PART A: Perspectives on stratospheric aerosol observations

Abstract: Stratospheric aerosols have a direct impact on the Earth's climate through their albedo and their impact on ozone. Thus, they must be accounted for in all chemistry climate models. One source for such aerosol information, used by the modeling community, is the Global Space-based Stratospheric Aerosol Climatology (GloSSAC, Thomason et al., 2018; Kovilakam et al., 2020). GloSSAC's primary product is a continuous record (currently from 1979-2022) of zonally and monthly averaged global stratospheric aerosol extinction coefficient at 525 and 1020 nm. Clearly, a continuation of the GloSSAC record with the current or improved coverage is highly desirable. However, two key instruments currently providing GloSSAC input data (Optical Spectrograph and Infrared Imaging System, OSIRIS, and Cloud-Aerosol Lidar with Orthogonal Polarization, CALIOP) are near the end of their life, leaving only the Stratospheric Aerosol and Gas Experiment (SAGE III/ISS) solar occultation observations, which will not provide the current coverage and temporal resolution. In addition, the in situ instruments, which have been used in the past for validation of the space-borne measurements, are being replaced with new improved instruments, but still need to be tied to the legacy records. Plus, the rather simple picture of stratospheric aerosol dominated by sulfate is being challenged by recent pyrocumulonimbus (pyroCb) events, by the discovery of nitrates in the lower stratosphere above the Asian monsoon, and by the incursion of organics into the lower stratosphere.

To address these issues we propose a project divided into four tasks: 1) To review the GloSSAC climatology. Does it capture current understanding of stratospheric aerosol? Could the parameter space be improved? 2) To explore options for GloSSAC continuation and possible data record additions (i.e. what other instruments could be included?). 3) To review challenges and limitations for comparisons between in situ aerosol observations and 4) To identify key variables that represent the stratospheric aerosol layer, key existing gaps and to develop strategies to fill them.

Science rationale and objectives

Stratospheric aerosol play an important role in the Earth's climate system directly by reflecting incoming solar radiation back to space and indirectly by influencing chemical reactions in the ozone layer and by altering the local radiative balance and thus dynamical processes. Our understanding of stratospheric aerosol and their climate effects have been comprehensively reviewed by Kremser et al. (2016). Two remaining challenges identified in that work are the uncertain outlook of space-borne stratospheric aerosol observations and the limited ability to account for effects of non-sulfate aerosols in chemistry climate models.

Space-borne observations are necessary to get a global view on the variability, transport and radiative properties of stratospheric aerosols, and to test their representation in climate models against the real world. GloSSAC, a comprehensive multi-sensor climatology, has only recently become available and has been widely used by atmospheric modeling groups for prescribing aerosol properties (e.g., Aubry et al., 2020) and for validating interactive aerosol schemes (e.g., Timmreck et al., 2018, Quaglia et al., 2023). Clearly, a continuation of the GloSSAC record with the current or even improved coverage and resolution is highly desirable, yet this will require including instruments beyond SAGE III/ISS.

The need for better representation of non-sulfate aerosol and their uncertainties in models has become even more evident since Kremser et al. (2016). There is a significant contribution of mainly anthropogenic ammonium nitrate particles in the Upper Troposphere and Lower Stratosphere (UTLS) over Asia, forming the Asian Tropopause Aerosol Layer (ATAL), first observed by Vernier et al. (2011) with the nitrate identified by Höpfner et al. (2019). Second, the strong and long lasting 2020 Australian wildfires have triggered massive stratospheric aerosol injections through pyroCb events with a rather complex composition, which is still poorly understood. Such fire events may become both stronger and more frequent with global warming (Smith et al., 2020), and their increasing contribution to the stratospheric aerosol load will add further complexity to their composition and their radiative, microphysical and chemical properties.

The specific information needed to fully understand the radiative forcing and chemical properties of such complex aerosol mixtures can only be obtained from targeted in situ observations from balloons and aircraft and from lidars. While a large number of such observations have been made around the world, often in the context of interesting features (e.g. ATAL) or following specific volcanic eruptions or fire events, there is little homogeneity in terms of instruments used and parameters measured. Hence, it is sometimes difficult to access these data records and associated meta-data. This issue has additionally, recently been discussed within the Stratospheric Processes and its Role in Climate (SPARC) Hunga Tonga multi-Model Intercomparison Project (MIP) initiative. Furthermore, several important aerosol properties and parameters cannot be measured with current instrumentation.

We propose to bring together leading experts on space-borne, ground based and in-situ observations of stratospheric aerosol and modelers working on the representation of stratospheric aerosols, their properties, radiative effects and chemistry, in global climate simulations as an international team at ISSI to ensure the continuity of stratospheric aerosol observations and improve their homogeneity and accessibility to modelers.

Work plan

We define four tasks as the focus for the proposed Team while at ISSI, with additional work being carried out in preparation for and following the ISSI meetings.

Task 1: Review the added value of GloSSAC

After being used by the global modelling community for about 5 years now, a critical review of GloSSAC in terms of parameters included, uncertainties, coverage and resolution is warranted. In particular, with new sensors and retrieval algorithms in various stages of development (cf. Task 2 below). It is vital to take into account the needs of the climate modelling community for improving models and to provide the best possible climate services.

Prior to the meetings in Bern, team members will look into the available literature and interview members of modelling groups not represented in the proposed ISSI team. In Bern, the insights from the literature and the interview feedback will be discussed. A short report will be written that should, in the end, clearly identify any shortcomings and/or desired improvements to the GloSSAC data record. This report will serve as input for Task 2, and depending on its substance, may be considered for publication in an appropriate scientific journal, and to the extent possible be used to amend GloSSAC.

Task 2: Explore and evaluate options for the continuation of, and possible additions to, the GloSSAC data record

As described above, the mid- and long-term continuation of the GloSSAC record, with its current wavelengths, coverage, and resolution, is highly insecure. The proposed ISSI Team wants to ensure continuity of this robust dataset by adding additional space-based measurements and adapting it to the changing needs of the climate modeling community.

First, the long term needs in terms of minimum number and optimum wavelengths, coverage and resolution will be identified, taking into account the input from Task 1. This will be done in close collaboration with the SPARC. Within this effort, we also want to accommodate for the need of a consensus stratospheric aerosol forcing dataset, following the eruption at Hunga Tonga (mid-January 2022), identified by the Hunga Tonga multi-MIP initiative. Challenges arising when accounting for information with different spectral- vertical- and horizontal resolution will be addressed in general terms.

Second, potential sensors and datasets that are already available, or expected to become available soon, will be critically considered. The Ozone Mapping and Profiler Suite limb profiler (OMPS-LP, Taha et al., 2021) provides a continuous aerosol extinction dataset from 2012 to the foreseeable future, and could potentially be incorporated into GloSSAC. However, while the OMPS-LP stratospheric aerosol extinction product is valuable with its large sampling volume and global coverage, a recent study shows an overestimation of OMPS-LP aerosol extinction following the Hunga Tonga eruption when compared against the tomographic retrieval of OMPS developed by University of Saskatchewan (OMPS-USask) and SAGE III/ISS (Bourassa et al., 2023). Further validation of OMPS-LP aerosol product with other space-based and in-situ/surface-based measurements will be a point of considerable analysis before incorporating OMPS-LP into GloSSAC. Besides the already established OMPS-LP dataset, we will consider 'near' future space-borne missions (e.g. aerosol backscatter observations from Atmospheric Lidar, ATLID, on the Earth Clouds, Aerosols, and Radiation Explorer, EarthCARE, with its launch planned for early 2024) as well as other planned missions for aerosol observations (e.g. Changing-Atmosphere Infra-Red Tomography Explorer, CAIRT, Atmosphere Observing System, AOS, High-altitude aerosols, water vapor and clouds, HAWC).

Besides looking at space-borne observations, we want to explicitly explore the use and potential integration of ground-based lidar measurements from multiple networks (e.g., the international Network for the Detection of Atmospheric Composition Change, NDACC, and the Latin American Lidar Network, LALINET). While ground based lidar observations do not provide global coverage, the long-term records often cover several decades and could be useful in ensuring enhanced continuity within GloSSAC that currently relies entirely on satellite instruments with more limited lifetimes. Furthermore, an enhancement of the inter comparability between stratospheric aerosol lidar observations (aerosol extinction) is necessary to increase homogeneity within GloSSAC. To that end, lidar experts on stratospheric aerosols lidar observations will be consulted about promoting actions to produce standardized procedures and sources of auxiliary information required for the lidar processing chain. Further contacts with existing lidar networks will be established to pursue this goal.

New opportunities as well as remaining gaps and risks for the next two decades of GloSSAC will be compiled in a report, parts of which will be summarized in a perspectives article in a peer reviewed journal.

Task 3: Database of in situ stratospheric aerosol observations

While it is important to have continued space-based stratospheric measurements that provide global observations, it is equally important to have in situ measurements as they provide unique, small scale, aerosol size distribution observations, from which various aerosol properties important for the modeling community can be derived, e.g. aerosol surface area, volume, cross section, in addition to extinction and backscatter for comparison with remote measurements. They are crucial to validate space-based measurements that are used in the GloSSAC dataset and climate model simulations. Unfortunately, when it comes to ground based and in-situ aerosol observations, the current state of such measurements, and corresponding meta-data, are often in formats difficult to use by the modelling community.

During the past decade, targeted measurement flights on weather balloons, carrying small aerosol analyzers have become popular. A variety of instruments, measuring optical parameters, concentration and composition perform measurement flights on a regular basis and/or during targeted field campaigns, creating a multitude of different instruments and stratospheric aerosol datasets. Key instruments for balloon-borne stratospheric aerosol observations are: Printed Optical Particle Spectrometer (POPS) (Gao et al., 2016), Laboratory for Atmospheric and Space Physics Optical Particle Counter (LOPC) (Kalnjas and Deshler, 2022), Light Optical Aerosol Counter (LOAC) (Renard et al., 2016), Compact Optical Backscatter and AerosoL Detector (COBALD) (Brabec et al., 2012), the newly developed Stratospheric Total Aerosol Counter (STAC) by the Laboratory of Atmospheric and Space Physics, and the Particle plus Optical Particle Counter (POPC), developed at Langley, NASA (Vernier et al., in prep). Within this project, we want to gather experts and PIs of such instruments, highlight their respective strengths and weaknesses, and tackle the following questions: What variables should be compared for different sensors? How do different laser wavelengths, measurement angles and various detectors affect such comparisons? What are the measurement uncertainties? How is counting efficiency characterized/accounted for? What composition information, if any, can be obtained from the measurements?

Task 4: Identify gaps in observational capacities and develop strategies to fill them

While the representation of stratospheric aerosol processes and effects in global models has constantly improved over the past decades, uncertainties remain in many aspects and some processes are not yet represented or poorly constrained. Often, targeted measurements of certain properties of different aerosol types or mixtures in specific locations and situations could help, but are not available or even not yet possible.

In this task, we want to identify the most important and most relevant gaps and uncertainties in process or property representation and develop strategies to fill the knowledge gaps with novel observations. Our considerations will include both the difficulty of readily making measurements with existing sensors in the right places at the right times, e.g., to comprehensively measure the plume evolution after a volcanic eruption or fire event, and the need for measuring additional aerosol parameters to better understand their radiative and/or chemical properties.

The output of Task 4 will be a white paper that will form the basis for future developments and science proposals.

Schedule and expected outcomes:

We will start in June 2023 with an online kick-off meeting to select dates for the team meetings at ISSI, nominate additional team members (Early-Career Researchers, ECR) and assign preparatory work for Tasks 1 and 3. At the first ISSI meeting (~3 days, fall 2023), we will mainly work on Tasks 1 and 3 in parallel. Results of these tasks will be written up and preparatory work for Task 2 will be carried out before a second meeting (~3 days, fall 2024). During the second meeting Task 2 will be the main focus together with discussion on the measurement gaps and new strategies. The write up of a report and paper for Task 2 and white paper for Task 4 will be finalized during a third meeting (3 days, spring 2025). Between ISSI meetings, regular online meetings of task related sub-groups will be organized.

Key outcomes:

- GloSSAC evaluation report with publication in peer reviewed literature.
- Report and peer reviewed perspectives type article on continuity, opportunities, risks and upgrades of the GloSSAC dataset.
- White paper on observational needs and strategies to address uncertainties and knowledge gaps related to stratospheric aerosols and their representation in climate models.

Facilities and financial support required

We request ISSI to cover the living costs of all 11 team members while residing in Bern during two 3-day meetings and one additional similar meeting that consists of 7-8 core members at the end of the project. Including travelling time to Bern, the average per diem is required for 4 days for each meeting (1^{st} meeting: 44 person-days, 2^{nd} meeting: 44 person-days, 3^{rd} meeting: 28-32 person-days). With a total of 116-120 requested person-days, we stay below the proscribed guidelines of 24 person-weeks (120 person-days). In addition, we would like to request ISSI to cover per diem for 2-3 ECRs, which we would like to add to our team. We expect some additional travel support to come from some participant's home institutions to enable participation in meetings at the Bern ISSI facility. We may ask up to 2 experts (e.g. future space-borne instrument PIs) to join the meeting additionally on their own costs. An additional small room for break out groups at the end of each day, for specific discussions would be appreciated.

References Part A (see also Appendix of Part B): Aubry et al. (2020) *https://doi.org/10.1029/2019JD031303*; Bourassa et al (2023) *https://doi.org/10.1029/2022GL101978;* Brabec et al. (2012) *https://doi.org/10.5194/acp-12-9135-2012*; Gao et al. (2016) *https://doi.org/10.1080/02786826.2015.1131809*; Höpfner et al. (2019) *https://doi.org/10.1038/s41561-019-0385-8*; Kalnajs & Deshler (2022) *https://doi.org/10.1029/2022JD037485*; Kovilakam et al. (2020) *https://doi.org/10.5194/essd-12-2607-2020*; Kremser et al. (2016) *https://doi.org/10.1002/2015RG000511*; Quaglia et al. (2023) *https://doi.org/10.5194/acp-23-921-2023*; Renard et al. (2016) *https://doi.org/10.5194/amt-9-3673-2016*; Smith (2020) *https://ueaeprints.uea.ac.uk/id/eprint/77983/* ; Taha et al. (2021) *https://doi.org/10.5194/amt-14-1015-2021*; Thomason et al. (2018) *https://doi.org/10.5194/essd-10-469-2018* ; Timmreck et al. (2018) *https://doi.org/10.5194/gmd-11-2581-2018*; Vernier et al. (2011) *https://doi.org/10.1029/2010GL046614*