Project: **1093**

Project title: **Revisiting the volcanic impact on atmosphere and climate – preparations for the next big volcanic eruption (VolImpact)**

Principal investigator: **Christian von Savigny**

Report period: **2023-11-01 to 2024-10-31**

The major goal of **VolIMpac**t is to improve the scientific understanding of the volcanic influence on atmosphere and climate(von Savigny et al., 2020). It is divided into five individual science projects, each of them deal with its own specific research goal and use different versions of the ICON model. Below, we summarize main contributions of the different subprojects

VolPlume contributions

We performed large-eddy simulation (LES) with ICON-ART on the R2B12 grid (600 m grid spacing) for the 2022 Hunga Tonga submarine eruption to understand the plume dynamics which transported the plume up to the stratos- and mesosphere and the generation of gravity waves. As the Hunga Tonga eruption was mainly driven by steam from evaporating ocean water, we assumed a point source of water vapor at the surface. Our results show that the plume is rising within 15-20 min up to about 50-60 km and generated gravity waves from surface to the mesosphere, which is in agreement with observations. A large amount of the emitted water vapor undergoes phase changes and appears in the stratosphere as ice and snow, as it was observed. However, observations also showed an increase of 150 Tg water vapor after this eruption, which we could not reproduce yet. Understanding the microphysical processes in our simulations is a topic of ongoing work.

VolARC contributions

At MPI-M several different topics have been covered within the VolARC activities. We have performed simulations with aerosol microphysics (ECHAM-HAM) with continuous injections of sulfur, one and two Tg(S)/y, over 20 years. These simulations are analyzed with satellite retrieval methods to find the lower limit of sulfur injections that can be detected by satellite. After the very successful simulation of the water vapor transport after the 2022 Hunga Tonga eruption with ICON-XPP (Niemeier et al, 2023), high-resolution ICON simulations of the water vapor transport eruption were performed on GPUs (ICON-Sapphire, R2B9 ~5 km grid resolution). The transport was simulated well, but the initial descent of the water vapor in the first two weeks was too weak. The reason was a too strong formation of ice which impacted the radiative cooling of the volcanic cloud. We also tested ICON-XPP on GPUs (R2B6~40 km grid resolution), but at this resolution the performance on CPU was better. Therefore, we continued the tuning of the stratosphere of ICON-XPP at R2B6 resolution on CPUs. These tuning simulations are important to continue our work on tracer transport where we are currently determining the role of the model resolution on the transport of tracers.

VolCloud contributions

The Leipzig team has adapted its plans and focused on an analysis of available simulations in the reporting period. Specifically, simulations from CMIP6 were analysed. The experiment with reduction of the solar constant was taken as an idealised analogue to identify robust changes to atmospheric properties, clouds and radiation as adjustments to this solar forcing. The results are submitted as a publication (Lange and Quaas, 2025).

AT KIT, in one part of our study, we performed high-resolution simulations of volcanic eruptions (e.g. the 2021 La Soufrière eruption) with the ICON-ART model in LAM (2.5 km). To obtain the most appropriate results, we had to perform many sensitivity runs to correct the errors. After correcting the errors, we carried out two simulations, both considering the volcanic eruption, but the difference between them is that in one of them, in addition to the soluble particle, the mixed mode aerosol (an insoluble particle coated with a soluble one) was also activated as CCN. Comparing the results of these two simulations shows that the number concentration of cloud droplets decreased in the mixed-mode simulation, while the number concentration of raindrops and graupel increased in this simulation. The reason for this behavior is the presence of more larger particles (coarse and accumulation) in the mixed-mode simulation than in the other simulation. These particles are first activated as CCN and remove the water vapor. Thus, the number of cloud droplets decreased, but their size increased. By increasing the size of the cloud droplets, the autoconversion and riming processes are increased, resulting in an increase in the number concentration of raindrops and graupel. These results are part of the PhD thesis of Fatemeh Zarei (May 2024).

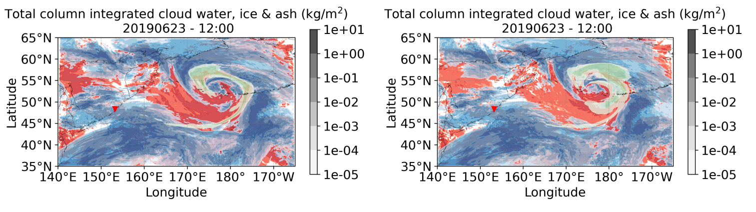

Figure 1: Total column integrated cloud water (red), cloud ice (blue) and volcanic ash (green) for simulations without ARI/ACI (left) and with ARI/ACI (right)

In the case study of the Raikoke eruption 2019 we investigated the effect of aerosol-radiation-interactions (ARI) and aerosol-cloud-interactions (ACI) on cloud hydrometeors. For this we did ICON-ART simulations in LAM with 5km resolutions with different interactions enabled and compared the resulting hydrometeor and aerosol distributions. In *figure 1* a simulation with ARI and ACI can be seen compared to a simulation without interactions. The interactions show a large impact especially on aerosol distribution and are subject to further analysis. For volcanic ash a new INP parameterization by Umo et al. (2021) has been implemented in the ICON-ART code and is compared to the parameterization for mineral dust by Ullrich et al. (2017).

VolDyn contributions

The primary focus of the VolDyn project this year has been the transport of water vapour through the middle atmosphere caused by the Hunga volcanic eruption in January 2022. For the first time in this project, we used the general circulation chemistry – climate model Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA) having a model top at 1.7*10 -7 hPa altitude (approx. 250 km) with a triangular truncation at wavenumber 31 (T31) and 119 vertical levels. To assess the capability of HAMMONIA to simulate the transport of water vapour in the stratosphere and mesosphere accurately, we did a H_2O – Experiment analogous to the Hunga eruption and increased the specific humidity of a restart file before letting the simulation run freely for 3 years. In total, five H_2O ensembles were run using different restart years and their results were each compared to a non – H_2O reference run. A comparison with Microwave limb Sounder (MLS) instrument data confirmed a good agreement with observations (Wallis et al., 2024).

After the HAMMONIA model results indicated a reasonable middle atmospheric transport scheme, we used the model for a first test case simulation of the Krakatau eruption. There is an on – going discussion in the scientific community, whether the H_2O emitted by the historic Krakatau eruption 1883 was responsible for the first sightings of mesospheric noctilucent clouds two years later. We performed a Krakatau experiment where we altered the specific humidity of a restart file in late summer, simulated five H_2O ensemble members and compared them to the non – H_2O reference run. First analysis indicates that the H_2O could have reached the NH polar summer mesopause two years after the eruption, laying the groundwork for further investigations.

VolClim contributions

In the reporting period, we have further analyzed our 100-member ensembles of idealized volcanic eruptions (EVA-ENS) within the MPI Grand Ensemble (MPI-GE) historical framework which differ only in their sulfur emission strength and geographical location. With the EVA-ENS, we demonstrate that global and hemispheric mean near-surface temperature and precipitation anomalies scale linearly for different emission strengths if the volcanic forcing pattern is similar. (Timmreck et al., 2024). We also find that the locations of the eruption and its emission strength can all lead to distinct El Niño Southern Oscillation (ENSO) responses, highlighting the importance of the changes in the position of the Intertropical Convergence Zone in driving such responses (Fang et al, submitted). To better understand whether changes in the atmospheric temperature profile or in the surface temperature are the main driving components for volcanically induced precipitation anomalies we have extended the EVA-ENS ensemble in the reporting period with sensitivity experiments that consider only longwave or shortwave forcing.

Based on the EVA-ENS, we have developed a data driven methodology that is able to classify in reanalysis data and proxy reconstructions whether a volcanic eruption occurred and where it is located based on seasonal mean near-surface temperature anomalies (Meuer et al., 2024). Accurately estimating uncertainty in climate scenarios typically demands the generation of large ensembles of high-resolution simulations, a process that is both computationally expensive and memory intensive. To address this challenge, we have developed a novel deep learning framework that efficiently generates climate simulation ensembles by combining a variational autoencoder for dimensionality reduction with a denoising diffusion probabilistic model based on a spatio-temporal transformer architecture (Meuer et al, submitted).

References

- Fang, S.-W., et al., Seasonal ITCZ Control on ENSO Responses to Volcanic Forcing, submitted to Journal of Climate
- Lange, C., and J. Quaas, Short-Term Adjustments of the Earth Climate System to an Abrupt Solar Forcing: Findings from the CMIP6 abrupt-solm4p experiment, EGUsphere, submitted.
- Meuer, J. et al (2024), Fingerprints of past volcanic eruptions can be detected in historical climate records using machine learning. Commun Earth Environ 5, 455 https://doi.org/10.1038/s43247-024-01617-y
- Meuer, J., et al. Latent Diffusion and Spatio-Temporal Transformers Generate Large Ensemble Climate Simulations, submitted to Journal of IEEE transcations on artificial intelligence
- Niemeier, U., et al. (2023). How the Hunga Tonga—Hunga Ha'apai water vapor cloud impacts its transport through the stratosphere: Dynamical and radiative effects. Geophys Res Lett, 50, e2023GL106482. https://doi.org/10.1029/2023GL106482
- Timmreck, C., et al., (2024), Linearity of the climate response to increasingly strong tropical volcanic eruptions in a large ensemble framework, J. of Climate, 37, 2455–2470, https://doi.org/10.1175/JCLI-D-23-0408.1.
- Ullrich, R., et al. (2017), A New Ice Nucleation Active Site Parameterization for Desert Dust and Soot. *J. Atmos. Sci.*, **74**, 699–717, https://doi.org/10.1175/JAS-D-16-0074.1.
- Umo, N. et al. (2021). The influence of chemical and mineral compositions on the parameterization of immersion freezing by volcanic ash particles. JGR Atm. https://doi.org/10.1029/2020JD033356
- Von Savigny C., et al. (2020), The Research Unit VolImpact: Revisiting the volcanic impact on atmosphere and climate — preparations for the next big volcanic eruption, Meteorologische Zeitschrift, pp.3-18.
- Wallis, S., DeLand, M., and von Savigny, C.: Has the 2022 Hunga eruption impacted the noctilucent cloud season in 2023/24 and 2024?, EGUsphere [preprint], doi.org/10.5194/egusphere-2024-2165,
- Zarei, F., Response of warm and cold clouds to prognostic volcanic aerosols simulated with ICON-ART, PhD thesis, KIT Karlsruhe, 2024.