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Innovative Projects

The Research Unit VolImpact: Revisiting the volcanic impact on atmosphere and climate – preparations for the next big volcanic eruption

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Abstract

This paper provides an overview of the scientific background and the research objectives of the Research Unit "VolImpact" (Revisiting the volcanic impact on atmosphere and climate – preparations for the next big volcanic eruption, FOR 2820). VolImpact was recently funded by the Deutsche Forschungsgemeinschaft (DFG) and started in spring 2019. The main goal of the research unit is to improve our understanding of how the climate system responds to volcanic eruptions. Such an ambitious program is well beyond the capabilities of a single research group, as it requires expertise from complementary disciplines including aerosol microphysical modelling, cloud physics, climate modelling, global observations of trace gas species, clouds and stratospheric aerosols. The research goals will be achieved by building on important recent advances in modelling and measurement capabilities. Examples of the advances in the observations include the now daily near-global observations of multi-spectral aerosol extinction from the limb-scatter instruments OSIRIS, SCIAMACHY and OMPS-LP. In addition, the recently launched SAGE III/ISS and upcoming satellite missions EarthCARE and ALTIUS will provide high resolution observations of aerosols and clouds. Recent improvements in modeling capabilities within the framework of the ICON model family now enable simulations at spatial resolutions fine enough to investigate details of the evolution and dynamics of the volcanic eruptive plume using the large-eddy resolving version, up to volcanic impacts on larger-scale circulation systems in the general circulation model version. When combined with state-of-the-art aerosol and cloud microphysical models, these approaches offer the opportunity to link eruptions directly to their climate forcing. These advances will be exploited in VolImpact to study the effects of volcanic eruptions consistently over the full range of spatial and temporal scales involved, addressing the initial development of explosive eruption plumes (project VolPlume), the variation of stratospheric aerosol particle size and radiative forcing caused by volcanic eruptions (VolARC), the response of clouds (VolCloud), the effects of volcanic eruptions on atmospheric dynamics (VolDyn), as well as their climate impact (VolClim).

Keywords: Volcanic effects on the atmosphere, Radiative forcing, Aerosol/cloud interactions, Dynamical effects of volcanic eruptions

1 Introduction

The possibility of large future volcanic eruptions represents arguably the largest uncertainty concerning the evolution of Earth's climate on time scales of a few years to a decade. At the same time, volcanic eruptions provide an unparalleled opportunity to study the behaviour of the climate system. Such studies allow us to improve our theoretical understanding of the climate system and to strengthen the foundation of future climate predictions.

Volcanic sulfate aerosol resulting from the eruptive release of sulfur into the atmosphere can influence the global climate in various ways, directly by reducing the

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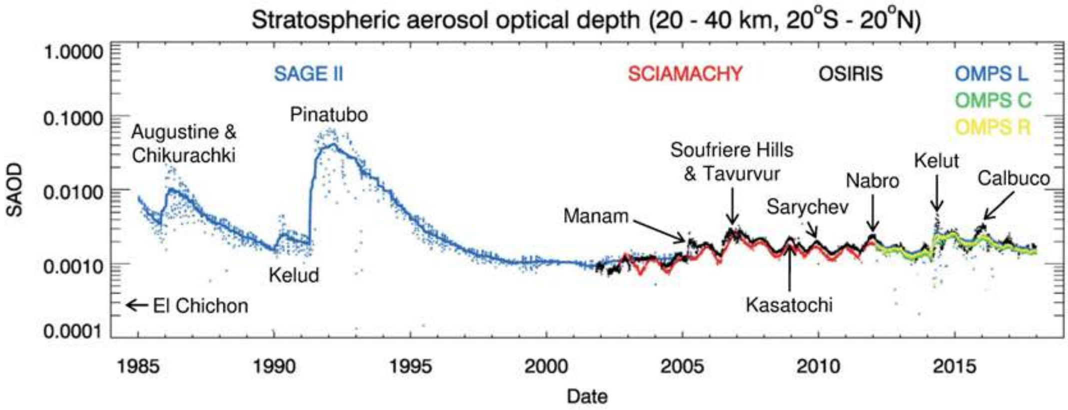

Figure 1: Stratospheric aerosol optical depth over the VolImpact core period obtained from different satellite instruments integrated over the 20–40 km altitude range and the 20° S–20° N latitude range. The small dots correspond to daily and zonally averaged data, while the solid lines present 3-month running means. SAGE II provided solar occultation measurements from 1984 to 2005 (e.g., Damadeo et al., 2013), while OSIRIS (2001 – present) (e.g., Bourassa et al., 2012), SCIAMACHY (2002–2012) (e.g., von Savigny et al., 2015) and OMPS-LP (2011–present) (e.g., Loughman et al., 2018) are limb-scatter instruments. Note that OMPS measures three profiles simultaneously using the left (L), center (C) and right (R) slits.

amount of solar radiation reaching the Earth's surface and indirectly by affecting clouds and the dynamical structure as well as the chemical composition of the atmosphere (Robock, 2000; Timmreck, 2012). As the ocean has a much longer memory than the atmosphere, large volcanic eruptions have a long lasting impact on the climate system that extends beyond the duration of the volcanic forcing (e.g., Stenchikov et al., 2009; Zanchettin et al., 2012).

The most recent and regarding its climate impact best-observed large volcanic eruption was that of Mt. Pinatubo, Philippines, in June 1991. By now it is well established that this eruption led to global surface cooling for a period of about seven years, reaching a maximum of about 0.4 K one to two years after the eruption (Thompson et al., 2009). In addition, sea level fall (Church et al., 2005), significant changes in the hydrological cycle (Trenberth and Dai, 2007), stratospheric warming, and a significant ozone loss in the midlatitudes over the northern hemisphere (NH, note that all acronyms are defined in the Glossary at the end of the article) (Pawson et al., 2014) have been observed. Since the 1991 Mt. Pinatubo eruption, several small to moderate volcanic eruptions have affected the upper troposphere and lower stratosphere (UTLS) aerosol layer (Figure 1), with SO_2 emissions up to about an order of magnitude smaller than Mt. Pinatubo. The effects of these eruptions on climate are not as pronounced as for eruptions like Mt. Pinatubo, but are still relevant in many respects. Neglecting them likely contributed to an overestimation of projected global warming by climate models compared to the observed global temperature record after 2000 (Solomon et al., 2011; Smith et al., 2016), as the eruptions affected the aerosol radiative forcing (e.g., Santer, 2014; Andersson et al., 2015).

To date, there has been no satellite instrument designed specifically for the detection of volcanic gas and particles. Researchers have instead had to make do with various existing Earth-observing instruments. A detailed survey of past, ongoing and future satellite missions relevant for volcanic sulfur and ash detection can be found in Prata (2016). Carn et al. (2016) provided an overview of multi-decadal satellite measurements of global volcanic degassing. At the time of the Mt. Pinatubo eruption, only a few satellite instruments (HALOE and SAGE II) were able to provide observations relevant to volcanic aerosol (SPARC (2006) and references therein). Since then several new satellite instruments have become operational (Kremser et al., 2016).

Due to the wealth of satellite observations and major modeling improvements, significant advances have been made in recent years in understanding the physical and chemical processes that determine the volcanic forcing and the consequent dynamical and climatic responses of the coupled ocean–atmosphere system (e.g., Timmreck, 2012; Raible et al., 2016). In addition, much has been learned about the climate impact of small to moderate volcanic eruptions (e.g., Kremser et al., 2016; Monerie et al., 2017; Schmidt et al., 2018). However, our knowledge is still dominated by "bits and pieces" gleaned from a limited amount of observations and specific model studies of mostly large individual eruptions, which differ in their eruption characteristics (e.g., Toohey et al., 2011; Stoffel et al., 2015; Haywood et al., 2013; Bittner et al., 2016a). In addition, the scientific understanding of several effects of volcanic eruptions is unsatisfactory. The difficulties start with the uncertain amount of emitted sulfur even for the best-observed eruptions and the exact distribution, particle size, and development of emitted material over time. Related to this are uncertainties concerning the effects on atmospheric composition, circulation and clouds, and, finally, radiative forcing and climate.

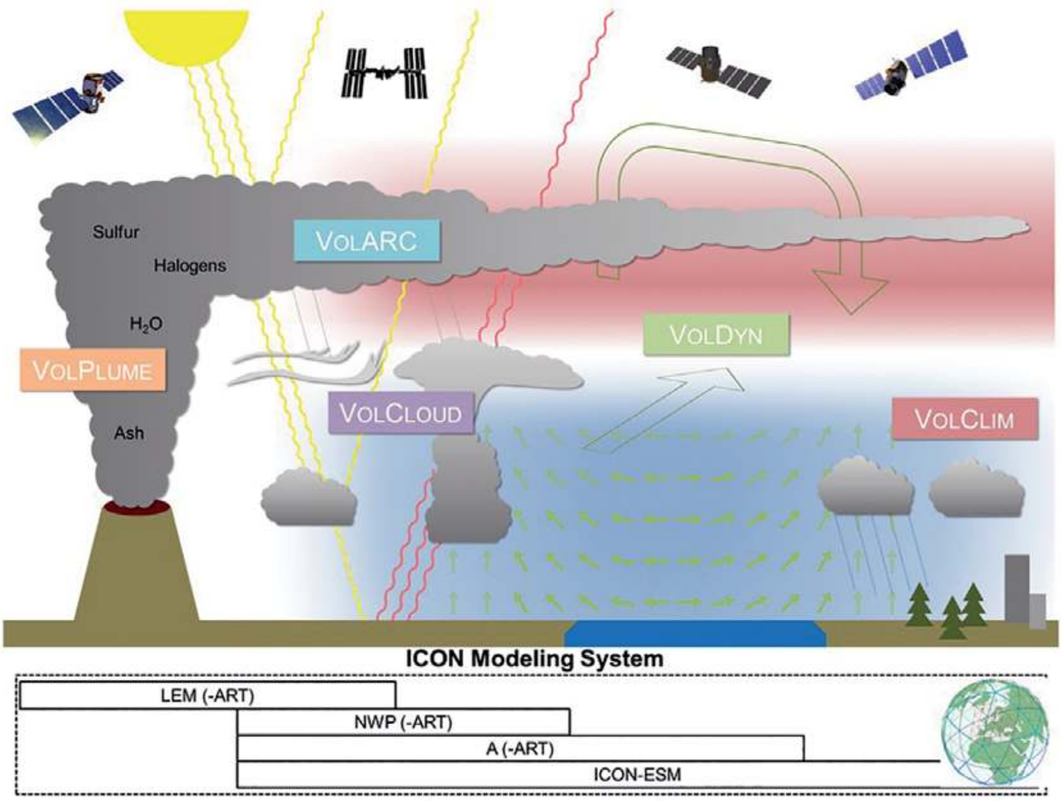

Figure 2: Overview of the research unit.

2 State of the Art

The following paragraphs provide brief overviews of the scientific knowledge and gaps in these areas with special emphasis on the state-of-the-art in terms of satellite observations and numerical modelling capabilities of the atmospheric response to volcanic eruptions.

Crucial for the vertical distribution of volcanic emissions and their subsequent dispersion in the atmosphere is the dynamics of the convectively driven volcanic plume. Complex dynamical and chemical processes within the plume play an important role in controlling the chemical composition and the vertical distribution of the gases (Hoshyaripour, 2015), as well as the particulate matter lofted into the atmosphere, and thus in controlling the radiative and climatic impact of the eruption. Large uncertainties exist in our understanding of eruptive plumes, especially in terms of the amount of volcanic emissions reaching the UTLS or higher altitudes, and the physicochemical characteristics of the injected matter (Textor et al., 2005; Van Eaton et al., 2012). For instance, the 2011 Nabro eruption, which emitted 1.0–1.5 Tg SO_2 (Clarisse et al., 2014), was a complex event for which it was difficult to separate the upper tropospheric and lower stratospheric injections (Carn et al., 2016).

The amount and vertical distribution of SO_2 emitted by the Mt. Pinatubo eruption are still highly uncertain and debated in recent studies (e.g., Mann et al., 2015; Kremser et al., 2016; Mills et al., 2016). Interestingly, to reach the best agreement with observations of stratospheric aerosol optical depth (SAOD) and aerosol lifetimes, some recent global aerosol modelling studies (e.g., Mills et al., 2016; Feinberg et al., in review) support smaller stratospheric sulfur amounts than those inferred from satellite observations (Guo et al., 2004). This discrepancy between observations and modelling studies needs to be understood, in particular to reduce the uncertainty of predictions of the effects of future volcanic eruptions.

The chemical and radiative effects of volcanic aerosol are strongly influenced by the particle size distribution (PSD), which may change significantly over time after a volcanic eruption. Observational information about the volcanic PSD is therefore essential for providing most realistic volcanic forcing estimates and for validating and constraining global aerosol models, which are sensitive to the applied aerosol model configuration (e.g., Mann et al., 2015). Obtaining these quantities – which are poorly constrained (Kremser et al., 2016) – from remote sensing measurements requires comprehensive inversions. At present, information on the volcanic PSD from satellite observations is limited and typically restricted to only a single particle size parameter, e.g., effective radius or the mode radius of a log-normal distribution with fixed width (e.g., Bourassa et al., 2008; Zalach et al., in review). In some studies the median radius and the distribution width of an assumed mono-modal log-normal PSD are retrieved (Bingen et al., 2003; Bingen et al., 2004; Wurl et al., 2010; Malinina et al., 2018). Existing in-situ balloon observations show evidence for a bi-modal distribution with a main population of small particles and a second mode of particles with radii on the order of 400–500 nm (e.g., Deshler, 2008). The exact origin of this second particle mode, particularly under volcanically quiescent periods, is not well understood.

A few studies provided experimental evidence of direct volcanic H_2O injections into the lower stratosphere (Schwartz et al., 2013; Sioris et al., 2016), where H_2O has a particularly strong effect on the radiative balance of the Earth system (Solomon et al., 2010). How this affects the tropical tropopause layer (TTL) and the cold-point tropopause (CPT) is uncertain. In general circulation models (GCMs), often an increase of the CPT temperature is simulated (e.g., Joshi and Shine, 2003), but this depends strongly on the characteristics of the prescribed aerosol distribution (Arfeuille et al., 2013). An increased CPT temperature would theoretically lead to more water vapour entering the stratosphere, with consequences for chemical composition and radiative forcing, but due to the potential artifacts in satellite observations of water vapour caused by volcanic aerosols, there is no clear observational indication of such an effect even for Mt. Pinatubo (Fueglistaler et al., 2013).

The responses of different types of clouds to perturbations due to volcanic eruptions are uncertain. A volcanic aerosol effect on cirrus clouds in the upper troposphere has been discussed controversially in the literature (e.g., Campbell et al., 2012; Friberg et al., 2015; Meyer et al., 2015), and possible effects are not well understood. Several observational studies provide indications for volcanically-induced effects on cirrus cloud formation after Mt. Pinatubo (e.g., Sassen, 1992; Song et al., 1996). Concerning low-level clouds, tropospheric volcanic sources were one of the primary sources of cloud condensation nuclei (CCN) in the preindustrial atmosphere (Schmidt et al., 2012). Global model studies (e.g., Gettelman, 2015; Rap et al., 2013) and observations (McCoy and Hartmann, 2015) have indicated the capacity of tropospheric volcanic emissions to affect low level cloud properties. Malavelle et al. (2017) have shown that the 2014–2015 eruption of the icelandic Holuhraun volcano has modestly influenced the effective radius of cloud droplets in the North Atlantic region, but not the cloud liquid water path, different to what some models have simulated. It is unclear which mechanisms lead to such an apparent buffering of the aerosol effect on clouds (Toll et al., 2019). Model studies (Toohey et al., 2011; Gregory et al., 2016) suggest that rapid cloud adjustments damp the radiative forcing and global mean forcing of major volcanic eruptions.

Indeed, much can be learned about aerosol-cloud interactions from such eruptions or effusive eruptions also from other volcanoes. The limiting factor is, however, the availability of observational data for particular eruptions. The eruptions of Eyjafjallajökull (2010) and Holuhraun (2014) are especially interesting for aerosol-cloud interaction studies, because both eruptions are very well-constrained from modeling and measurement perspectives (e.g., Steinke et al., 2011; Vogel et al., 2014; Malavelle et al., 2017). In particular, these two eruptions provided unique opportunities to constrain the effects of volcanic aerosols on ice clouds (Seifert et al., 2011) and liquid clouds (Malavelle et al., 2017). This research background not only provides extensive data but also lays the ground for comparison studies.

Despite considerable scientific attention, the dynamical response of the atmosphere to volcanic aerosols remains poorly understood. Observations and early modeling studies suggest for example a robust strengthening of the Arctic polar vortex as a consequence of enhanced diabatic heating of the tropical lower stratosphere by volcanic aerosols (Robock, 2000). However, only weak enhancements of the Arctic polar vortex can be diagnosed from CMIP5 climate model simulations (Bittner et al., 2016b; Zambri and Robock, 2016). Inadequacies in the simulated dynamical response may be related to the prescribed volcanic forcing sets used in simulations (Toohey et al., 2014), which have generally not included aspects of volcanic aerosol forcing that are now understood to be important, e.g., the variability of aerosols within the lowermost extratropical stratosphere (Andersson et al., 2015; Ridley et al., 2014). This is particularly relevant for the small-to-moderate 21st century eruptions.

Many aspects of the large-scale atmospheric circulation – especially in the middle atmosphere – are driven by waves. However, few studies (e.g., Toohey et al., 2014; Bittner et al., 2016a) have specifically addressed the volcanic impact on wave propagation and breaking. For example, the mesospheric residual circulation and the mesospheric temperature field are controlled by the breaking of gravity waves, and observed post-volcanic mesospheric anomalies (e.g., She et al., 2015; Hervig et al., 2016) are likely mediated by changes in gravity wave breaking, although the mechanisms remain unexplored.

A complete picture of the volcanic effects on surface climate is still missing. Most challenging is the volcanic imprint on tropical hydroclimate, which is highly influenced by internal variability. It has been demonstrated that volcanic eruptions influence the interhemispheric energy budget (e.g., Haywood et al., 2013) and modulate the African and Asian Monsoon systems (e.g., Oman et al., 2006; Liu et al., 2016), impacting areas that are now home to ~60 % of the world's population. The recent generation of climate models is capable of reproducing the main characteristics of the observed precipitation response to volcanic forcing quite reasonably, but they significantly underestimate the magnitude of the regional responses in specific seasons (Iles and Hegerl, 2014). According to the analysis by Paik and Min (2017), models show a weaker response in latent heat flux and 500 hPa vertical motion, which could be a critical factor for their underestimation of precipitation reduction. This questions their capability for providing reliable future predictions of changes in the tropical water cycle.

3 Aims and objectives

As outlined above, the scientific understanding of volcanic aerosols and their effects has improved during the last decade. Nevertheless, many relevant processes are still poorly understood. Due to new developments in observational and modelling capabilities we will now be able to answer questions that could not be addressed before. A sound understanding of the different processes involved will help us to more reliably predict climate effects of future volcanic eruptions, which may be different under future climate conditions. The overarching goal of the research unit VolImpact is to improve the scientific understanding of crucial aspects of volcanic influence on the atmosphere and climate, taking advantage of new developments in observational and modelling capabilities. This will enhance our capacity to quantify potential consequences of the next large volcanic eruption, to understand observed past climate variability, to determine the ramifications of suggested climate engineering via stratospheric aerosols and to design observing systems, software tools and strategies that will allow us to learn the most from future eruptions.

With the now available observational and modelling tools (see Section 5) we will be able to study the effects of volcanic eruptions consistently over the full range of spatial and temporal scales involved, i.e., from the processes in the initial plume during the first hours of the eruption to the global dispersal and its consequences from the surface to the mesosphere. Such coupling of the convective and planetary scales has not been possible before. Tackling the volcanic impacts on multiple scales will allow us to significantly improve the knowledge of and reduce the uncertainties in a chain of closely linked processes, including:

- the evolution of the eruptive plume
- the growth of sulfate aerosols, their global spread and radiative properties
- the effect of volcanic aerosols on clouds
- the impact of volcanic radiative forcing on atmospheric circulation
- the integrated impact of volcanic aerosols and feedbacks on climate

These five aspects are also the central themes of the five VolImpact science projects (see Section 4). For each of them, important and open science questions have been identified that will be addressed by the corresponding project. In the following five paragraphs, exemplary science questions are discussed for each of the projects, including the goals with respect to the individual uncertain processes and the scientific approaches involved.

1. How well can state-of-the-art models reproduce the effect of moist convection on the development of eruption plumes and volcanogenic H_2O injections into the stratosphere and to what extent is the modelled chemical and microphysical evolution within the plume dependent on model resolution?
Modelling approaches used so far do not allow for a consistent treatment of both the plume development and the dispersal of the volcanic material (Textor et al., 2005). A central goal of VolImpact is to overcome the current modelling limitations and to provide seamless simulations over scales relevant for the initial plume development (<100 m) up to global scales. The ICON model system in combination with satellite remote sensing data will provide the tools to better understand the plume development in the first few hours to days of a volcanic eruption. Of particular interest is the role of moist processes in determining the injection height profile of volcanic emissions.
The spatial resolution of the models employed significantly affects the results obtained. For a given volcanic SO_2 amount, the model grid and the prescribed injection profile will affect the SO_2 concentration in the volcanic plume, and subsequently the simulation of microphysical processes. To reduce these uncertainties a very highly resolved region around the volcano is a prerequisite. The ICON model family provides this unprecedented opportunity. This will offer new opportunities for investigating chemical and microphysical processes after volcanic eruptions and their interaction with atmospheric dynamics, clouds and precipitation, e.g., the effect of stratospheric H_2O injections directly through the eruption or indirectly through tropopause changes.

2. What is the exact effect of volcanic eruptions on stratospheric aerosol particle size and what is the role of size changes for the overall chemical and radiative effects of volcanic eruptions?
An open key question in current stratospheric aerosol research is the variability of the PSD of volcanic aerosols during and after an eruption (Robock, 2015). Knowledge on the PSD and its variability are essential for an accurate determination of the chemical and radiative effects caused by volcanic eruptions. For this purpose various satellite data sets – including past missions such as SCIAMACHY as well as current missions, e.g., OMPS/LP and SAGE III/ISS – will be employed to retrieve particle size information. A sound understanding of the temporal development of the aerosol size distribution and the processes involved is a prerequisite for evaluating and validating global aerosol model simulations, which is necessary for providing reliable forcing estimates of future eruptions.

3. What are the effects of volcanic aerosols on clouds and what is the contribution of these aerosol-cloud interactions to the overall effective radiative forcing associated with volcanic eruptions?

Apart from the direct aerosol effect related to scattering of solar radiation and absorption of terrestrial and solar radiation, aerosol-cloud interactions potentially have a significant impact on the overall effective radiative forcing associated with volcanic eruptions. However, the scientific knowledge of volcanism-related cloud effects is particularly poor or lacking. Several essential microphysical processes related to these uncertainties will be addressed by VolImpact. Volcanic aerosols serve as CCN and as such as a source for cloud particles in the liquid phase, and – via homogeneous nucleation – in the ice phase. It is unclear to what extent volcanic aerosols may also serve as ice nucleating particles (INP) leaving their influence on heterogeneous nucleation of cloud ice an open question. For all pathways, the response of clouds beyond changes in cloud particle concentration is uncertain. Apart from this impact of the volcanic aerosol on droplet and crystal formation, clouds also respond to the changes in surface temperature, as well as changes in the temperature and moisture profiles, further adding to the effective radiative forcing (e.g., Heyn et al., 2017), a response that also is very poorly understood and quantified.

4. How do the effects of volcanic eruptions on atmospheric dynamics depend on the specific characteristics of the eruptions and how does the dynamics of the mesosphere respond to major volcanic eruptions?

Some of the most important climatic anomalies related to large volcanic eruptions involve changes in large-scale atmospheric circulation. Unfortunately, climate models do not robustly reproduce many of the expected dynamical responses to volcanic forcing – a result which mirrors the uncertainties in future climate projections due to non-robustness of simulated atmospheric circulation (Shepherd, 2014). One important goal of the proposed research is to investigate the sensitivity of the atmospheric dynamical response to the specific distribution of the volcanic aerosol. To our best knowledge, volcanically induced changes in the mesospheric residual circulation have not been investigated before, and will be used in VolImpact together with evidence from the stratosphere and troposphere to develop a holistic understanding of the impact of volcanic aerosol on the dynamics in the whole atmosphere.

5. What are the possible effects of volcanic eruptions on the hydrological cycle and what conditions do specific responses depend on?

A fundamental and detailed understanding of the climatic effects of future volcanic eruptions is essential for prediction of weather and climatic anomalies in their aftermath. Most challenging is the volcanic impact on the hydrological cycle, as aerosol-cloud processes are poorly understood and clouds rapidly adjust to volcanic forcing. The CMIP6 VolMIP experiments (Zanchettin et al., 2016) can only answer part of these questions, as the experiments are defined with a well constrained forcing for specific eruptions (e.g., Pinatubo, early 19th century eruptions). Together with the volcanic forcing generator EVA and sound statistical methods, the ICON based Earth system model (ICON-ESM) – which allows for highly resolved global simulations – offers the possibility to leap-frog current efforts and to provide a more holistic picture of the volcanic-climate system. We can now address open questions which could not be answered adequately before, e.g., why current climate models underestimate the observed precipitation decrease (e.g., Iles and Hegerl, 2014). The high-resolution ICON-ESM has the potential of tackling this problem as increasing resolution of climate models improves the representation of complex and heterogeneous regions, such as the Maritime Continent, and apparently increases the regionally averaged latent heat flux and precipitation (Qian, 2008; Schiemann et al., 2014). A special goal is to understand the impact of the small-to-moderate 21st century volcanic eruptions on the hydrological cycle.

4 Structure and organisation of the research unit

VolImpact is a truly interdisciplinary project, integrating complementary expertise in satellite remote sensing of atmospheric composition, stratospheric aerosol parameters and clouds as well as in modelling of aerosol microphysical and cloud processes, and in climate modelling. Each member of VolImpact is an expert in a specific discipline, but only as a consortium joined in a Research Unit do they provide the expertise necessary to answer the challenging scientific questions related to the volcanic impact on atmosphere and climate. With their different backgrounds and tools the VolImpact partners form an excellent team that will be able to fulfill the project objectives. The research goals outlined above are addressed in five individual science projects, which answer the scientific questions and which are complemented by a coordination project. Each of the science projects – briefly summarized below – will deal with one specific aspect of VolImpact (see Figure 2).

Volcanic Plume evolution and injection profiles (VolPlume) focuses on the initial plume development in the first few hours to days of a volcanic eruption by combining state-of-the-art atmospheric modelling and satellite remote sensing. The project will create the important capability to quickly carry out similar studies for future volcanic eruptions. This includes both the modelling framework and the satellite data retrieval algorithms. The project will also provide some of the model development and initial conditions relevant for the entire research unit.

Constraining the effects of Volcanic Aerosol on Radiative forcing and stratospheric Composition (VolARC) addresses the direct radiative effects of volcanic aerosols in the stratosphere. This project aims at (i) quantifying the temporal variability of stratospheric aerosol extinction and PSD as well as radiative forcing using available satellite data sets and state-of-the-art modelling capabilities; (ii) improving current aerosol microphysical modelling capabilities to better link observed SO_2 emission and AOD and thereby constraining volcanic SO_2 emission, e.g., of the 1991 eruption of Mt. Pinatubo.

Cloud response to Volcanic eruptions (VolCloud) treats the cloud response to volcanic eruptions due to aerosol-cloud interactions and cloud adjustments making use of a range of ICON simulations as well as of satellite data. Two adjustment effects are investigated: (i) the microphysical response of clouds to the volcanic aerosol, for liquid and ice clouds; and (ii) the response of thermodynamic profiles and the subsequent alteration of cloud distributions and properties, in collaboration with the VolDyn and VolClim projects.

Volcanic impacts on atmospheric Dynamics (VolDyn) investigates the impact of volcanic eruptions on the dynamics of the atmosphere. It will focus on building a mechanistic understanding of the dynamical responses to the direct radiative effects of volcanic aerosol, and the sensitivity of these responses to the structure of the forcing. The area of focus includes the mesosphere, stratosphere and troposphere, and the project will integrate results from other projects of the research unit which help defining the structure and uncertainty range of volcanic forcing based on observations and detailed modelling.

Volcanic impact on surface Climate (VolClim) investigates the impact of volcanic eruptions on surface climate. The central goal of VolClim is to develop a conceptual understanding of how volcanic eruptions influence tropical hydroclimate which helps estimating the impact of future eruptions. The unique combination of the highly resolved ICON-ESM with the volcanic forcing generator EVA and advanced statistical methods will allow to assess how important specific eruption characteristics and the background climate state are for the volcanic influence on tropical hydroclimate. ICON-ESM model results will be jointly analyzed within VolImpact.

While each project has its specific topic, all projects are interrelated in a chain of closely linked processes and contribute to the overall research themes. Tight links exist between the individual VolImpact projects due to the fact that all groups use models of the ICON model system (Section 5.2) and focus on selected volcanic eruptions.

The governance structure of the research unit comprises a General Assembly (GA), a Steering Committee (SC) consisting of the PIs of the individual projects and a project office located at the University of Greifswald. The science results obtained will be published in open access journals and the retrieved and/or modelled data sets will be made publicly available under CC-BY 4.0 license. For both the VolImpact simulations and the VolImpact retrieval products a final long-term archiving is planned at DKRZ within the WDCC to allow analysis beyond the project period.

5 Tools and methodology

5.1 Observational data

Central for VolImpact is the analysis and exploitation of satellite data. Satellite measurements will be used in two different ways in VolImpact. Some of the research activities will employ raw satellite data (Level 1 data) to retrieve relevant aerosol parameters (aerosol extinction and aerosol particle size information), e.g., in VolARC. In addition, we will also make use of existing Level 2 satellite data of aerosol parameters, chemical composition and the atmospheric background state.

We expect to greatly benefit from:

(a) the daily near-global observations from the well-established limb-scatter instruments (OSIRIS (Llewellyn et al., 2004); SCIAMACHY (Bovensmann et al., 1999); OMPS-LP (Jaross et al., 2014)) and the recently launched and upcoming satellite missions including SAGE III/ISS (launched in 2017), EarthCARE (scheduled for launch in 2021) and ALTIUS (Fussen et al., 2016) (currently scheduled for launch in 2022), which provide high-resolution observations of aerosols, clouds, and aerosol-cloud interactions.

(b) multi-spectral observations of the scattered or transmitted solar radiance which allow the retrieval of more than one parameter of the aerosol particle size distribution – a key variable for volcanic forcing constraints.

(c) advanced optical observations to retrieve the volcanic plume geometry, such as MISR multi-angle observations and geostationary observations with high spatio-temporal resolution.

(d) cloud property retrievals by active remote sensing (CloudSat and CALIPSO) for evaluation of the simulation of perturbed and unperturbed liquid and ice clouds.

Table 1 provides an overview of the satellite datasets we plan to use within the individual projects. A depiction of the temporal coverage of past, current and future satellite missions providing stratospheric aerosol measurements is given in Figure 3. Regarding future satellite measurements, the short term prospects for global space-based aerosol measurements are excellent with observations from OSIRIS, CALIPSO and OMPS-LP expected to last several more years. Furthermore, the new SAGE-III instrument was successfully deployed on the International Space Station (ISS) in early 2017. The SAGE-III instrument on ISS is an improved version of the SAGE-III/Meteor-3M instrument that provided stratospheric aerosol observations from 2002 to 2006 (e.g., Thomason et al., 2008). The EarthCARE mission, conducted jointly between the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA), will provide highly valuable observations of clouds and aerosols. It will, e.g., be capable

Table 1: List of satellite data sets to be used within the research unit.

Instrument / Satellite	Atmospheric parameter
AATSR / Envisat, SLSTR / Sentinel-3	Plume top height, Aerosol and cloud properties
ABI / GOES	Cloud/plume horizontal structure and temporal evolution Plume motion winds, Plume top height
ACE-FTS / Scisat	H_2O, HCl, HF, $ClONO_2$, O_3, ClO
ALI / EO-1	Plume top height
ASTER / Terra	Plume top height
AVHRR / NOAA, MetOp	Aerosol and cloud properties, Plume top height
CALIOP / CALIPSO	Aerosol & cloud/plume backscatter, cloud/plume vertical structure
CATS / ISS	Cloud/plume vertical structure
CERES / Terra, Aqua	Radiative fluxes
CHRIS / PROBA-1	Plume top height
CloudSat	Cloud/plume vertical structure
GOMOS / Envisat	Aerosol extinction
HALOE / UARS	Aerosol extinction, O_3, ClO, HCl, HF, Temperature
IASI / MetOp	H_2O
MIPAS / Envisat	SO_2
MISR / Terra	Plume top height, Aerosol properties (size, Angstrom exponent, non-spherical fraction) Plume motion winds, Angular reflectances
MLS / Aura	H_2O, OH, SO_2, O_3, BrO, ClO, HCl, CH_3Cl, Temperature
MODIS / Terra, Aqua	Cloud microphysics, horizontal plume structure
OMPS-LP / NPP-Suomi	Aerosol extinction & particle size (if available), O_3
OSIRIS / Odin	Aerosol extinction, O_3
POAM II / SPOT-3	Aerosol extinction
POAM III / SPOT-4	Aerosol extinction
SAGE II / ERBS	Aerosol extinction & particle size, O_3
SAGE III / Meteor-3M	Aerosol extinction & particle size, O_3
SAGE III / ISS	Aerosol extinction & particle size
SBUV / NOAA series	Noctilucent cloud occurrence, albedo & ice mass
SCIAMACHY / Envisat	Aerosol extinction & particle size, H_2O, BrO
SEVIRI / MSG	Cloud/plume horizontal structure
EarthCARE (2021 onwards)	3-D reconstruction of plume structure, profiles of cloud and aerosol properties
FCI / MTG (2021 onwards)	Plume horizontal structure/temporal evolution Plume motion winds, Plume top height

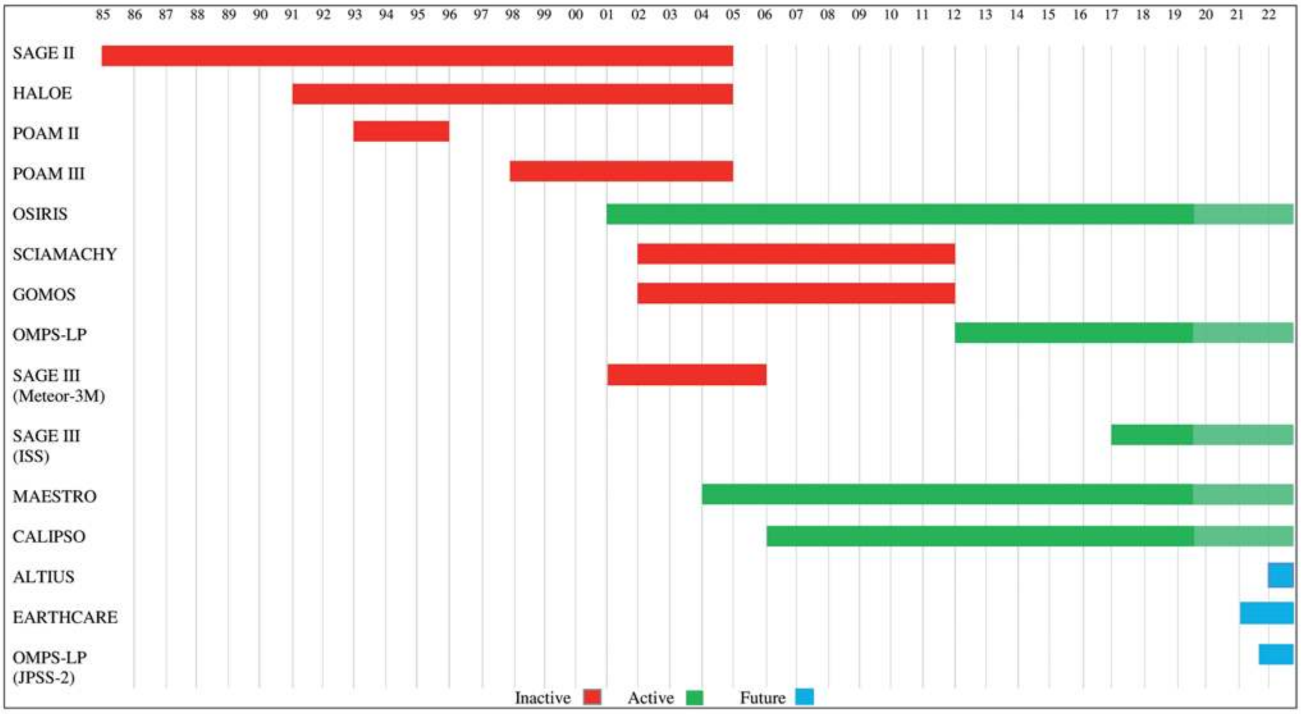

Figure 3: Availability of past, current and future satellite observations of stratospheric aerosol parameters (extinction, backscatter or particle size information).

of distinguishing clouds and different types of aerosols and even detect vertical motion within clouds. From the remote sensing perspective, the next moderate to large volcanic eruptions will very likely be well characterized through the retrieval of optical, microphysical and geometrical properties of both volcanic ash and sulfate aerosol provided by a range of complementary Earth-observing platforms.

In VolImpact other observational data will also be used. Collaborations with different in-situ and remote sensing measurement groups are planned including the Network for Observation of Volcanic and Atmospheric Change (NOVAC), the Network for the Detection of Atmospheric Composition Change (NDACC), IAGOS-CARIBIC and the upcoming Strateole-2 balloon campaign.

5.2 Models and Forcing data

In VolImpact the ICON modeling framework will be applied to better understand the impacts of volcanic eruptions from the dynamics of the eruption plume to global climate effects. The ICON model is a joint development of the German Weather Service (DWD) and the Max Planck Institute of Meteorology Hamburg (MPIM). ICON scales very efficiently on massively parallel computers and is therefore especially suited to run on current high performance computing architectures. The atmospheric component of the ICON model system has been developed around a dynamical core that solves the fully compressible non-hydrostatic equations, and includes a mass conserving tracer transport scheme. Three packages for parameterisations of subgrid-scale diabatic and turbulent processes have been developed for climate simulations at a grid resolution of ~100 km (ICON-A, Giorgetta et al. (2018); Crueger et al. (2018)), numerical weather prediction at a grid resolution of ~10 km (ICON-NWP, Zängl et al. (2015)) and large eddy simulations at grid resolutions down to ~100 m (ICON-LEM, Heinze et al. (2017)). The model allows for global or regional simulations and has the option for online nesting with multiple refinement levels.

In VolImpact we will also apply the UA-ICON, an extension of ICON to the Upper Atmosphere, more specifically up to the lower thermosphere (Borchert et al., 2019) and the fully-coupled aerosol and chemistry extension ICON-ART. ICON-ART has been developed at the Karlsruhe Institute of Technology (KIT) (Rieger et al., 2015). ART stands for Aerosols and Reactive Trace gases and simulates atmospheric chemistry and aerosol microphysics, and related feedback processes. Currently, a version of ICON-ART is being jointly developed by MPI-M and KIT to simulate stratospheric ozone on a global scale. ICON-ART allows a two-way nesting to consider specific areas with a high resolution. Such nests will be employed around volcanoes. The climate effect of the volcanic eruptions will be addressed with the ICON-based coupled Earth system model (ICON-ESM) which is currently in the testing phase. The first version consists of the atmosphere model ICON-A at 160 km grid resolution with 47 layers up to 80 km height and the ICON-O ocean model (Korn, 2017) at 40 km resolution with 64 vertical layers. The land component ICON-L which is embedded in ICON-A, is based on the JSBACH model (Reick et al., 2013). The ocean component ICON-O is a hydrostatic general circulation model and includes also a dynamic/thermodynamic sea-ice model and the ocean biogeochemistry sub-model HAMOCC.

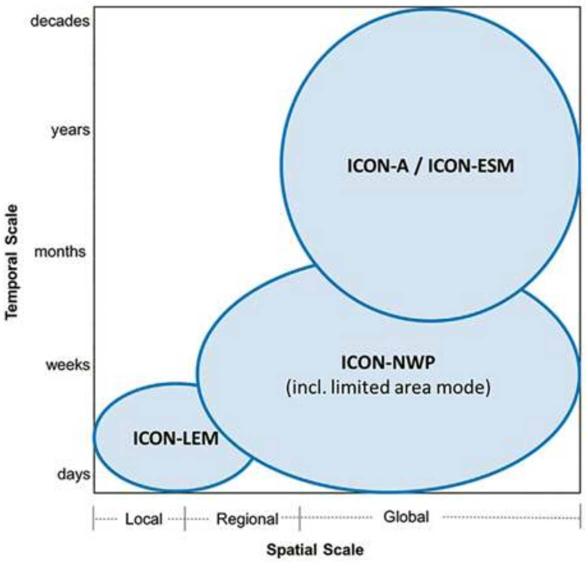

Figure 4: Schematic overview of the range of spatial and temporal scales of the ICON models to be used in VolImpact.

The ICON model family provides a unique modeling framework that allows to directly link simulations of the volcanic plume, aerosol microphysics and climate (see Figure 4). Starting with large eddy simulations with ICON-LEM in VolPlume, the chain of model configurations evolves via ICON-NWP simulations in VolCloud to global simulations with ICON-A/UA-ICON (VolARC, VolDyn) and with ICON-ESM (VolClim). Using models from the same model system will foster synergies between the individual VolImpact projects. One of the great advantages of ICON(-ART) is the nesting option which will allow bridging the different spatial scales involved in a very elegant way and which will be used in two projects (VolPlume, VolARC).

Reconstructions of volcanic aerosol properties from observations represent best estimates of the past history of volcanic eruptions and aerosol properties. However, they are by design static data sets and therefore not adaptable to idealized experiments, experimentation in a global climate model framework or addressing potential effects of future eruptions. To address these issues, the Easy Volcanic Aerosol (EVA) forcing generator has been developed (Toohey et al., 2016). EVA provides stratospheric aerosol optical properties for a given input list of volcanic eruption dates and locations based on a parameterized three-box model of stratospheric transport and simple scaling relationships used to derive mid-

Table 2: Overview of volcanic eruptions, which will be the focus of the VolImpact project (#Maximum).

Name	Location	Date	Type	VEI	Height# [km]	Available satellite Observations Note that "SCIA" corresponds to "SCIAMACHY".
Mt. Pinatubo	15.13° N, 120.35° E	15 06 1991	explosive	6	25	SAGE II, HALOE
Tavurvur	4.14° S, 152.12° E	07 10 2006	explosive	4	18	SCIA, GOMOS, CALIOP
Kasatochi	52.18° N, 175.51° E	07 08 2008	explosive	4	15	SCIA, GOMOS, CALIOP
Sarychev Peak	48.09° N, 153.2° E	15 06 2009	explosive	4	17	SCIA, GOMOS, CALIOP
Eyjafjallajökull	63.63° N, 19.62° W	14 04 2010	explosive	4	9	SCIA, GOMOS, CALIOP, CloudSat, MODIS
Cordon Caulle	40.59° S, 72.11° W	04 06 2011	explosive	5	14	SCIA, GOMOS, CALIOP
Nabro	13.37° N, 41.7° E	13 06 2011	explosive	4	18	SCIA, GOMOS, CALIOP, OSIRIS
Kelut	7.93° S, 112.31° W	13 02 2014	explosive	4	19	CALIOP, OMPS-LP, OSIRIS
Holuhraun	64.85° N, 16.83° W	31 08 2014	effusive	4	5	CALIOP, CloudSat, MODIS
Calbuco	41.33° S, 72.62° W	22 04 2015	explosive	4	20	CALIOP, OMPS-LP, OSIRIS
Raikoke	48.29° N, 153.24° E	21 06 2019	explosive	4	15	CALIOP, OMPS-LP, OSIRIS

visible (550 nm) aerosol optical depth and aerosol effective radius. EVA is constructed in a way to enable easy modification of different aspects of aerosol properties, including spatiotemporal structure of the aerosol distribution or the spectral properties related to the aerosol size distribution. Volcanic forcing compiled with EVA is recommended for experiments in the CMIP6 VolMIP (Zanchettin et al., 2016) and the PMIP4 past 1000 (Jungclaus et al., 2017) activities.

VolImpact projects will focus on the late 20th century and early 21th century. This period includes a large volcanic eruption, i.e., Mt. Pinatubo in 1991, but also several small to moderate ones (Figure 1). A set of volcanic eruptions has been selected from this VolImpact core period (1990–2016) based on eruption characteristics and data availability (Figure 5 and Table 2) which will be studied across the different projects, including Mt. Pinatubo (1991), Sarychev Peak (2009), Eyjafjallajökull (2010), Nabro (2011) and Holuhraun (2014). VolImpact will also address the Raikoke eruption in June 2019 which happened after the start of the project.

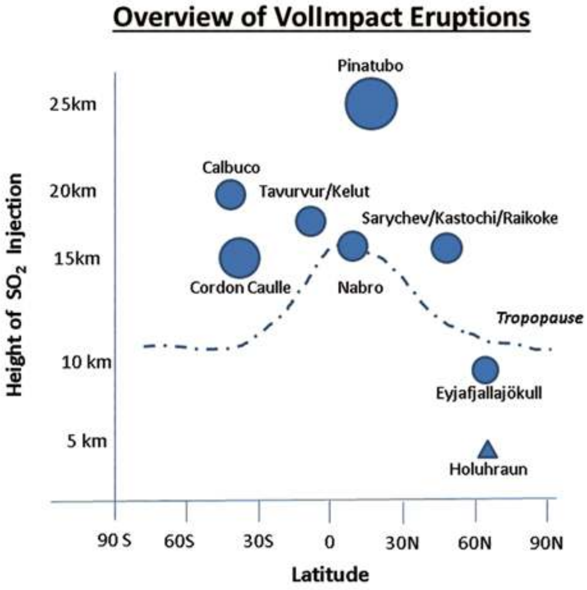

Figure 5: Selected volcanic eruptions from the VolImpact core period which will be specifically addressed in process studies in the individual projects. Circles denote explosive eruptions, triangles effusive ones. The size of the symbol is indicative of the VEI (the VEIs of the eruptions shown vary between 4 and 6). The tropospheric Icelandic eruptions will be used in VolPlume and VolCloud for process-oriented studies. More details about the eruptions including available measurements are found in Table 2.

6 Collaborations with national and international projects

The VolImpact research activities will greatly benefit from collaborations with a variety of national and international research programmes, measurement campaigns as well as satellite missions. Members of the science teams of the OSIRIS/Odin, SAGE III/ISS or OMPS/Suomi satellite missions are, for example, involved in the VolImpact projects as collaborators or Mercator fellows. Close cooperation is foreseen between the research unit VolImpact and several international initiatives with similar science objectives. The VolImpact research objectives are highly relevant for the WCRP core project SPARC (Stratosphere-troposphere processes and their role in climate), which facilitates coordination of international research activities in various sub-disciplines related to stratospheric processes. VolImpact has in particular strong links to the SSiRC initiative VolRES (Volcano Response) which aims at improving our understanding of the impacts of large volcanic eruptions by coordinating a global response plan with the community to be ready for the next large volcanic eruption. With its central goal, VolImpact is in line with the broader objectives of the science community to better understand the role of volcanoes on climate and to be prepared for the next eruption and will hence serve as a role model for international activities. The impact of aerosols on clouds, precipitation and climate is one of the most urgent questions in current climate science. Studying volcanic eruptions and their atmospheric and climate effects is a promising avenue towards im-

Table 3: Glossary of used acronyms and abbreviations.

AATSR	Advanced Along-Track Scanning Radiometer
ABI	Advanced Baseline Imager
ACE	Atmospheric Chemistry Experiment
ACPC	Aerosols, Clouds, Precipitation and Climate
ALI	Advanced Land Imager
ALTIUS	Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere
AOD	Aerosol Optical Depth
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
AVHRR	Advanced Very High Resolution Radiometer
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CARIBIC	Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container
CATS	Cloud-Aerosol Transport System
CCN	Cloud Condensation Nuclei
CERES	Clouds and the Earth's Radiant Energy System
CHRIS	Compact High Resolution Imaging Spectrometer
CMIP6	Coupled Model Intercomparison Project, phase 6
CPT	Cold-point tropopause
DFG	Deutsche Forschungsgemeinschaft
DKRZ	Deutsches Klimarechenzentrum GmbH
DWD	Deutscher Wetterdienst
EarthCARE	Earth Clouds, Aerosol and Radiation Explorer
ESA	European Space Agency
ESGF	Earth System Grid Federation
ESM	Earth System Model
EVA	Easy Volcanic Aerosol
FCI	Flexible Combined Imager
GCM	General Circulation Model
GEWEX	Global Energy and Water Exchanges
GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring by Occultation of Stars
HALOE	Halogen Occultation Experiment
IAGOS	In-service Aircraft for a Global Observing System
ICI	Ice Cloud Imager
ICON	ICOsahedral Nonhydrostatic model
ICON-ART	ICOsahedral Nonhydrostatic – Aerosols and Reactive Trace gases model
ICON-A	ICOsahedral Nonhydrostatic model – Atmosphere model for climate simulation
ICON-ESM	ICOsahedral Nonhydrostatic model – Earth system model
ICON-LEM	ICOsahedral Nonhydrostatic – LargeEddy Model
ICON-NWP	ICOsahedral Nonhydrostatic – Numerical Weather Prediction Model
ICON-O	ICOsahedral Nonhydrostatic – Ocean model
IGAC	International Global Atmospheric Chemistry
iLEAPS	Integrated Land Ecosystem-Atmosphere Processes Study
INP	Ice Nucleating Particles
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
ISS	International Space Station
ITCZ	Intertropical Convergence Zone
IUP	Institut für Umweltphysik, Universität Bremen
KIT	Karlsruhe Institute of Technology
JAXA	Japanese Aerospace Exploration Agency
LES	Large Eddy Simulation
MAESTRO	Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation
MetOp	Meteorological Operational satellites
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MISR	Multi-angle Imaging SpectroRadiometer
MLS	Microwave Limb Sounder
MODIS	Moderate Imaging Spectroradiometer
MPI-ESM	Earth System model of Max Planck Institute for Meteorology
MPIM	Max Planck Institute for Meteorology
MTG	Meteosat Third Generation

NDACC	Network for the Detection of Atmospheric Composition Change
NOVAC	Network for Observation of Volcanic and Atmospheric Change
NH	Northern Hemisphere
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OMPS-LP	Ozone Mapping and Profiler Suite–Limb Profiler
OPC	Optical Particle Counter
OSIRIS	Optical Spectrograph and InfraRed Imager System
PMIP4	Paleoclimate Model Intercomparison Project phase 4
PI	Principal Investigator
POAM	Polar Ozone and Aerosol Measurement
PSD	Particle Size Distribution
SAOD	Stratospheric Aerosol Optical Depth
SAGE	Stratospheric Aerosol and Gas Experiment
SC	Steering Committee
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY
SEVIRI	Spinning Enhanced Visible Infra-Red Imager
SLSTR	Sea and Land Surface Temperature Radiometer
SPARC	Stratosphere-troposphere Processes And their Role in Climate
SSiRC	Stratospheric Sulfur and its Role in Climate
Strateole-2	Super Pressure Balloon Campaign for long duration measurements in the TTL
TTL	Tropical Tropopause Layer
UA-ICON	ICOsahedral Nonhydrostatic – upper atmosphere model
UG	University of Greifswald
UTLS	Upper Troposphere Lower Stratosphere
VEI	Volcanic Explosivity Index
VolMIP	Model Intercomparison Project on the climate response to Volcanic forcing
VolRES	Volcano Response Plan after the next major eruption
WCRP	World Climate Research Programme
WDCC	World Data Climate Center

proving our understanding of the climate system, as they constitute strong singular perturbations of the climate system. The research goals of VolImpact therefore also contribute to the research goals of the International Global Atmospheric Chemistry (IGAC) project and the Aerosols, Clouds, Precipitation and Climate (ACPC) initiative of GEWEX, iLeaps and IGAC.

7 Conclusions and perspectives

The DFG Research Unit VolImpact will improve the scientific understanding of key aspects of the volcanic influence on atmosphere and climate, taking advantage of new developments in observational and modelling capabilities. This will enhance our capacity to understand observed past climate variability, to quantify potential consequences of the next large volcanic eruption and to design observing systems, software tools and strategies that will allow us to learn the most from future eruptions.

The overall success of the VolImpact research unit does, however, not depend on the occurrence of major volcanic eruptions during the project period. Independent of the occurrence of a major eruption during the project period, the new remote sensing and modelling capabilities will help improving the scientific understanding of poorly known processes related to volcanic eruptions. In addition, the developed tools can also be applied to study pyrocumulus events, which occur much more frequently than major volcanic eruptions (e.g., Fromm et al., 2005; Siddaway and Petelina, 2011; Peterson et al., 2017).

Research of the described phase 1 (4/2019–3/2022) of VolImpact will pave the way for a potential 2nd phase. Physical and chemical modules developed in phase 1 will be combined into one modelling suite. Experiments with convection-permitting resolution will be performed on the global scale with an ultra-fine nest around the volcano. Such simulations could become an early demonstrator for the potential benefits of the approach to use extreme computing for understanding natural extreme events. On the observational side a special emphasis in a 2nd phase of VolImpact will be on the exploitation of future data sets relevant for the VolImpact research goals. This includes in particular upcoming satellite missions such as ESA's EarthCARE, comprising different instruments that are highly relevant for several of the VolImpact science projects. In addition, ESA's ALTIUS mission (scheduled for launch in 2022) as well as the U.S. mission OMPS JPSS 2 (scheduled for launch in 2021) will continue satellite limb observations and fill the looming "limb-gap", i.e., the potential interruption of the vertical profiling capability of the middle atmosphere using satellite sensors.

More information on VolImpact and instructions on how to access datasets created within the VolImpact projects are provided on the VolImpact website (www.uni-greifswald.de/volimpact).

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