Wrana, Ulrike Niemeier, Larry W. Thomason, Sandra Wallis, and Christian von Savigny

doi: 10.5194/egusphere-2023-837
3. Strat. aerosol size reduction

On next slides we will look at 3 phases of volcanic activity in SAGE III/ISS data:

1. Aerosol extinction: Northern hemisphere
2. Aerosol extinction: Tropics
3. Aerosol extinction: Northern hemisphere

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Date</th>
<th>SO₂ emission estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambae 1</td>
<td>15°S</td>
<td>168°E</td>
<td>March – April 2018</td>
<td>0.1 Tg</td>
</tr>
<tr>
<td>Ambae 2</td>
<td></td>
<td></td>
<td>July 2018</td>
<td>0.4 Tg</td>
</tr>
<tr>
<td>Raikoke</td>
<td>48°N</td>
<td>153°E</td>
<td>June, 21st/22nd 2019</td>
<td>1.37 Tg</td>
</tr>
<tr>
<td>Ulawun 1</td>
<td>5°S</td>
<td>151°E</td>
<td>June, 26th 2019</td>
<td>0.14 Tg</td>
</tr>
<tr>
<td>Ulawun 2</td>
<td></td>
<td></td>
<td>August, 3rd 2019</td>
<td>0.3 Tg</td>
</tr>
<tr>
<td>La Soufrière</td>
<td>13°N</td>
<td>61°W</td>
<td>April, 9th – 22nd 2021</td>
<td>0.4 Tg</td>
</tr>
</tbody>
</table>
Ambae (15 °S) eruptions

- Ambae (15°S) had 2 main eruptive phases relevant for the stratosphere: In April and in July 2018
  → Size decrease (darker colors) in lowermost stratosphere
  → narrower Particle size distribution (PSD) with peak at smaller radius

- Effect lasts for many months!
Raikoke (48 °N) and Ulawun (5 °S) eruptions

- Raikoke eruption: June 22nd 2019
- Ulawun eruptions: June 26th and August 3rd 2019

→ Size increase over Raikoke, while decrease over Ulawun!
La Soufrière (13 °N) eruption

- La Soufrière eruption: April 9th 2021
  → Size decrease similar to Ambae eruption
### Short summary

**Ambae, Ulawun and La Soufrière**
- Strong decrease in median radius and absolute distribution width
- Strong increase in number density
- SO₂ injections 0.1-0.4 Tg
- Tropical latitudes → lower temperatures

**Raikoke**
- Increase in median radius and absolute distribution width
- Increase in number density
- SO₂ injection of 1.37 Tg
- Mid latitude

**Possible explanation for size decrease:**
Enhanced homogeneous nucleation as opposed to condensation onto existing particles

Factors controlling nucleation vs condensation:
- Temperature
- Background aerosol PSD
- SO₂ mass injected / H₂SO₄ oversaturation
1. Overview VollImpact research group
2. Aerosol size retrieval method
3. Aerosol size reduction after smaller volcanic eruptions
4. **Model simulations of Raikoke/Ulawun**
5. Short look at Hunga Tonga – Hunga Ha’apai
4. Model simulations of Raikoke/Ulawun

Comparison to model simulations

- MAECHAM5-HAM = general circulation model coupled with aerosol microphysical model
- ECHAM includes stratospheric sulfur chemistry and aerosol microphysics (nucleation, coagulation etc.)
- ECHAM model simulations in this work set up by Ulrike Niemeier (Max-Planck Institut für Meteorologie Hamburg)
- Can the ECHAM model be used to understand the underlying causes of the aerosol size decrease?
4. Model simulations of Raikoke/Ulawun

- **Test case chosen**: Raikoke and Ulawun eruptions of 2019
- **Reminder**: both had opposite effects on stratospheric aerosol size
- **A vertically resolved profile of SO$_2$ masses is injected into the lower stratosphere for each eruption**

<table>
<thead>
<tr>
<th></th>
<th>Raikoke</th>
<th>Ulawun</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Latitude</strong></td>
<td>48°N</td>
<td>5°S</td>
</tr>
<tr>
<td><strong>Longitude</strong></td>
<td>153°E</td>
<td>151°E</td>
</tr>
<tr>
<td><strong>Date of eruption</strong></td>
<td>22.06.2019</td>
<td>26.06.2019</td>
</tr>
<tr>
<td><strong>Injected SO2 mass</strong></td>
<td>1.37 Tg</td>
<td>0.14 Tg</td>
</tr>
<tr>
<td><strong>Injection Pressure Level</strong></td>
<td>140 hPa</td>
<td>100 hPa</td>
</tr>
</tbody>
</table>

Relevant parameters of the Raikoke and Ulawun eruptions as used in the ECHAM simulations
4. Model simulations of Raikoke/Ulawun: Extinction

Aerosol extinction at 550 nm

Time

- Temporal and spatial sampling of SAGE III/ISS sampling applied to ECHAM model output
- Good agreement between model and observations
- Important to include previous eruptions in simulations
Both model and simulations show increase over Raikoke area and decrease over Ulawun area in lowermost stratosphere.

Starting in September, tropical values increase strongly in the model, but not in observations.
• Possible explanations for discrepancy in longer-term aerosol size evolution:
  • possible overestimation of coagulation in the model
  • Lack of interactive OH chemistry in the model
  • Deviations in dynamics
  • Wrong assumption on aerosol composition in retrieval

• → started to compare with other models now (with sectional PSD instead of 4 modes)
1. Overview VolImpact research group
2. Aerosol size retrieval method
3. Aerosol size reduction after smaller volcanic eruptions
4. Model simulations of Raikoke/Ulawun

5. **Short look at Hunga Tonga – Hunga Ha’apai**
Spatial evolution of aerosol size after Hunga-Tonga

**Time**

- 02.2022
- 04.2022
- 06.2022
- 08.2022
- ... 01.2023

- **Median radius**
- **Absolute mode width**
- **Number density**
How did the size distributions change?

- Plot to the right: Characteristic PSDs before and after HT:
  - 15°S, 22.5 km altitude, monthly mean
  - Graphs shown:
    - “Background” November 2021
    - After Hunga-Tonga: June 2022
  - Although $\sigma$ decreased the size distribution became wider
    (as previously shown by the increase in absolute mode width $\omega$)
  - See more in recently submitted paper: Duchamp et al. (2023,GRL)
● Some volcanic eruptions lead to a strong decrease in average stratospheric aerosol size

● This size decrease can last for many months

● MAECHAM5-HAM could well reproduce the first months of strat. aerosol size development after Raikoke and Ulawun

● The model seems to struggle to reproduce the longterm development of the stratospheric aerosol size

● We will look at different models to compare to (e.g. sectional models)
VOLIMPACT summer school on volcanic effects on atmosphere and climate

September 4 – 8, 2023
Institute of Physics
University of Greifswald
Germany

Topics include:
- Volcanic emissions
- Climate effects, cloud effects and dynamical effects of volcanic eruptions
- Plume and global modelling
- Volcanic dispersion modelling
- In-situ and satellite observations
- Retrieval theory
The summer school also includes modelling and remote sensing labs

Confirmed speakers:
Prof. John Burrows FRS (U Bremen)
Dr. Thor Hansteen (Geopmar Kiel)
Prof. Jim Haywood (U Exeter)
Dr. Ákos Horváth (U Hamburg)
Dr. Ali Heshyari (KIT)
Dr. Christopher Kadow (DKRZ)
Prof. Dr. Kirstin Krüger (U Oslo)
Dr. Alexei Rozanov (U Bremen)
Prof. Pasquale Setitto (IPS)
Dr. Ghassan Taha (NASA/GSFC)
Dr. Claudia Timmreck (MPI-M Hamburg)
Prof. Matt Toohy (U Saskatchewan)

To apply & for more information visit: https://volimpact.org
Application deadline: July 15, 2023
Limited to 30 participants

Funding for the summer school is provided by DFG through the research unit VOLIMPACT (FOR 2820)
2. Filtering out noisy data

- Uncertainties of the SAGE III/ISS aerosol extinction coefficients accounted for in terms of a defined “accuracy parameter” $a$:

\[ a = \frac{\Delta x}{\delta f_x} \cdot \frac{\Delta y}{\delta f_y} \]

- Where $\Delta x$ and $\Delta y$ are the distances between the curves and $\delta f_x$ and $\delta f_y$ are the error bars of an individual measurement point

- Noisy data are filtered out at below a threshold