SPARC

Stratosphere-troposphere Processes And their Role in Climate

Newsletter n° 58
January 2022

www.sparc-climate.org

Polar stratospheric clouds formed over Scotland. They form in the winter polar stratosphere at altitudes of arround 15 - 20 km and are known to play a key role in ozone destruction. The SPARC Polar Stratospheric Cloud Initiative (PSCi) summarized their activity highlights from the past seven years.(article on page 6).

Image credit: Kit Carruthers (CC BY-NC 2.0).

Contents

WCRP World Climate Research Programme

World Meteorological Organization

United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

International Science Council

News from the SPARC IPO

Stefanie Kremser[1] and Sabrina Zechlau[2]

[1] Bodeker Scientific, Alexandra, New Zealand; [2] SPARC Office, DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

Now that an agreement between WCRP and DLR to host the SPARC international project office (IPO) has been signed, DLR will continue to host the IPO until the end of 2023. The new project scientist, Sabrina Zechlau, joined the IPO (part-time) in August 2021. At the same time, Stefanie Kremser joined the team as a stand-in (part-time) for Mareike Heckl while she is on parental leave. Both Sabrina and Stefanie are settling into their new roles and look forward to supporting the SPARC co-chairs, scientific steering group (SSG), and the many SPARC activities underway.

A focus for the IPO over the coming months will be finalising the new SPARC strategy (led by Amanda Maycock) and organising the next SPARC General Assembly (GA; led by Andrew Charlton-Perez) which will take place in October 2022 (Figure 1). The organisation of the GA is in full swing with a call for abstracts expected to be sent out in Feb 2022. To ensure a smooth execution of the GA, Andrew and the IPO staff will be supported by the local organising committees of the three regional hubs.

The new SPARC strategy will outline a new structure for SPARC, partly in response to the renewed priorities of WCRP, but also to enable SPARC to be more agile in an increasingly rapidly shifting scientific landscape. While the SPARC co-chairs and steering group will provide overall leadership, they will now be supported by advisory panels, providing enhanced connectivity and greater oversight of the impact of SPARC's work. Current and new SPARC activities will be grouped into Research Advisory Panels (RAPs) with the goal of enhancing collaboration and communication between activities and enabling more coordinated SPARC science to be done. The new SPARC strategy will be presented at the next JSC meeting.

We would like to take the opportunity to thank the co-chairs, SSG members and activity leads for their patience and support, while we are settling into our new roles at the SPARC office. We look forward to working with you all over the next months.

***Figure 1:** Advert of the SPARC General Assembly, taking place at three hubs.*

Personal reflections on the outlook for SPARC

The past few months have seen the publication of the IPCC WGI Sixth Assessment Report on the state of scientific knowledge of climate change. While awaiting the companion reports on adaptation and mitigation, the world's nations have already started to tackle climate change. During COP-26, countries made several new commitments including reductions in the use of coal power and cuts in methane emissions. These developments reflect the growing concerns of climate change worldwide. Whatever way you look at such an outcome, it is clear that substantial efforts are still required to both mitigate and adapt to climate change.

As the urgency for climate information increases, SPARC needs to be ready to provide new insights and updated information on climate change to many groups. Especially there may well be more demand for high-quality climate information from regional, national and sub-national governments and other organisations. It may include a dynamical attribution of extreme events, sub-seasonal-to-decadal climate prediction, and climate intervention.

Scientific knowledge of chemical, dynamical and physical processes in the whole atmosphere is going to be central for the development of firmly-based mitigation and adaptation policies to climate change. The science required for this is at the heart of SPARC - Stratosphere-troposphere Processes And their Role in Climate. We think our new research strategy means we are ready for that challenge and we strongly encourage the scientific community to get behind it and give it new energy and momentum. While SPARC's core role is research, we collectively need to ensure excellence in both research and in the translation of that into valuable scientific information and advice. Such efforts are in line with the lighthouse activities and the new core programs of WCRP.

To better address regional climate issues and improve regional representation, SPARC is moving to a three co-chair model with two new co-chairs, Amanda Maycock and Karen Rosenlof. Neil Harris is stepping down (see below). More emphasis is being placed on having a regionally representative steering group. Together, these changes should help strength regional communities as well as make joining meetings with partner organisations more straightforward. Organising our internal meetings is becoming more challenging – the inevitable result of becoming truly global.

Finally, the SPARC Office is starting to assess the carbon footprint associated with SPARC meetings. The idea is to develop an understanding of our current activities (current – pre-COVID!!) to act as a benchmark for future comparison and to provide guidance on how to set priorities and targets. If the SPARC Office starts asking for more information as travel starts, please help them out. The General Assembly with its 3-hub model should be an excellent start on this road.


Seok-Woo Son and Neil Harris,
SPARC co-chairs

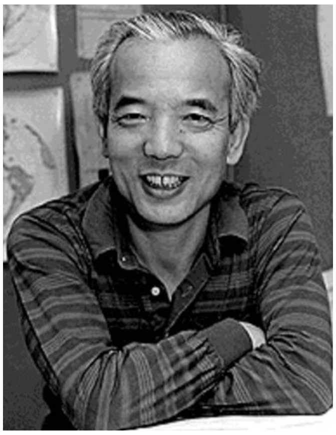
PS from Neil

As I prepare to step down from my role as co-chair after seven and a bit years, I would like to personally thank my three co-chairs (Joan Alexander, Judith Perlwitz and Seok-Woo Son) for their patience and enthusiasm over the years. It has been a tricky time in many ways and working with them has made it rewarding as well as fun. The SPARC Office in both its Zurich and Oberpfaffenhofen incarnations (and now New Zealand branch office) deserves particular mention for their truly devoted work to supporting the SPARC community as well as their patience and good humour. Most of all though, I would like to acknowledge all the friends and colleagues I have met through SPARC. It is a remarkable organisation for that: if you are new and unsure, do not assume that everything is set in stone just because it has existed for 30 years. It isn't and SPARC responds really well to new ideas and energy.

Syukuro Manabe's Pioneering Contributions to Stratospheric Science

Kevin Hamilton

International Pacific Research Center, University of Hawaii, USA.



Syukuro Manabe, Princeton University, Princeton, NJ, USA

Syukuro "Suki" Manabe shared the 2021 Nobel Prize in Physics (www.nobelprize.org/prizes/physics/2021) "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming". This award is both an exciting public recognition for Manabe's seminal personal contributions and an acknowledgment of the importance and intellectual standing of the field of global climate modelling which he helped found. Here I take this opportunity to briefly review aspects of Manabe's early work that have a particular relevance to SPARC science, notably his pioneering efforts in modelling stratospheric circulation and composition.

In 1956, following promising results by researchers with models using simplified governing equations, Joe Smagorinsky at the US Weather Bureau (USWB) began constructing a code to numerically integrate the dry, primitive equations on a hemisphere. He initially concentrated on a two-level discretization and this first version of what would become the Geophysical Fluid Dynamics Laboratory (GFDL) atmospheric general circulation model (AGCM) was described in Smagorinsky (1963). This USWB (later GFDL) effort had early competitors (Hamilton, 2020), but would lead the world in pioneering global atmospheric modeling (Smagorinsky, 1983).

In 1958 Manabe, then a new University of Tokyo Ph.D. graduate, moved to the USWB to work on the numerical simulation project. He led the enhancement of the dry model to include radiative transfer and representations of the hydrological cycle and related land surface processes. This resulted in the Manabe *et al.* (1965) paper which established Manabe as the leading scientist, and GFDL as the leading research center, in the new field of global atmospheric modeling. The 1965 paper describes a model discretized in the vertical on 9 levels with the top two levels at about 74 and 9 hPa, which was run for 6 months with annual mean solar radiative forcing and prescribed climatological ozone concentrations. No topography was included and a "swamp" lower boundary was adopted (i.e. the surface is wet land with zero heat capacity). Manabe *et al.* (1965) were primarily interested in the lower atmosphere but they did briefly show that their model simulated a somewhat reasonable temperature and humidity structure in the marginally-resolved lower stratosphere. The pioneering nature of this work is apparent in Manabe's recollection in a 2005 interview that "..we didn't know if we could couple successfully radiative transfer together into a 3D model[…] whether we get a stratosphere" (Speidel, 2005).

About 1966 a young scientist from the Australian Weapons Research Establishment, Barrie Hunt, proposed in an unsolicited letter to have an extended visit at GFDL to research modeling of stratospheric ozone. Hunt had recently written a paper "The Need for a Modified Photochemical Theory of the Ozonosphere" (Hunt, 1966) suggesting that the simple Chapman chemistry by itself would lead to unrealistically large stratospheric ozone concentrations. Manabe liked the proposal and collaborated with Hunt, first on producing a version of the GFDL AGCM with enhanced resolution of the stratosphere (18 levels including ~185, 142, 117, 91, 69, 51, 36, 23, 13, and 4 hPa) which they referred to as a "stratospheric general circulation model". The model was forced with annual mean solar radiation and the results of a 9 month integration are reported in Manabe and Hunt (1968). The model was then used to simulate the evolution of idealized conservative tracers (Hunt and Manabe, 1968). Their results showed that the tracer field evolution was driven by both a large-scale overturning and by quasi-horizontal eddy transports that usually produce downgradient fluxes. Hunt and Manabe demonstrated that a tracer field which was initialized with a simple vertical stratification evolved in 6 months to one that resembles the observed distribution of ozone mixing ratio.

Continuing his work at GFDL, Hunt then applied this AGCM to simulations of ozone in two versions, one "based on photochemistry in an oxygen-only atmosphere, the other on photochemistry in an oxygen-hydrogen atmosphere" (Hunt, 1969). Hunt concluded that "substantial qualitative agreement was obtained with observation, particularly as regards the accumulation of ozone in the lower stratosphere at extratropical latitudes. The results also suggest that photochemistry for an oxygen-hydrogen atmosphere may be the more applicable to the actual atmosphere." This pioneering work on catalytic ozone destruction soon became very relevant when the issue of the environmental effects of stratospheric operation of supersonic aircraft arose (Halaby, 1970).

After Hunt returned to Australia, Manabe was still very interested in stratospheric dynamics and composition, relating in an interview, by Stouffer (2007), that "I saw the stratosphere had so many interesting features. [It was] one of the fascinating problems." By 1970 Manabe had taken the first steps in the initiation of two novel projects related to stratospheric research. He had run a full year of a global version of his most recent AGCM code with 11 levels (up to ~10 hPa) and including full seasonal variation, as well as a realistic topography and land-sea distribution. He saved the detailed wind fields from this integration with the aim of producing an offline global transport model to study atmospheric chemistry. Manabe had also begun coding what he called the "skeleton" of a version of his AGCM (Stouffer, 2007) with domain extending to the mesopause and greatly enhanced vertical resolution, which later was developed into the GFDL "SKYHI" AGCM. In 1970 GFDL hired Jerry Mahlman, followed soon by Steve Fels and Hiram Levy who would all play important roles in these two new initiatives.

Manabe and Mahlman (1976) published a paper on the stratospheric dynamics aspects of the 11-level model simulation. They note that their model "qualitatively reproduces the seasonal reversals of zonal wind direction in the mid-stratosphere between westerlies in winter and the zonal easterlies prevailing during the summer season. In the mid-latitude region of the lower model stratosphere, zonal mean temperature is highest in the winter when solar radiation is weak". They acknowledged significant deficiencies as well, including an overly strong polar night vortex and a lack of sudden stratospheric warmings and the tropical quasibiennial oscillation. Important papers followed on the SKYHI model (e.g., Fels *et al.*, 1980) and the offline transport model (e.g., Levy *et al.*, 1979). The key contribution of these GFDL projects, initiated by Manabe, was acknowledged by the American Meteorological Society with the award of the 1994 Rossby Medal to Mahlman "for pioneering work in the application of general circulation models to the understanding of stratospheric dynamics and transport".

Figure 2: *Nobel Prize Medal © The Nobel Prize Medal is a registered trademark of the Nobel Foundation.*

Suki Manabe's career began when many even quite basic aspects of the dynamics of the global atmosphere were poorly understood and has continued to the present day when mankind has been provided with powerful tools for quantitative prediction of the climate system. An important component of this spectacular progress was the pioneering work on stratospheric modelling by Manabe and his close colleagues at GFDL.

References

Fels, S. *et al.*, 1980: Stratospheric sensitivity to perturbations in ozone and carbon dioxide: Radiative and dynamical response. *Journal of the Atmospheric Sciences*, 37(10), 2265-2297.

Halaby, N. 1970: Environment: SST: Boon or Boondoggle?, *Time*

Hamilton K., 2020: At the dawn of global climate modeling: the strange case of the Leith atmosphere model, *History of Geo- and Space Sciences*, 11, 93-103.

Hunt, B. G., 1966: The Need for a Modified Photochemical Theory of the Ozonosphere. *Journal of the Atmospheric Sciences*, 23(1), 88- 95.

Hunt, B. G., 1969: Experiments with a Stratospheric General Circulation Model III. Large-Scale Diffusion of Ozone Including Photochemestry. *Monthly Weather Review*, 97(4), 287- 306.

Hunt, B. G. and S. Manabe, 1968: Experiments with a stratospheric general circulation model: II. Large-scale diffusion of tracers in the stratosphere. *Monthly Weather Review*, 96(8), 503-539.

Levy *et al.*, 1979: Preliminary report on the numerical simulation of the three-dimensional structure and variability of atmospheric N_2O. *Geophysical Research Letters*, 6(3), 155-158.

Manabe, S., et al.. 1965: Simulated climatology of a General Circulation Model with a hydrologic cycle. *Monthly Weather Review*, 93(12), 769-798.

Manabe, S. and B. G. Hunt, 1968: Experiments with a stratospheric general circulation model: I. Radiative and dynamical aspects. *Monthly Weather Review*, 96(8), 477-502.

Manabe, S. and J. D. Mahlman, 1976: Simulation of seasonal and interhemispheric variations in the stratospheric circulation. *Journal of the Atmospheric Sciences*, 33(11), 2185-2217.

Nobel Prize Website, 2022: https://www.nobelprize.org/prizes/physics/2021/summary/.

Smagorinsky, J., 1963: General Circulation Experiments with the Primitive Equations, *Monthly Weather Review*, 91(3), 99-164.

Smagorinsky, J., 1983: The Beginnings of Numerical Weather Prediction and General Circulation Modeling: Early Recollections, *Advances in Geophysics*, 25, 3-37.

Speidel, G., 2005: "Suki" Manabe Pioneer of Climate Modeling. *Newsletter of the International Pacific Research Center*. 5(2), 11- 15

Stouffer, R., 2007: Transcript of Oral History Interview of Syukuro Manabe, *Tape Recorded Interview Project (AMS)*.

The SPARC Polar Stratospheric Cloud Initiative (PSCi)

Ines Tritscher[1], Michael C. Pitts[2], Lamont R. Poole[3], and Thomas Peter[4]

[1]Forschungszentrum Jülich, Germany (**i.tritscher@fz-juelich.de**); [2]NASA Langley Research Center, USA; [3]Science Systems and Applications, Incorporated, USA; [4]ETH Zürich, Switzerland.

An open access article by Tritscher *et al.* published in June 2021 in Reviews of Geophysics concluded the work of a SPARC activity on polar stratospheric clouds (PSCs). The article, which involves 17 authors, is titled "Polar Stratospheric Clouds: Satellite Observations, Processes, and Role in Ozone Depletion."

Initial discussions about starting a new PSC activity under the SPARC umbrella were held at the 5th SPARC General Assembly in Queenstown, New Zealand, in January 2014. To gauge the interest of the broader community in such an activity, a first PSC workshop was organized at ETH Zurich, Switzerland, in August 2014. More than 40 scientists attended the workshop, with presentations and discussions of new spaceborne PSC observations and modeling results, as well as the identification of key advances and remaining gaps in our understanding of PSC processes. One scientific highlight was the recent discovery of nitric acid trihydrate (NAT) PSCs on synoptic scales, whose existence could not be explained by known NAT nucleation mechanisms involving ice. The participants concluded that a new SPARC PSC activity would be a timely and effective means for collecting, synthesizing, and reporting these new findings.

The SPARC PSC initiative (PSCi) started in 2015 and successfully applied for support as an international team activity to the International Space Science Institute (ISSI) in Bern, Switzerland. Three week-long workshops hosted by ISSI in 2015, 2016, and 2017 facilitated intensive and productive discussions among all attendees. Several individual PSC publications (Lambert *et al.*, 2016; Spang *et al.*, 2016, 2018; Grooß *et al.*, 2018; Höpfner *et al.*, 2018; Pitts *et al.*, 2018; Tritscher *et al.*, 2019; Snels *et al.*, 2019, 2021) were triggered by work within PSCi and published by activity team members. The 2021 comprehensive review paper represents the overall outcome of the SPARC activity.

Motivation for a summary of PSC science

The overall role of PSCs in the depletion of stratospheric ozone is well established. Heterogeneous reactions on PSCs convert the stable chlorine reservoirs HCl and $ClONO_2$ to chlorine radicals that destroy ozone catalytically. The rates of these reactions depend on particle surface area densities and compositions, i.e. whether they are binary sulfuric acid aerosols (H_2SO_4/H_2O, SSA) or supercooled ternary solution ($HNO_3/H_2SO_4/H_2O$, STS) droplets, solid NAT crystals, or H_2O ice crystals. PSCs also remove HNO_3 from the polar stratosphere via the formation and sedimentation of large NAT particles (denitrification), a process that enhances ozone depletion by delaying the re-formation of stable chlorine reservoir species. Despite this clear understanding of the role of PSCs in ozone loss and more than three decades of research, some details of PSC processes are still not fully understood, such as how NAT particles form, grow, and sediment, leading to the denitrification required for sustained ozone loss. While ozone is expected to globally recover to pre-1980 levels over the next 50 years, reliable projections of ozone recovery in polar regions remain challenging. This is due to both a lack of detailed understanding of the feedback process between ozone chemistry and atmospheric dynamics, which may be altered by climate change, and inaccurate representations of critical PSC processes in global chemistry-climate models (CCMs).

In the past, a limiting factor in understanding PSC processes was the sparse observational record, consisting primarily of long-term, but spatially limited remote sensing measurements from solar occultation satellites and ground-based lidars, supplemented by data from occasional intensive, but highly localized field campaigns. The observational database has expanded greatly over the past two decades with data from three satellite instruments with measurements covering nearly the entire polar regions: (i) the Michelson Interferometer for

Passive Atmospheric Sounding (MIPAS) on Envisat (2002-2012), (ii) the Microwave Limb Sounder (MLS) on Aura (2004-present), and (iii) the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations, 2006-present). These satellite instruments provide information on PSC occurrence and composition, as well as relevant gas species on unprecedented polar vortex-wide scales. They have been complemented by continuing ground-based lidar observations and by in situ measurements obtained during several focused airborne campaigns in the Arctic. Together, these data sets have ushered in a new era in PSC research that has advanced both our knowledge of PSC processes and our capability to represent these processes in global models.

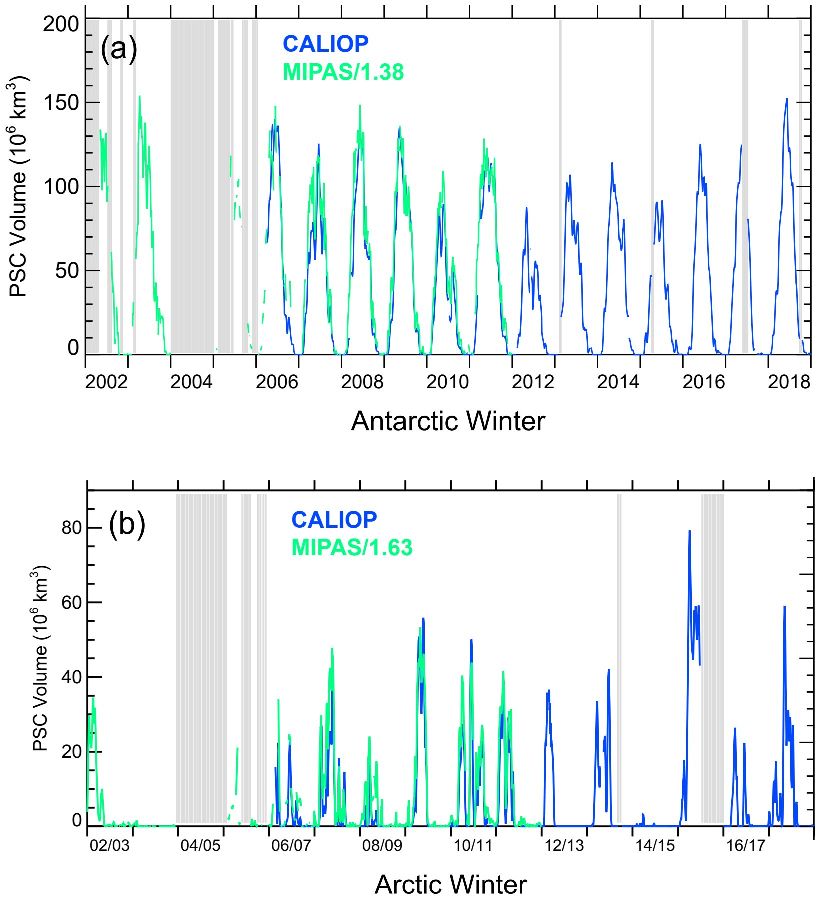


Figure 3: *CALIOP and scaled MIPAS daily PSC volumes for 2002–2018 for (a) Antarctic, May-September and (b) Arctic, December-March. Light gray vertical stripes indicate periods with no data. Note the different scales in (a) and (b). (Figure from Tritscher et al., (2021))*

Elements of the review

The Reviews of Geophysics paper starts with a comprehensive historical overview of PSC observations and their evolving relevance in polar ozone chemistry. The focus of the paper deals extensively with data from MIPAS, MLS, and CALIOP and the resulting better understanding of PSC distributions and composition. It details our understanding of nucleation pathways of solid PSC particles, where significant progress has been made concerning heterogeneous nucleation processes. The paper also includes a review of the dynamical forcing of PSCs on different spatial scales, highlighting how small-scale dynamical motions contribute to overcoming nucleation barriers for the formation of solid PSC particles, which strongly affects particle number densities and sizes, thus the properties of the nascent PSCs. Furthermore, it reviews our present understanding of heterogeneous chemistry, denitrification, and dehydration by PSCs and their effect on ozone, highlighting the differences between the Arctic and Antarctic polar vortices. Finally, the paper describes how PSCs are implemented in present-day chemical transport models (CTMs) and CCMs, distinguishing between explicitly resolved and parameterized cloud processes.

Highlights

PSC Spatial and Temporal Distributions and Composition

PSCi analyzed the impressive vortex-wide data records of PSCs in both hemispheres obtained from MIPAS, MLS, and CALIOP, which provide fundamentally different, but complementary information about PSC composition.

- CALIOP and MIPAS multi-year records show consistent PSC spatial coverage when the MIPAS data are downscaled to account for PSC patchiness over the large MIPAS field of view (Figure 3). For spatially homogeneous cloud scenes, there is general consistency between MIPAS and CALIOP in the major PSC composition classes.

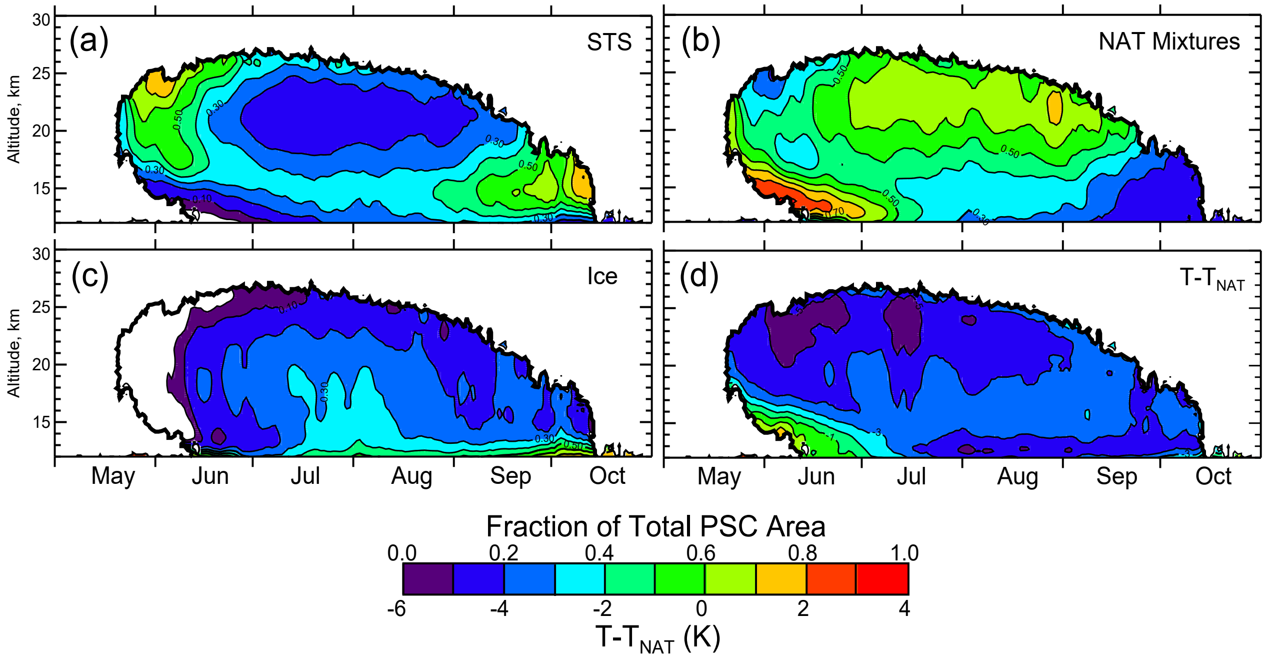


Figure 4: *Thirteen year (2006–2018) average CALIOP Antarctic fractional spatial coverage for (a) STS; (b) NAT mixtures, including enhanced NAT mixtures; and (c) ice, including wave ice. Thick black line: PSCs in at least 6 of the 13 Antarctic seasons. White region in (c): no ice occurrence detected. Panel (d) shows 2006–2018 mean distribution of $T–T_{NAT}$ (Figure from Tritscher et al., (2021))*

- PSC spatial volume is similar from year-to-year in the Antarctic and is typically much larger than in the Arctic, where each year is unique.
- General consistency was found between CALIOP PSC occurrence frequency and data obtained from ground-based lidar stations at McMurdo and Dumont d'Urville (Antarctica) and Ny-Ålesund (Arctic).
- During each winter, PSC composition varies with time, altitude, and spatial position in response to changes in temperature and changes in HNO_3 and H_2O due to denitrification and dehydration. Figure 4 shows the 13-year (2006-2018) average seasonal variation of PSC composition in the Antarctic shown by CALIOP.
- CALIOP and MLS data reveal that the temperature-dependent uptake of HNO_3 in NAT mixture PSCs is bimodal in nature. There is one mode near the NAT equilibrium temperature (T_{NAT}) for long exposure times to temperatures below T_{NAT}, and another mode near the STS equilibrium temperature (T_{STS}) for short exposure times and kinetically limited HNO_3 uptake on NAT.
- Over decadal timescales, Antarctic PSC coverage is very similar between the CALIOP (2006–2017) and SAM (Stratospheric Aerosol Measurement) II (1979–1989) observations. However, there is systematic increase in Arctic PSC occurrence in December and January being observed, in response, in part, to early winter cooling related to climate change.

Formation Pathways and Particle Characteristics

The availability of vortex-wide PSC data has led to significant advances in our understanding of PSC formation processes and particle characteristics. An illustration of PSC formation pathways emerging from recent studies is provided by Figure 5.

- There is compelling evidence for widespread heterogeneous nucleation of NAT above T_{ice} based on spaceborne lidar observations, confirming earlier limited observations pointing in this direction (Pathway 2).
- Heterogeneous nucleation of NAT on foreign nuclei (perhaps of meteoric origin) is slow, leading to low number densities of very large NAT particles. These particles sediment readily and are observed vortex-wide, thus producing efficient denitrification.
- Ice-induced NAT nucleation is well-characterized, but requires very low temperatures, which in the Arctic are typically only reached in mountain waves. This NAT nucleation mechanism typically leads to dense clouds of small NAT particles, which move through the vortex and may release individual larger, denitrifying particles (Pathway 6).

- There is evidence that ice PSCs form not only homogeneously (Pathway 5), but also via heterogeneous nucleation (Pathway 4).
- Airborne and spaceborne spectroscopic measurements indicate that NAT particles may be highly aspherical, which can possibly explain heretofore unreconcilable in situ measurements of the largest NAT particles.

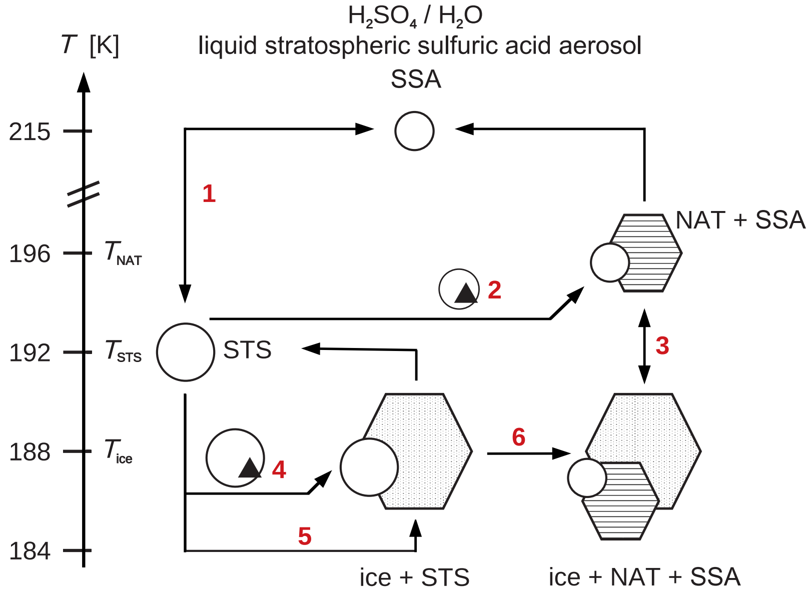


Figure 5: *Schematic description of different PSC formation pathways reflecting the current state of scientific understanding. Circles: liquid droplets; hexagons: NAT or ice crystals; black triangles: solid nuclei (e.g., meteoritic). PSC particle compositions observed in the atmosphere include SSA, STS, NAT, and ice. Aerosol droplets that contain a foreign nucleus are symbolized with a triangle surrounded by a circle. The temperatures indicated for T_{STS}, T_{ice} and T_{NAT} are approximate, reflecting typical polar stratospheric conditions. Red numbers describe PSC formation pathways: (1) growth of STS droplets; (2) heterogeneous NAT nucleation on foreign nuclei; (3) heterogeneous ice nucleation on preexisting NAT particles; (4) heterogeneous ice nucleation on foreign nuclei; (5) homogeneous ice nucleation; (6) heterogeneous NAT nucleation on preexisting ice; in detail. Note that some arrows are unidirectional (i.e., the opposite direction is kinetically blocked), while others are bidirectional. (Figure from Tritscher et al., (2021))*

Dynamical Forcing of PSCs

The cooling of the polar winter stratosphere may result in widespread PSC occurrence once synoptic-scale temperatures decrease to that required for their formation. Local-scale dynamical processes can also result in an increase in PSC formation and occurrence by enabling small-scale temperatures to fall below their formation threshold values even when the synoptic-scale temperatures remain too high. The PSCs formed by these small-scale dynamical processes may then be advected far downstream of their formation regions.

- Antarctic year-to-year variability of synoptic scale dynamical forcing of PSCs is relatively small. In the Arctic, synoptic scale forcing varies dramatically from year to year with PSC occurrence ranging from negligible to an abundance comparable to that of warmer Antarctic winters.
- As has been recognized for some time, PSCs can be formed in the cool phases of mountain (and non-orographic) waves that propagate into the stratosphere, which are mostly unresolved by current global models. Mountain wave forcing of PSCs is particularly important where synoptic-scale temperatures are near the PSC existence threshold, such as at the start of the PSC season and close to the edge of the stratospheric vortex.
- Mesoscale and global atmospheric models, as well as reanalyses, have improved over the last two decades in resolving mountain waves (Figure 6). Non-orographic waves may also act as a source of PSCs, affecting the number density of nucleated ice particles and hence PSC structure. Increased efforts are therefore required to develop accurate parameterizations to account for the temperature fluctuations induced by unresolved waves.

Heterogeneous Chemistry, Denitrification, and Dehydration by PSCs

Although the general role of PSCs in polar ozone depletion has been well established for decades, our understanding of the details continues to evolve.

- Heterogeneous chlorine activation takes place under most conditions on/in liquid SSA/STS droplets, and much less on NAT or ice particles.

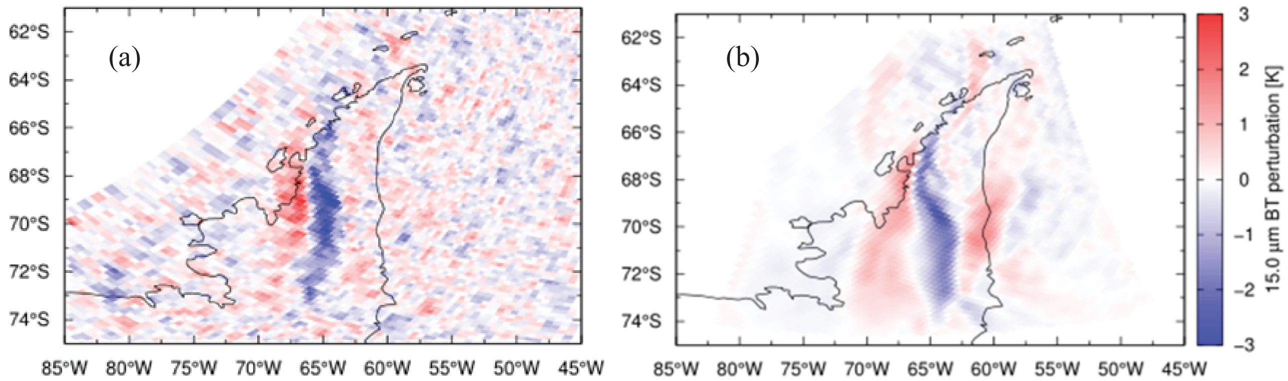


Figure 6: *Measured (a) and mesoscale modeled (b) estimates of the 15 µm brightness temperature perturbations (units K) over the Antarctic Peninsula corresponding to the 666.5 cm^{-1} AIRS (Atmospheric InfraRed Sounder) channel. (Figure from Tritscher et al., (2021))*

- Extensive chemical loss of polar O_3 in both hemispheres is always accompanied by extensive denitrification. This is evidence for a selective NAT nucleation mechanism, resulting in NAT number densities suitable for denitrification.

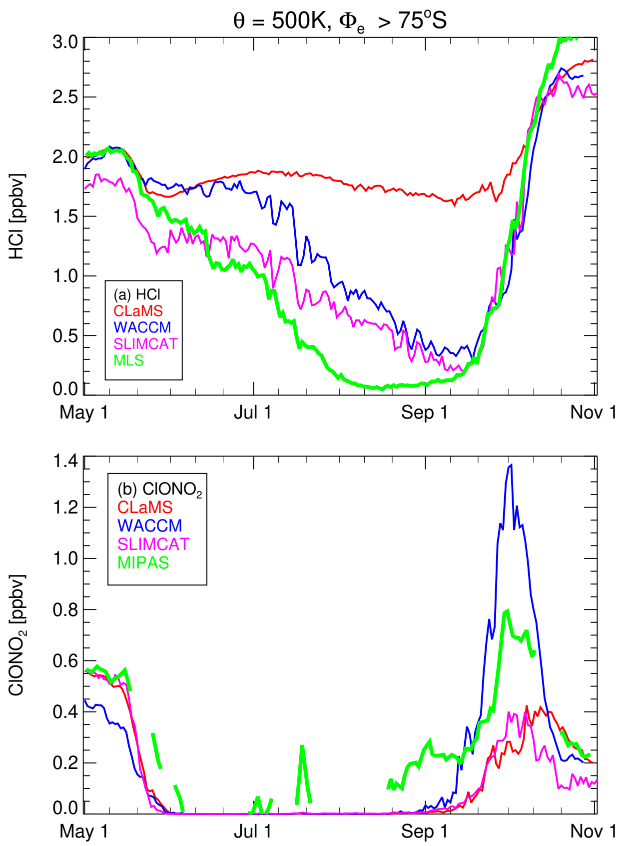


Figure 7: *Seasonal evolution of chlorine reservoir species in the lower stratosphere inside the 2011 Antarctic vortex. Panels show vortex-core averages (>75°S) on the 500 K isentrope for (a) HCl and (b) $ClONO_2$ for different model simulations and satellite measurements. Green lines: observations by MLS and MIPAS. Red lines: CLaMS Lagrangian trajectory model. Blue lines: SD-WACCM global Eulerian model simulations with horizontal resolution of 1.2°. Magenta lines: TOMCAT/SLIMCAT CTM with horizontal resolution of 1.2°.*

- The rapidity of the loss of HCl and $ClONO_2$ and the production of ClO and associated other active chlorine species at temperatures below ~195 K has been confirmed by satellite and in situ observations in both hemispheres.
- Models appear to systematically overestimate HCl inside the Antarctic vortex in early winter (Figure 7). This may suggest yet another PSC-related chemical process that results in HCl loss in the dark winter polar vortex. However, this likely has only a minor impact on the total ozone depletion during a winter/spring season.

Parameterizations of PSCs in Global Models

There have been notable advances in the ability of CTMs and CCMs to reproduce PSC temporal/spatial distributions and composition observed from space. For example, Figure 8 illustrates the excellent agreement between the PSC composition classification by CALIOP along one orbit track on 18 January 2010 and the corresponding model result by the CTM CLaMS (Chemical Lagrangian Model of the Stratosphere).

- Free-running CCMs often show significant synoptic-scale temperature biases and miss local temperature fluctuations, which results in misrepresentations of PSCs and PSC-related processes. However, these model deficiencies are often mitigated by the fact that chlorine activation is limited by the available reactants and not by the details of the PSC-catalyzed heterogeneous chemistry.
- A detailed PSC scheme is necessary for the simulation of PSCs and their impact when temperatures are barely low enough for PSC for-

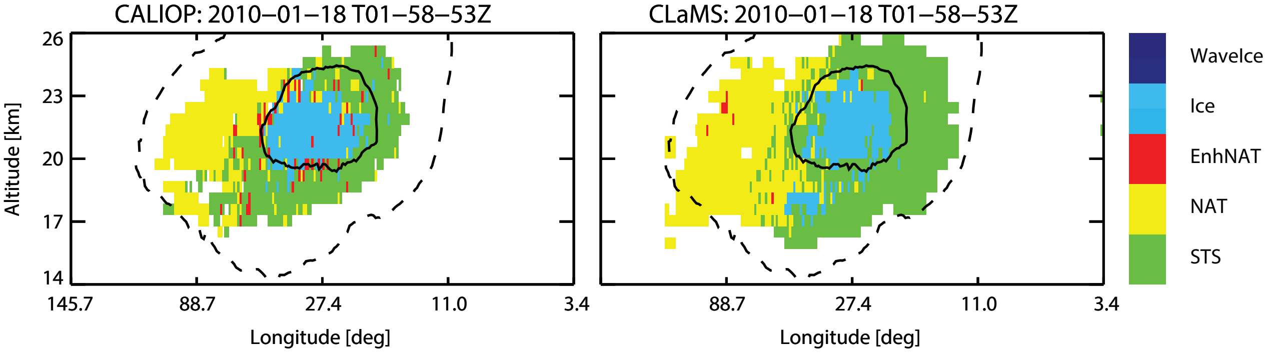


***Figure 8:** PSC classification derived from CALIOP for a single satellite orbit between latitudes 60°N–82°N on 18 January 2010 (left) and corresponding simulation by CLaMS (right). The solid and dashed lines in the panels enclose the regions with temperatures below T_{ic_e} and T_{NAT}, respectively. (Figure from Tritscher et al., (2021))*

mation. These conditions typically occur at the beginning/end of the PSC season or at the geographical edges of activated regions, and hence are more relevant in the Arctic than the Antarctic winter stratosphere.

Concluding remarks

The 2021 Reviews of Geophysics on PSCs summarized the present knowledge on understanding of these clouds. This review is a valuable addition to the series of topical reports and review papers sponsored by SPARC to date.

Acknowledgements

We are thankful to the SPARC office and SPARC leadership for their continuing support. We would like to thank all co-authors and PSCi members: Simon P. Alexander, Francesco Cairo, Martyn P. Chipperfield, Jens-Uwe Grooß, Michael Höpfner, Alyn Lambert, Beiping Luo, Sergey Molleker, Andrew Orr, Ross Salawitch, Marcel Snels, Reinhold Spang, and Wolfgang Woiwode. This work could not have been performed without the tremendous effort they have put into this group project.

References

Grooß, J.-U., *et al.*, 2018: On the discrepancy of HCl processing in the core of the wintertime polar vortices, *Atmos. Chem. Phys.*, 18, 8647-8666.

Höpfner, M., *et al.*, 2018: The MIPAS/Envisat climatology (2002–2012) of polar stratospheric cloud volume density profiles, *Atmos. Meas. Tech.*, 11, 5901-5923.

Lambert, A., Santee, M. L., and N. J. Livesey, 2016: Interannual variations of early winter Antarctic polar stratospheric cloud formation and nitric acid observed by CALIOP and MLS, *Atmos. Chem. Phys.*, 16, 15219-15246.

Pitts, M. C., Poole, L. R., and R. Gonzalez, 2018: Polar stratospheric cloud climatology based on CALIPSO spaceborne lidar measurements from 2006 to 2017, *Atmos. Chem. Phys.*, 18, 10881-10913.

Snels, M., *et al.*, 2021: Quasi-coincident observations of polar stratospheric clouds by ground-based lidar and CALIOP at Concordia (Dome C, Antarctica) from 2014 to 2018, *Atmos. Chem. Phys.*, 21, 2165–2178.

Snels, M., *et al.*, 2019: Comparison of Antarctic polar stratospheric cloud observations by ground-based and space-borne lidar and relevance for chemistry–climate models, *Atmos. Chem. Phys.*, 19, 955-972.

Spang, R., *et al.*, 2016: A multi-wavelength classification method for polar stratospheric cloud types using infrared limb spectra, *Atmos. Meas. Tech.*, 9, 3619-3639.

Spang, R., *et al.*, 2018: A climatology of polar stratospheric cloud composition between 2002 and 2012 based on MIPAS/Envisat observations, *Atmos. Chem. Phys.*, 18, 5089-5113.

Tritscher, I., *et al.*, 2019: Lagrangian simulation of ice particles and resulting dehydration in the polar winter stratosphere, *Atmos. Chem. Phys.*, 19, 543-563.

Tritscher, I., *et al.*, 2021: Polar stratospheric clouds: Satellite observations, processes, and role in ozone depletion. *Rev. Geophys.*, 59, e2020RG000702.

S-RIP Final Report Published

Masatomo Fujiwara[1], Gloria L. Manney[2, 3], Lesley J. Gray[4, 5], and Jonathon S. Wright[6]

[1]Hokkaido University, Japan (**fuji@ees.hokudai.ac.jp**); [2]NorthWest Research Associates, USA; [3]New Mexico Institute of Mining and Technology, USA; [4]University of Oxford, UK; [5]NERC National Centre for Atmospheric Science, UK; [6]Tsinghua University, China

The SPARC Reanalysis Intercomparison Project (S-RIP) has published its final report in January 2022 (SPARC, 2022). Several global atmospheric reanalysis data sets (Table 1) are extensively evaluated for selected diagnostics and regions in which SPARC researchers have strong interests (Figure 9, Table 2). The report is expected to be a valuable resource for anyone using reanalysis datasets in their research.

***Table 1:** Global atmospheric reanalysis data sets available as of July 2018. See SPARC (2022) for the abbreviations. (Taken from Table 1.1 of SPARC (2022).)*

Reanalysis Centre	Name of Reanalysis Product
ECMWF	ERA-40, ERA-Interim, ERA20C, CERA-20C, ERA5[1]
JMA	JRA-25/JCDAS, JRA-55
NASA	MERRA, MERRA-2
NOAA/NCEP	NCEP-NCAR R1, NCEP-DOE R2, CFSR/CFSv2[2]
NOAA and Univ. Colorado	20CR

[1] Some ERA5 data have been available since July 2018, ERA5 data from 1979 onward have been available since January 2019, and a preliminary version of ERA5 1950-1978 data have been available since November 2020. Because most of the studies in the report were finalized before ERA5 was readily available, full evaluation of ERA5 has not been made. However, Chapter 2 includes information on the ERA5 system, and some chapters show some ERA5 results.

[2] CFSR is for the period from January 1979 to December 2010, and CFSv2 is for the period from January 2011 to present. We strongly recommend explicitly referring to the combination "CFSR/CFSv2" in documenting any study that uses these products across the 2010-2011 transition.

The report has 12 chapters with a total of >600 pages, including Chapter 1 for introduction, 2 for description of the reanalysis systems evaluated, 3–11 for the actual evaluations (Figure 9), and 12 for the synthesis summary. Please see Table 2 for the list of chapter titles and co-leads. Note that one PDF file per chapter is provided.

The detailed analyses in Chapters 3–11 result in several overarching findings and recommendations, including:

- More recent reanalyses typically outperform earlier products.
- NCEP-NCAR R1 and NCEP-DOE R2 are unsuitable for many diagnostics and should generally not be used.
- Conventional-input and pre-satellite reanalyses are useful for many diagnostics but should be carefully validated against full-input satellite era products.
- Studies relying on reanalysis products should use multiple reanalyses whenever possible
- All reanalyses show discontinuities; trends and climate shifts identified in reanalysis products

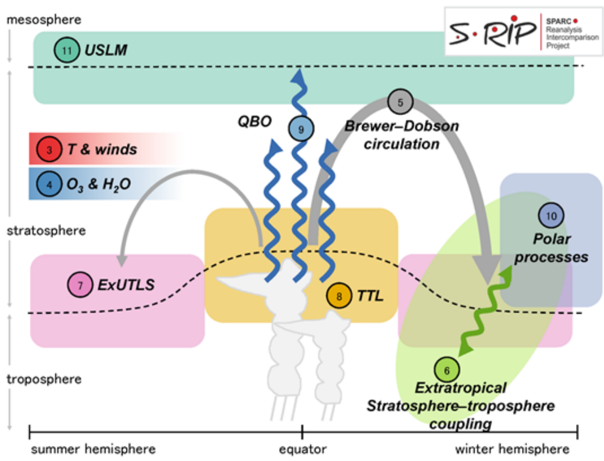


***Figure 9:** Schematic illustration of the atmosphere showing the processes and regions that are covered in the report SPARC (2022). The numbers are the chapter numbers. Domains approximate the main focus areas of each chapter and should not be interpreted as strict boundaries. Chapters 3 and 4 cover the entire domain. (Taken from Figure 1.1 of SPARC (2022).)*

should be carefully validated and justified.

- Reanalysis products on model levels should be used for all studies when sharp vertical gradients or fine-scale vertical features are involved.
- Homogenized and continuing data records are essential for reanalysis production and evaluation.

***Figure 10:** Photograph from the 2018 S-RIP chapter-lead meeting at NWRA at Boulder, USA. (Taken from Figure 1.5 of SPARC (2022).)*

In addition to the report there are currently over 50 associated papers published in a special inter-journal S-RIP issue of Atmospheric Chemistry and Physics (ACP) and Earth System Science Data (ESSD).

We would like to take this opportunity to say a huge 'thank you' to the many people who have contributed over the past 10 years. The Chapter Leads and Reanalysis Center Representatives were key to its success, together with the large number of contributors to individual chapters (please see S-RIP report for details of all those involved; Figure 10 shows most of the participants for the 2018 S-RIP chapter-lead meeting). We would also like to acknowledge the strong support of the reviewers, review editors, special issue editors, SPARC chairs, and the SPARC IPO without whom the report and special issue could not have been achieved.

A "Phase 2" of S-RIP is currently under discussion, to include a full evaluation of ERA5 and upcoming reanalyses such as JRA-3Q and MERRA-3. We would welcome ideas for new inter-comparison diagnostics and also proposals for new areas of interest, including those that cover tropospheric processes. New leadership at various levels will also be encouraged, so please contact us if you would like to be involved!

References

SPARC, 2022: SPARC Reanalysis Intercomparison Project (S-RIP) Final Report, edited by Masatomo Fujiwara, Gloria L. Manney, Lesley J. Gray, and Jonathon S. Wright, SPARC Report No. 10, *WCRP-6/2021*, 610 pp., doi: 10.17874/800dee57d13.

***Table 2:** Chapter titles and co-leads. (Taken from Table 1.2 of SPARC, 2022.) Note that one PDF file per chapter is provided.*

	Chapter Title	Chapter Co-leads
1	Introduction	Masatomo Fujiwara, Gloria Manney, Lesley Gray, Jonathon Wright
2	Description of the Reanalysis Systems	Jonathon Wright, Masatomo Fujiwara, Craig Long
3	Overview of Temperature and Winds	Craig Long, Masatomo Fujiwara
4	Overview of Ozone and Water Vapour	Sean Davis, Michaela Hegglin
5	Brewer-Dobson Circulation	Beatriz Monge-Sanz, Thomas Birner
6	Extratropical Stratosphere-Troposphere Coupling	Edwin Gerber, Patrick Martineau
7	Extratropical Upper Troposphere and Lower Stratosphere (ExUTLS)	Cameron Homeyer, Gloria Manney
8	Tropical Tropopause Layer (TTL)	Susann Tegtmeier, Kirstin Krüger
9	Quasi-Biennial Oscillation (QBO)	James Anstey, Lesley Gray
10	Polar Processes	Michelle Santee, Alyn Lambert, Gloria Manney
11	Upper Stratosphere and Lower Mesosphere (USLM)	Lynn Harvey, John Knox
12	Synthesis Summary	Masatomo Fujiwara, Gloria Manney, Lesley Gray, Jonathon Wright

Report on the 11th Atmospheric Limb Workshop

David Flittner[1], Glen Jaross[2], Natalya Kramarova[2], and Nathaniel Livesey[3]

[1]NASA Langley Research Center, Hampton, Virginia; [2]NASA Goddard Space Flight Center, Greenbelt, Maryland; [3]NASA Jet Propulsion Laboratory, Pasadena, California

Dates:
10-13 May, 2021

Organizing Committee:
Glen Jaross, Natalya Kramarova, Nathaniel Livesey, and David Flittner

Meeting venue:
Online

Number Of Participants: 90

Sponsors:
Website:
https://ozoneaq.gsfc.nasa.gov/limb_2021/

Introduction

In an all too familiar scene, as of late, over 90 scientists (representing approximately 20 institutions from 10 countries) eager to exchange results, plans and puzzles, positioned themselves in-front of computer screens to convene the 11th Atmospheric Limb Workshop in the first virtual version of this long-running grassroots scientific forum dedicated to topics related to atmospheric limb-sounding and solar occultation observations. The Workshop was organized by National Aeronautics and Space Administration atmospheric science teams at JPL, LaRC, and GSFC. The emphasis of the workshop continued to be remote sensing limb measurements of the Earth and other bodies, but the organizers invited presentations on all topics related to the vertical structure and composition of the atmosphere. The 57 presentations were grouped into four topical themes: Missions & Instruments; Algorithms & Error Analysis; Trace Gases; Aerosols. The agenda and presentation abstracts can be found on the workshop website.

Missions and Instruments

As noted at various meetings over the past five years, there are less than a handful of limb-observing instruments in orbit with all but one well past their prime mission duration. It was encouraging to see that there is no shortage of ideas and five talks showcased new concepts for proposal. These included: a mission to improve knowledge of the coupling of atmospheric circulation composition and regional climate change, Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT) by **Björn-Martin Sinnhuber**; Keystone by **Daniel Gerber** which is a concept for future limb sounding of the upper mesosphere and thermosphere; an instrument concept measuring 2D multispectral images of limb scattered sunlight with the Aerosol Limb Imager (ALI) by **Adam Bourassa**; the Spatial Heterodyne of Water (SHOW) to provide accurate, dense, high vertical resolution measurements of water vapor in the upper troposphere and lower stratosphere (UTLS) by **Jeff Langille**; and the Stratospheric Aerosol & Gas Experiment IV (SAGE IV) by **Robert Damadeo** which is a solar occultation imager sensorcraft for retrieving aerosols, ozone, and water vapour. Two invited talks provided status updates to new satellite missions in implementation, i.e. The Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS), by **Didier Fussen**, which will measure stratospheric ozone and aerosol profiles as the main mission objective with other constituents and atmospheric parameters essential to the climate research community and the Mesosphere Airglow/Aerosol Tomography Spectroscopy (MATS) mission presented by **Jörg Gumbel** that will study gravity waves and atmospheric structures over a wide range of spatial scales. In addition, status and future-plans of several operating missions were given. **Marilee Roell** provided an update of the youngest operating limb sensor, Stratospheric Aerosol and Gas Experiment III/ISS (SAGE III/ISS), while **Thomas Rogers** shared planned improvements of stray light performance for future versions of the Ozone Mapping Profiler Suite – Limb Profiler (OMPS-LP). **Doug Degenstein** presented over 20 years of achievements for the Optical Spectrograph and Infra-Red Imager Suite (OSIRIS) and the capability of UV-VIS limb sounders, such as ALTIUS, to constrain modelled stratospheric ozone was investigated by **Quentin Errera**.

Algorithms and Error Analysis

A keynote talk was given by **P.K. Bhartia** on the synergy between nadir, limb scattering and solar occultation measurement for climate and chemistry studies. **Frank Werner** provided results using artificial neural networks to improve near-real-time products from the Aura Microwave Limb Sounder (MLS) observations. Rapid data analysis with Jupyter notebooks applied to SAGE III/ISS data was shown by **Kevin Leavor** and created extended discussion in the "chat box". A comparison of vectorial spherical radiative transfer models in limb scattering geometry was reviewed by **Daniel Zawada**. Several presentations focused on dataset from past and current instruments. For the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), an update on the Institute of Meteorology and Climate Research (IMK) retrievals applied to version 8 radiances was given by **Gabriele Stiller**, and **Thomas von Clarmann** explained details of uncertainty estimates for this retrieval dataset that follow recommendations of the SPARC activity Towards Unified Error Reporting (TUNER). **Stefan Bender** provided examples of hyper-parameter optimization for SCIAMCHY 2-D limb retrievals of NO (nitric oxide) in the upper atmosphere. For Suomi National Polar-orbiting Partnership (NPP) OMPS-LP, **Natalya Kramarova** reviewed the standard ozone profile product, while **Zhong Chen** showed sensitivity to aerosol particle size distribution assumptions and **Leslie Moy** discussed the methods used for altitude registration. More general in nature, **Carlo Arosio** provided an error budget assessment for OMPS-LP ozone retrievals. A method for deriving time series of ozone and atmospheric vertical density from OMPS-LP data was given by **Zhong Chen**. An update of the Tikhonov regularized Ozone Profile retrieval with SCIATRAN (TOPAS) ozone profile retrieval from TROPOspheric Monitoring Instrument (TROPOMI) LIB version 2 dataset was given by **Nora Mettig**.

Trace Gases

The phenomenal injection of by-products from extreme terrestrial fires that has occurred over the past 4 years was the subject of several talks and discussions. **Michael Schwartz** presented an invited overview of pyro-convective stratospheric plumes from the 2019/2020 Australian bushfires using the perspective of Aura MLS. Also observing the impact of this event, **Soren Johansson** shared infrared limb imaging measurements of biomass burning trace gases by the airborne limb instrument the Gimballed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA). In the realm of 'traditional' terrestrial perturbations of the stratosphere, **Sandra Wallis** estimated the impact of volcanic eruptions on the thermal structure of the mesosphere by analyzing HALogen Occultation Experiment (HALOE) temperature data. Continuing the upper atmosphere focus, **Olexandr Lednyts'kyy** explained modeling updates for O and O_2 photochemistry in the mesosphere using the Multiple Airglow Chemistry approach. **Matthew DeLand** showed gravity wave-induced clouds observed by OMPS-LP. **Julia Koch** compared sodium retrievals obtained from OSIRIS with results from Envisat instruments SCanning Imaging Absorption spectrometer for Atmospheric CartographHY (SCIAMACHY) and Global Ozone Monitoring by Occultation of Stars (GOMOS) measurements. For data from the Aura MLS, **Krzysztof Wargan** introduced a new stratospheric composition reanalysis from the NASA Global Modeling and Assimilation Office, the GEOS-Stratospheric Composition Reanalysis with Aura MLS (GEOS-STREAM). **Nathaniel Livesey** showed investigation of long-term instrumental drifts in water vapour and the resulting improvements available in version 5 products. **Jerald Ziemke** displayed daily and hourly synoptic tropospheric ozone maps derived from Earth Polychromatic Imaging Camera (EPIC) and MLS measurements. **Michael Höpfner** compared the first global climatology of $BrONO_2$ (bromine nitrate) from MIPAS observations to atmospheric modelling. **Luis Millán** shared results from the SPARC initiative Observed Composition Trends and Variability in the UTLS (OCTAV-UTLS), emphasizing the importance of geophysically based coordinate systems for ozone trends. In a follow-up to a presentation at the 10th Limb Workshop, **Thomas von Clarmann** provided an update on the inverse method Analysis of the Circulation of the Atmosphere using Spectroscopic measurements (ANCISTRUS). **Chris Roth** presented OSIRIS ozone version 7 results and **Anqi Li** displayed 15 years of Odin-OSIRIS OH(3-1) nightglow. Verification of OMPS-LP ozone with Umkehr and ozone sondes time series was shown by **Irina Petropavlovskikh**. Regarding SAGE III/ISS data, **David Flittner** compared the NO2 product with ground-based observations from Lauder, New Zealand. For the ozone and water vapour products from SAGE III/ISS version 5.2 **Susan Kizer** presented validation results, while **Michael Heitz** presented an evaluation of water vapour sensitivity to aerosols. **Kaley Walker** presented climatological studies using Atmospheric Chemistry Experiment (ACE) data, and colleague **Patrick Sheese** assessed the quality of ACE-Fourier Transform Spectrometer (ACE-FTS) stratospheric ozone data.

Aerosols

A keynote presentation by **Stefanie Kremser** on the SPARC activity Stratospheric Sulfur and its Role in Climate (SSiRC) outlined the efforts to foster collaboration across observational and modeling groups to better understand the stratospheric aerosol layer and the drivers for its observed variations. Aerosol retrieval algorithm developments for several sensors was a sub-topic: OMPS-LP by **Robert Loughman**, GOMOS by **Christine Bingen** and SCIAMACHY solar occultation by **Christoph G. Hoffman**. Science highlights within the new OMPS-LP v2.0 multi-wavelength aerosol extinction profile records were discussed by **Ghassan Taha**. Limb scattered aerosol measurements in the Upper Troposphere and Lower Stratosphere (UTLS) from OSIRIS version 7 were compared by **Landon Rieger** with other space-based sensor records. Detection of tropospheric aerosols in tropical regions using multiple sensors (OMPS-LP, OMPS-Nadir and CALIPSO/CALIOP) was presented by **Wesley Combs**. Information regarding stratospheric aerosol particle size was the topic of several talks. **Christian von Savigny** compared distributions derived from various measurements and model results. Size distributions and extinction coefficients from SCIAMACHY limb data was compared by **Christine Pohl** to balloon-borne measurements and ECHAM5-HAM simulations. **Felix Wrana** illustrated satellite observations of volcanic eruptions leading to smaller average stratospheric aerosol sizes. For the 2017 Canadian boreal fires **Ernest Nyaku** derived unimodal size distributions with OMPS-LP data and validated derived Ångström exponents with SAGE measurements. For the Canadian 2017 and Australian 2020 pyro-convective events **Omar Torres** presented stratospheric aerosol mass. The ability to distinguish between smoke and sulfuric acid with SAGE III/ISS data was discussed by **Travis Knepp.**

Conclusions

The workshop closed with a social time acknowledging the human side of scientific research and the value of establishing relationships, especially for young scientists, built through meetings of moderate to small size. While virtual meetings may allow wider participation through much reduced costs and travel, they poorly replicate the time between talks and sessions where relationships can be built. On a positive note the ALTIUS scientific team volunteered to organize the 12th workshop, hopefully in-person, in Belgium, tentatively in 2023. Meeting details will be announced as plans solidify.

The breadth of scientific insight from past and present limb observations presented at this workshop are testimony to the value of continuing these types of measurements to understand the Earth's current and future climate. However, the aging of current missions and lack of confirmed future missions is concerning. Limb observations are a scientifically necessary component of the global Earth observing system and should also be an essential programmatic component as well.

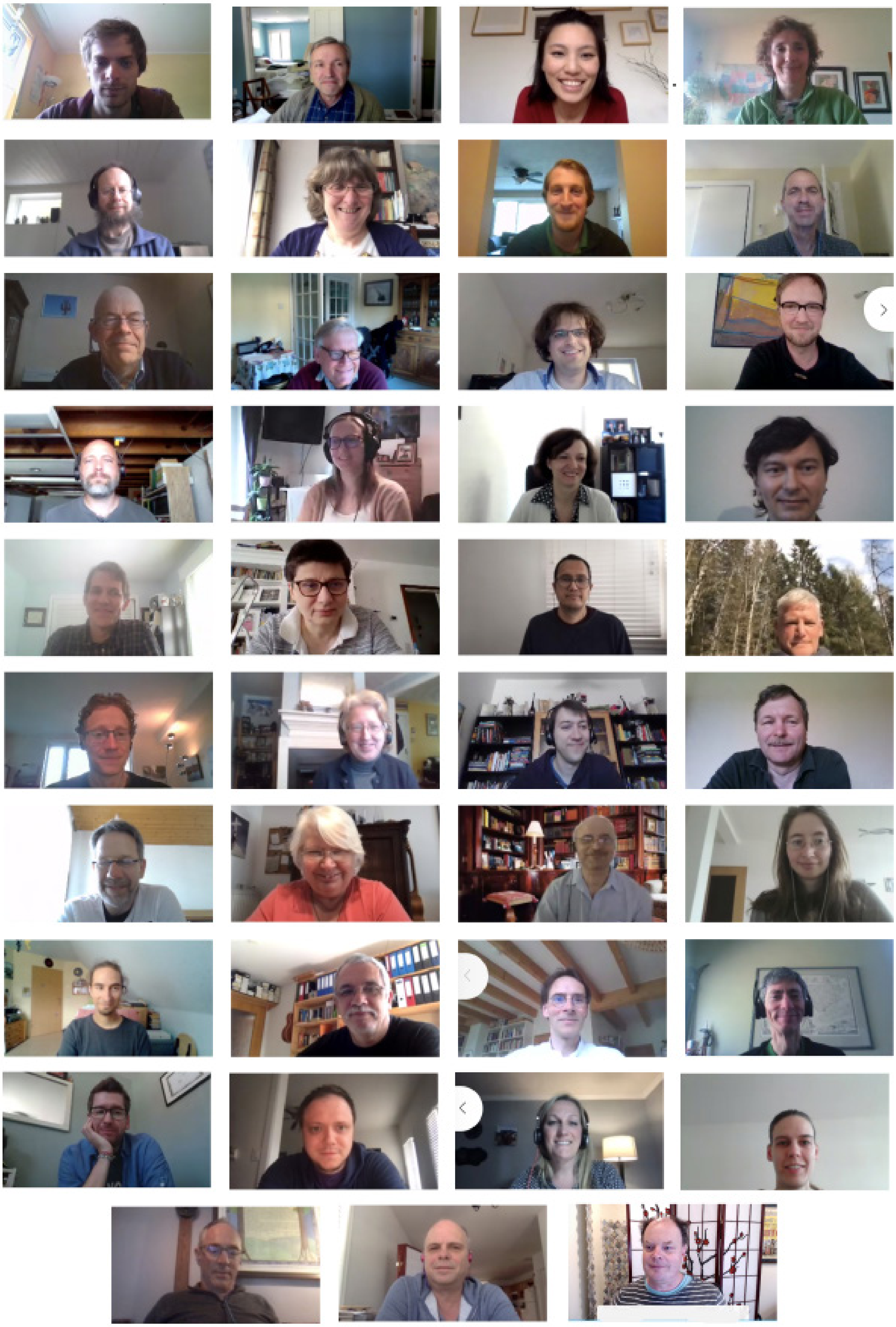


Figure 11: *Some participants of the 11th Internationsl Limb Workshop. Online from May 10 - 13, 2021*

Report on the 4th ACAM Training School

Federico Fierli[1], Bhupesh Adhikary[2], Ritesh Gautam[3], Mian Chin[4], and Hans Schlager[5]

[1]EUMETSAT, Darmstadt, Germany; [2]ICIMOD; Kathmandu, Nepal, [3]EDF, Washington D.C. Office, USA; [4]NASA Goddard Space Flight Center, Greenbelt, USA; [5]DLR, Oberpaffenhofen, Germany

Dates:
22 June – 01 July 2021

Organizing Committee:
F. Fierli (EUMETSAT), B. Adhikary (ICIMOD), R. Gautam (EDF), and D. Vomhofe (EUMETSAT)

Contributers:
H. Schlager (DLR), M. Chin (NASA), S. Ghude (IITM), L. Pan (NCAR), I. Aben (SRON), J. Flemming (ECMWF), M. Parrington (ECMWF), H. Jethva (NASA), and J. Wagemann (ECMWF)

Meeting venue:
Online

Number Of Participants: 30

Number of countries/regions: 14

Endorsements:
SPARC, IGAC

Workshop Website:
https://training.eumetsat.int/course/view.php?id=413

ACAM Website:
https://www2.acom.ucar.edu/acam

Background

ACAM (Atmospheric Composition and the Asian Monsoon) is a joint SPARC/IGAC activity that focuses on the connection between Asian monsoon dynamics and atmospheric composition, having important regional and global impacts. The aim is to build strong international collaborations for ACAM science, and to promote early career scientists (e.g. PhD students and Post Docs) in the monsoon region.

Training school Report

Following the previous ACAM training schools in Bangkok, Thailand, 2015, Guangzhou, China, 2017, and Bangi, Malaysia, 2019, the training school in 2021 provided again an excellent opportunity for students and early career scientists to learn about ACAM related science and to get familiar with how to access datasets from operational satellite instruments and chemistry-transport models, and to conduct small joint projects during the training school.

The fourth ACAM Training School was for the first time conducted as a fully virtual school due to the Covid-19 pandemic. It took place from 22 June until 01 July 2021 hosted by EUMETSAT in Darmstadt, Germany. It included 30 early career scientists and graduate students from 14 countries selected out of 81 applications. The focus of the training school was on "Satellite Observations and Analysis of Atmospheric Chemistry and Aerosols in the Asian Monsoon region". The school included lectures, practical exercises on data discovery, small student projects, and a special evening round-table event on science questions related to ACAM. Also, there was an opportunity for the participants of the training school to briefly introduced themselves

After an introduction to ACAM by **H. Schlager**, lectures were given by **S. Ghude** on ACAM science basics and **R. Gautam** on monitoring by satellites. **L. Pan** highlighted key science questions of transport and chemistry and **I. Aben** discussed the processing of satellite data. Further lectures were given by **H. Schlager** on results of aircraft campaigns during the Asian summer monsoon and **J. Flemming** on global atmospheric modeling. **B. Adhikary** dis-

Sponsors:

DLR

EDF Environmental Defense Fund — Finding the ways that work

ECMWF

EUMETSAT

Indian Institute of Tropical Meteorology, Pune

NASA

NCAR — National Center for Atmospheric Research

ICIMOD

SRON Netherlands Institute for Space Research

cussed regional atmospheric modeling and **M. Parrington** and **H. Jethva** addressed issues of fire emissions and air quality. Finally, **H. Schlager** presented results from aircraft measurements in pollution plumes of megacities and major population centers in Asia.

The practical part of the school started with an introduction by **F. Fierli**. Then, satellite data products and open-source platforms/scripts for reading, visualization, and analysis of data (e.g. Google Earth Engine and Python scripts) were presented. The various introduced satellite observations included trace gas (e.g. TROPOMI) and aerosol products (e.g. CALIPSO vertical aerosol profile). In addition, the Copernicus Atmospheric Monitoring Service was introduced (CAMS trace gas model products). During the second week of the training school the participants worked in groups to perform small projects using satellite observations and CAMS model output.

This was the second time that the ACAM training school included also practical work in groups besides the science lectures. This concept for the ACAM training school was again very well received by the participants. After the event the participants were able to evaluate the training school. Overall the students and early career scientists scored the lectures and practical work 4.8/5.0 and altogether 85% of the participants would recommend the training school to their colleagues – great success.

Figure 12: *Participants during the round-table discussion on ACAM science questions.*

SSiRC Virtual Meeting 2021 a Great Success with Largest Attendance Ever

Marc von Hobe[1], Landon Rieger[2], Alan Robock[3], and Anja Schmidt[4]

[1]Forschungszentrum Jülich GmbH, Institute for Energy and Climate Research (IEK-7), Jülich, Germany (m.von.hobe@fz-juelich.de); [2]University of Saskatchewan, Institute of Space and Atmospheric Studies, Saskatoon, Canada; [3]Rutgers University, Department of Environmental Sciences, New Brunswick, NJ, USA; [4]University of Cambridge, Centre for Atmospheric Science, Department of Chemistry, Cambridge, UK

Dates:
27-29 September 2021

Organizing Committee:
Marc von Hobe (Germany), Landon Rieger (Canada), Anja Schmidt (United Kingdom), Alan Robock (USA), Larry Thomason (USA), and Stefanie Kremser (New Zealand)

Meeting venue:
Online , hosted as a Zoom meeting by Rutgers University, thanks to Alan Robock.

Number Of Participants: 105

Website:
http://www.sparc-ssirc.org/

In spring 2020, everything was set for the fourth large meeting initiated and organized by the SPARC initiative SSiRC (Stratospheric Sulfur and its Role in Climate), which was to be hosted at the University of Leeds in late March. Like many other meetings and travel activities, the workshop had to be cancelled less than a month before it was about to take place because of the COVID pandemic.

Uncertainties regarding the rescheduling of the Leeds workshop were still high in autumn 2020, and the idea was born within the SSiRC Scientific Steering Group to also organize a virtual SSiRC workshop to bridge the gap until onsite meetings would be possible again. In the following months, plans for the virtual event were developed, taking ideas and inspiration from other virtual meetings, and considering the pros and cons of different formats and platforms. In May 2021, the organizers reached out to the SSiRC community for an Expression of Interest (EOI), asking for information like what topics should be covered, and what time zones people would participate from. Based on the EOI returns, dates and times were fixed to three 3-hour-sessions on three consecutive days at the end of September 2021, and a preliminary set of themes was ascribed to the sessions. Registrations with short (up to 10 min) presentations were accepted until early September, registrations without presentations were possible until the actual meeting date.
The meeting was held via Zoom and participation was not subject to a registration fee. Presentations (12 – 14 per day) were grouped into topical blocks with short breaks in between. Time slots for questions and short discussions were placed at the end of each block rather than after each presentation, but short questions could always be asked and answered in the written chat. At the end of each session, breakout rooms were created and extensively used for further discussion.

Observations and recent events

The first session on Monday focused on stratospheric aerosol observations and recent volcanic eruptions and fire events. It began with a presentation by **Juan Carlos Antuña Marrero** on results and current activities in rescuing relevant lidar datasets from the Agung 1963 and Mt Pinatubo 1991 volcanic eruptions. This work is part of the ongoing SSiRC stratospheric aerosols lidar data rescue initiative, also led by Juan Carlos Antuña Marrero, that aims at archiving lidar measurements from various sources and individual stations in a permanent open access repository (Antuña Marrero *et al.*, 2020; Antuña Marrero *et al.*, 2021). Ground-based observations of stratospheric aerosol were also shown by **Nina Mateshvili**, who reported novel twilight sky brightness spectral measurements carried out at stations in Tbilisi, Georgia, and Halle, Belgium.

Moving on to satellite observations, the following speakers reported novel means to retrieve aerosol properties as well as new scientific insights from these measurements. Based on the stratospheric aerosol size retrieval using the SAGE III/ISS (Stratospheric Aerosol and Gas Experiment III instrument on the International Space Station) solar occultation measurements, **Felix Wrana** reported the somewhat surprising result that some volcanic eruptions can lead to smaller average stratospheric aerosol sizes. The newly released Version 2.0 OMPS (Ozone Mapping and Profiler Suite) multi-wavelength aerosol extinction coefficient retrieval algorithm was discussed by **Ghassan Taha**, who showed a 3-D view of the OMPS Limb Profiler (LP) aerosol extinction vertical profiles ten years global climatology. Because of its continuous global coverage, this data set is well suited to validate global earth system models. **Christine Pohl** explained the particle size distribution retrieval from SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY, 2002 – 2012) and presented a comparison of the results to ECHAM5-HAM simulations for the 2009 Sarychev plume. Good agreement in aerosol size evolution was found, but also some differences in the effective radii due to cloud influences and uncertainties in the simulated vertical aerosol transport.

A series of presentations on dedicated case studies of very recent events was started by **Isabelle Taylor** showing the evolution of the volcanic plume from the Raikoke eruption in June 2019 as observed by the Infrared Atmospheric Sounding Interferometer (IASI). The bulk of the SO_2 was emitted to the upper troposphere/lower stratosphere (UTLS), where a clearly visible plume persisted for several weeks and appeared to be rising over time. TROPOspheric Monitoring Instrument (TropOMI) observations of the Raikoke eruption were employed by **Johannes de Leeuw** to evaluate the atmospheric dispersion model NAME. Good agreement could be demonstrated at least for the first days and weeks following the event, but it was also shown that the model's skill is strongly influenced by the eruption source parameters (e.g., emission height, strength, timing; see de Leeuw *et al.*, 2021). In two back-to-back presentations given by **Corinna Kloss** and **Pasquale Sellitto**, the stratospheric influence, and the estimated radiative forcing were reported for significant events during the past 5 years, including the eruptions of Ambae (2018, Kloss *et al.*, 2020), Raikoke and Ulawun (both 2019, Kloss *et al.*, 2021a) and extreme wildfires in British Columbia (2017, Kloss *et al.*, 2019) and Australia (2019/20, Kloss *et al.*, 2021b). A noteworthy finding was that the more absorbing nature of aerosols resulting from fires leads to radiative heating of the plume and a more negative radiative forcing at the surface than at the top of the atmosphere (TOA), while the surface and TOA radiative forcing of volcanic aerosols is similar. A similar conclusion was reached by **Christoph Brühl**, who studied the radiative forcing of these events using the ECHAM/MESSy Atmospheric Chemistry (EMAC) model and found instantaneous heating near the tropopause to be about an order of magnitude higher for organic and black carbon from fires than for volcanic sulfate.

The final two presentations of the Monday session looked at the role of volcanic ash. **Georgiy Stenchikov** addressed open questions concerning the role of ash in the long-term evolution of volcanic clouds. He showed that ash radiative heating causing the quick rising of volcanic debris is more important for large Pinatubo-size eruptions than for smaller events. In general, dynamic effects constrain the amount of ash and how long it stays in the atmosphere, and key factors that determine the ash lifetime are ash size distribution, the fine ash fraction, the efficacy of collective ash deposition, ash refractive index, and its microphysical properties. **Yunquian Zhu** showed that the persistence of supermicron ash inside the plume from the 2014 Kelut eruption (observed during the Airborne Tropical TRopopause Experiment, ATTREX) is consistent with a density near 0.5 g cm^{-3}, close to pumice and significantly lower than that of volcanic glass. Another finding presented was that the initial SO_2 lifetime is determined by SO_2 uptake on ash, rather than by reaction with OH as commonly assumed.

Sources and transport pathways

The Tuesday session was dedicated mainly to tropospheric sources and precursors of stratospheric aerosol and transport pathways to the stratosphere. The first talk, however, dealt with the impact of stratospheric aerosol injections on regional climate in the troposphere. Using climate-model simulations, **Suvarna Fadnavis** showed that stratospheric heating and tropospheric cooling induced by tropical volcanic eruptions can lead to dynamical changes that affect the Asian summer monsoon (ASM) and reduce precipitation in India.

The ASM also plays a role in transporting aerosol and precursors to the stratosphere. During the monsoon, a seasonal accumulation of aerosol is observed that is a significant source of UTLS aerosol in the absence of volcanic eruptions. This was the focus of three presentations. **Jean-Paul Vernier**, who in 2011 was the first to report and name the Asian Tropospheric Aerosol Layer (ATAL, Vernier *et al.*, 2011), gave an overview of a decade of research on characterizing and understanding ATAL. Key points included (i) satellite observations showing ATAL aerosol to be transported to the stratosphere with the aerosol optical depth (AOD) making up 60 – 80 % of the total stratospheric AOD in the northern hemisphere, (ii) balloon and aircraft measurements characterizing the optical, physical and chemical properties of ATAL, including the notion that nitrate, ammonia and organics play a key role, and (iii) transport simulations indicating China and India to be the major source regions for these aerosol precursors. **Pasquale Sellitto** reported decadal simulations of ATAL with the CESM-MAM7 (Community Earth System Model – Modal Aerosol Module with seven log-normal modes) model with state-of-the-art regional and global emissions inventories and compared the results to satellite observations (Bossolasco *et al.*, 2021). He mentioned dust to be the largely dominant aerosol type in terms of mass and pointed out the significant short-term variability of ATAL. He also reported an increase in ATAL AOD from 2000 to 2015. Exploiting SAGE I observations dating back as far as 1979 and revisiting SAGE II observations made in the 1990s, **Corinna Kloss** investigated the possible existence of an ATAL prior to 1998. And indeed, she showed signals and patterns in the observations suggesting that ATAL structures were present, and she supported this with model simulations showing that the presence of an ATAL around 1979/1980 may actually be expected.

The most abundant reduced sulfur gas in the troposphere and probably the most important non-volcanic precursor of stratospheric sulfate aerosol is carbonyl sulfide (OCS), which was subject of the next thematic block of the Tuesday session. **Chenxi Qiu** presented an analysis of satellite and in-situ OCS observations in the stratosphere and UTLS looking at the correlation with age-of-air parameters. The results support the picture given by global models, where the bulk of OCS conversion to SO_2 and sulfate takes place in the tropical pipe region (e.g., Brühl *et al.*, 2012). To estimate the amount of stratospheric sulfate originating from OCS, or in other words, how much OCS enters the stratosphere, it is important to understand the budget and cycling of OCS in the troposphere. Marine OCS emissions, both direct and indirect via carbon disulfide (CS_2) and dimethyl sulfide (DMS), are believed to be the largest single source in the global tropospheric budget. **Sinikka Lennartz** gave a summary of her recently published monthly gridded inventory of OCS and CS_2 emissions (Lennartz *et al.*, 2021). The global integration confirms previous estimates, and the first-of-its-kind climatological dataset will be valuable in global modelling efforts of atmospheric OCS and sulfur cycling. **Marc von Hobe** described new laboratory experiments of the DMS-to-OCS conversion in the atmosphere and indicated that the indirect marine OCS source from DMS could be larger than previously thought. However, he cautioned that the OCS yield depends on the chemical conditions and may be subject to strong regional variability. From the described and possibly further experiments, he and his team are trying to fully understand the chemical mechanism and eventually parameterize it for implementation in global models. An emerging tool to better constrain the behaviour of OCS is the measurement and use of isotope ratios. **Sophie Baartman** described a new measurement system and presented first ambient air measurements in the Netherlands, looking at seasonal variability and the influence of different air mass origins on isotope signatures. She also showed pictures of a recent balloon launch in Kiruna, Sweden, where air samples were taken in up to 32 km altitude. The analysis of these samples provides a unique opportunity to investigate OCS isotope signals from stratospheric photolysis. The power of OCS isotope measurements in constraining the global OCS budget was demonstrated by **Chen Davidson**, who presented the first data-based tropospheric COS isotopic mass balance (recently published in Davidson *et al.*, 2021). Results reveal a 60:40 ratio in the relative contributions of oceanic and anthropogenic emissions as the dominant OCS sources. Significant uncertainties still exist but are expected to be reduced as more OCS isotope ratio measurements and dedicated studies on some of the assumptions made become available.

Marcel Zauner-Wieczorek started the final block in the Tuesday session by showing airborne in-situ observations of precursor gases for particle formation in the troposphere and UTLS over Europe. These unique measurements were made with a novel mass spectrometer in summer 2020 during the HALO campaign CAFE-EU/BLUESKY (Chemistry of the atmosphere: Field Experiment in Europe) and showed interesting vertical structures that are currently being analysed. Another airborne chemical ionization mass spectrometer was introduced by **Fred Stroh**. FunMass enables the fast and sensitive measurement of several ultra-trace species including SO_2 and will be deployed as an addition to the IAGOS-CARIBIC instrument container that will regularly fly on an A350 passenger aircraft and provide near global measurements of the UTLS region starting from spring 2022. The final presentation on Tuesday was given by **Yaowei Li** on the composition dependence of stratospheric aerosol shortwave radiative forcing, with a particular focus on the role of the significant organic component of stratospheric aerosol. The shortwave radiative forcing of organic-containing aerosol can be rather different from pure sulfate and depends on the refractive index and mixing state. The wide range found in the calculations calls for a better understanding of the chemical evolution and the transport dynamics of organic aerosols in the stratosphere.

Understanding and simulating stratospheric aerosol processes

The final session on Wednesday was dedicated to the representation of stratospheric aerosol in climate models, with the first block of three presentations dealing with understanding important processes and model sensitivities to key parameters. Using satellite observations and simple model experiments to explore the relationship between eruption latitude, injection height and resulting lifetime of stratospheric aerosol, **Matthew Toohey** showed the latter is strongly sensitive to the height of the sulfur injection, especially within the lowest few kilometres of the stratosphere. The study also revealed that the aerosol lifetime is approximately a function of transport lifetime, with a lifetime reduction due to gravitational settling by about one third only for larger eruptions like Mt Pinatubo. Even so, the lifetime of aerosol from such major tropical eruptions is calculated to be on the order of 2 years when the delay between injection and the start of loss is considered. In the next presentation on the HErSEA experiments (Historical Eruptions SO_2 Emission Assessment), **Ilaria Quaglia** compared the response of different climate models to SO_2 amounts and injection heights of the Pinatubo eruption from different available estimates. The response to the various experimental setups was found to differ between models. Differences were also revealed when comparing simulations to observations. A single "best simulation," however, could not be identified. **Sandro Vattioni** gave an overview of recent improvements to SOCOL-AER (for details see Feinberg *et al.*, 2019), a dedicated aerosol CCM with a history spanning more than two decades. Also presented were simulations of recent volcanic eruptions that illustrate existing modelling uncertainties, and an application to solar geoengineering conditions.

In the next block on radiative forcing after volcanic eruptions, **Jennifer Schallock** presented results from a 30 year transient simulation with EMAC incorporating a volcanic emission inventory based on vertically resolved satellite observations. Besides the clearly visible negative radiative forcing at the tropopause caused by the 1991 Mt Pinatubo eruption and a few other eruptions (e.g., 2019 Raikoke and Ulawun), a small negative forcing caused by the accumulation of many smaller eruptions compared to volcanically quiescent conditions was also revealed. Based on her recently published paper (Marshall *et al.*, 2021), **Lauren Marshall** presented a study looking at the radiative forcing of historic volcanic eruptions, for which direct observations are not available and the SO_2 burden is estimated from sulfate deposition in ice sheets. The results show that a range of different eruption source parameters (including season, latitude, injection height) is consistent with the sulfate deposition signals, and that the corresponding uncertainty in radiative forcing leads to uncertainty in global-mean surface temperature response on order of 1 K. That the radiative forcing of a volcanic eruption strongly depends on the eruption source parameters was also shown by **Zhihong Zhuo**, who used the CESM2-WACCM6 model to compare the radiative forcing of tropical and extratropical eruptions of different magnitudes and in different seasons. The maximum stratospheric AOD and its temporal evolution were both higher for tropical eruptions. The talks emphasizing that the climate impact of a volcanic eruption depends on far more parameters than its sheer size or explosiveness set the scene for **Ben Black**, who presented the first attempt to define a new volcano climate index (an endeavour initiated and promoted by SSiRC). In the approach taken, the criteria for the Volcano-Climate Index (VCI) are defined from the climate impact side, i.e., the VCI of a given eruption is determined based on the observed climate effects after an eruption.

In the last thematic block, model studies taking a more comprehensive and/or differentiated look at climate impacts and, in some cases, also climate feedback, were presented. **Elizaveta Malinina** analyzed climate variables from a multi-model CMIP6 ensemble after the Krakatau (1883) and Pinatubo eruptions. In good agreement with previous studies, changes in most climate variables could be attributed to the eruptions. **Valentina Aquila** presented a case study on Mt Pinatubo from a recent publication (Aquila *et al.*, 2021) to show how a large eruption would change the seasonal forecasts produced with the current operational NASA GEOS-S2S (subseasonal-to-seasonal) system. When Pinatubo is included, forecast skills with respect to global and hemispheric surface temperature were improved, but decreased in the tropical Pacific. A significant drying of tropical Africa and a southward shift of the Inter-Tropical Convergence Zone (ITCZ) was also induced, as was a strengthening of El Niño, for which the driving mechanisms could not yet be clearly identified. The complexity linking climate variability to volcanic eruptions was illustrated by **Alan Robock** in his presentation on winter warming from tropical volcanic eruptions (see Coupe and Robock, 2021). Addressing the question whether observed winter warming in Eurasia following eruptions like Pinatubo was caused by those eruptions, he showed that heating of the upper atmosphere by smoke would produce this response in NCAR CAM5 simulations. In the simulations, such a winter warming becomes more likely when the volcanic eruption is combined with an El Niño, indicating that tropospheric as well as stratospheric mechanisms are important. **Thomas Aubry** reported from a recent publication (Aubry *et al.*, 2021) how the stratospheric volcanic sulfate aerosol life cycle and radiative forcing are affected by climate change, and that climate feedbacks should be considered when assessing the climate response to future eruptions. The simulations show that in a warmer climate (compared to today), the AOD perturbations and corresponding forcings are dampened for moderate tropical eruptions (e.g., Nabro 2011) but exacerbated for large eruptions (e.g., Pinatubo). A modelling study on the atmospheric impacts of high latitude eruptions was presented by **Herman Fuglestvedt**. Using CESM2-WACCM6, idealized Icelandic eruptions in a preindustrial atmosphere were simulated with different eruption parameters. One parameter, to which the model was sensitive, is the co-emission of halogens, which led to a slowing of SO_2 oxidation, dependent on the seasonality of OH, and to reduced SO_4 self-lofting as halogens catalyse ozone depletion. **Sandra Wallis** addressed the impact of strong volcanic eruptions on the middle atmosphere, i.e., up to the mesosphere and thermosphere. A model experiment showed that dynamic mechanisms following a strong tropical eruption led to changes in the middle atmosphere temperature and wind fields, such as warming of the SH polar summer mesopause region and a strengthening of the NH polar vortex.

The final presentation was given by **Daniele Visioni**, who addressed the topic of solar radiation management by stratospheric sulfur injection and reported on significant differences between climate models in simulating CMIP6 geoengineering scenarios (Visioni *et al.*, 2021).

Feedback and future SSiRC meetings

Overall, the virtual SSiRC workshop provided a good opportunity to exchange and discuss new results and ideas, with presentations given on recent papers, on material that is currently being written up for publication, and in some cases also on some very new unpublished work. Feedback received from participants was very positive. Many described the scientific exchange as very efficient and expressed the interest to hold similar meetings again in future. Some comments appreciated the accessibility of virtual meetings, i.e., that participation can be accommodated independent of budget and time restrictions. The choice to divide the meeting into 3-hour blocks on consecutive days made it possible to fit participation even into a busy schedule.

Given that the meeting worked out well with 39 presentations and more than 100 participants and in the light of the positive feedback, it is likely that this will not have been the last virtual SSiRC workshop. But the next SSiRC meeting will be the in person workshop in Leeds that has now been rescheduled to 28 – 30 March 2022 (https://eu.eventscloud.com/ehome/200197691/). We hope that everything will work out this time, and that it will be an equally great meeting experience but with all the hallway, coffee break, and dinner meetings that some of us have missed during the past 1.5 years.

References

Aquila, V. *et al.*, 2021: Impacts of the eruption of Mount Pinatubo on surface temperatures and precipitation forecasts with the NASA GEOS subseasonal-to-seasonal system, *J. Geophys. Res.: Atmospheres*, 126, e2021JD034830, doi:10.1029/2021JD034830.

Antuña-Marrero, J.-C. *et al.*, 2020: Shipborne lidar measurements showing the progression of the tropical reservoir of volcanic aerosol after the June 1991 Pinatubo eruption, *Earth Syst. Sci. Data*, 12, 2843–2851, doi:10.5194/essd-12-2843-2020.

Antuña-Marrero, J.-C. *et al.*, 2021: Recovery of the first ever multi-year lidar dataset of the stratospheric aerosol layer, from Lexington, MA, and Fairbanks, AK, January 1964 to July 1965, *Earth Syst. Sci. Data*, 13, 4407–4423, doi:10.5194/essd-13-4407-2021.

Aubry, T.J. *et al.*, 2021: Climate change modulates the stratospheric volcanic sulfate aerosol lifecycle and radiative forcing from tropical eruptions, *Nat. Commun.*, 12, 4708, doi:10.1038/s41467-021-24943-7.

Bossolasco, A. *et al.*, 2021: Global modeling studies of composition and decadal trends of the Asian Tropopause Aerosol Layer, *Atmos. Chem. Phys.*, 21, 2745–2764, doi:10.5194/acp-21-2745-2021.

Brühl, C., Lelieveld, J., Crutzen, P. J., and Tost, H., 2012: The role of carbonyl sulphide as a source of stratospheric sulphate aerosol and its impact on climate, *Atmos. Chem. Phys.*, 12, 1239–1253, doi:10.5194/acp-12-1239-2012.

Coupe, J., and Robock, A., 2021: The influence of stratospheric soot and sulfate aerosols on the Northern Hemisphere wintertime atmospheric circulation, *J. Geophys. Res.*, 126, e2020JD034513. doi:10.1029/2020JD034513.

Davidson, C., Amrani, A., and Angert, A., 2021: Tropospheric carbonyl sulfide mass balance based on direct measurements of sulfur isotopes. *Proc. Nat. Acad. Sci.*, 118, e2020060118. Doi:10.1073/pnas.2020060118.

de Leeuw, J. *et al.*, 2021: The 2019 Raikoke volcanic eruption – Part 1: Dispersion model simulations and satellite retrievals of volcanic sulfur dioxide, *Atmos. Chem. Phys.*, 21, 10851–10879, doi:10.5194/acp-21-10851-2021.

Feinberg, A. *et al.*, 2019: Improved tropospheric and stratospheric sulfur cycle in the aerosol–chemistry–climate model SOCOL-AERv2, *Geosci. Model Dev.*, 12, 3863–3887, doi:10.5194/gmd-12-3863-2019.

Kloss, C. *et al.*, 2019: Transport of the 2017 Canadian wildfire plume to the tropics via the Asian monsoon circulation, *Atmos. Chem. Phys.*, 19, 13547–13567, doi:10.5194/acp-19-13547-2019.

Kloss, C. *et al.*, 2020: Impact of the 2018 Ambae eruption on the global stratospheric aerosol layer and climate, *J. Geophys. Res.*, 125, e2020JD032410, doi:10.1029/2020JD032410.

Kloss, C. *et al.*, 2021a: Stratospheric aerosol layer perturbation caused by the 2019 Raikoke and Ulawun eruptions and their radiative forcing, *Atmos. Chem. Phys.*, 21, 535–560, doi:10.5194/acp-21-535-2021.

Kloss, C. *et al.*, 2021b: Australian Fires 2019–2020: Tropospheric and Stratospheric Pollution Throughout the Whole Fire Season, *Front. Environ. Sci.*, 9, 652024, doi:10.3389/fenvs.2021.652024.

Lennartz, S. T., Gauss, M., von Hobe, M., and Marandino, C. A., 2021: Monthly resolved modelled oceanic emissions of carbonyl sulphide and carbon disulphide for the period 2000–2019, *Earth Syst. Sci. Data*, 13, 2095–2110, doi:10.5194/essd-13-2095-2021.

Marshall, L. R., Schmidt, A., Johnson, J. S., Mann, G. W., Lee, L. A., Rigby, R., & Carslaw, K. S. (2021). Unknown eruption source parameters cause large uncertainty in historical volcanic radiative forcing reconstructions, *J. Geophys. Res.*, 126, e2020JD033578, doi:10.1029/2020JD033578.

Vernier, J.-P., Thomason, L. W., and Kar, J., 2011: CALIPSO detection of an Asian tropopause aerosol layer, *Geophys. Res. Lett.*, 38, L07804, doi:10.1029/2010GL046614.

Visioni, D. *et al.*, 2021: Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations, *Atmos. Chem. Phys.*, 21, 10039–10063, doi:10.5194/acp-21-10039-2021.

Quadrennial Ozone Symposium 2021 in Seoul, South Korea

Irina Petropavlovskikh[1], Ja-Ho Koo[2], Sophie Godin-Beekmann[3], Paul Newman[4], Andrea Pazmino[3], Andrew Klekociuk[5], Birgit Hassler[6], Corinne Vigouroux[7], Doug Kinnison[8], Gangwoong Lee[9], Johanna Tamminen[10], Julian Gröbner[11], Kaley Walker[12], Karin Kreher[13], Ken Jucks[4], Laura Pan[8], Lin Zhang[14], Mark Weber[15], Masatomo Fujiwara[16], Matt Tully[17], Nathaniel Livesey[18], Sang Seo Park[19], Seok-Woo Son[20], Stefan Reis[21], Steve Montzka[22], Sunyoung Park[24], Ulrike Langematz[24], Valerie Thouret[25] ,Wolfgang Steinbrecht[26], Yugo Kanaya[27].

[1] University of Colorado Boulder, USA, [2]Yonsei University, S. Korea, [3] LATMOS, France; [4] NASA, USA; [5] Australian Antarctic Division, Australia; [6] DLR, Germany; [7] BIRA-IASB, Belgium; [8] NCAR, USA; [9] HUFS, ROK; [10] FMI, Finland; [11] PMOD/WRC, Switzerland; [12] University of Toronto, Canada; [13]BK Scientific, Germany; [14] PKU, China; [15]Universität Bremen, Germany; [16] Hokkaido University, Japan; BoM, Australia; [18] JPL, USA; [19] Ulsan National Institute of Science, S. Korea; [20] Seoul National University, S. Korea; [21] UK Center for Ecology & Hydrology, UK; [22] NOAA, USA; [23] Kyungpook National University, S. Korea;[24] Freie Universität Berlin, Germany; [25] CNRS, France; [26] DWD, Germany; [27] Kobe University, Japan.

Dates:
27-29 September 2021

Meeting venue:
Online

Organizing Committee:
International Ozone commission (IO3C) and **Yonsei University in Seoul, South Korea**

Number Of Participants: 341

Website:
http://qos2021.yonsei.ac.kr/program.php

Introduction

The Quadrennial Ozone Symposium was organized by the International Ozone commission (IO3C), supported by the local organizing committee from Yonsei University in Seoul, South Korea. Originally, the gathering of researchers studying atmospheric ozone and related processes was planned in 2020, but had to be postponed to 2021 due to the COVID epidemic. However, even in 2021 travel was not possible due to pandemic-induced travel and quarantine restrictions. Therefore, the symposium was held remotely. Keynote talks, oral, and lightning poster presentations were organized in 6 three-hour sessions from October 3rd to 9th, 2021. Nearly all presentations were discussed very lively in the simultaneous chat. After each oral session, a short Q&A period summarized main results and allowed for a brief discussion of open questions. A special Q&A online board for all session allowed to post written questions to the authors for offline discussions. The large participation of 56 early career scientists and 22 researchers from developing countries of the symposium shows continuing interest in the excellent science of the QOS community. The symposium program and presentations given can be found on the symposium Website. Links to the lists of the presentations are provided at the end of the article.

A. Stratospheric ozone science

Session A of the Quadrennial Ozone Symposium was focused on stratospheric ozone science. **Ulrike Langematz** (FU Berlin, Germany) opened the session with her keynote "Polar Stratospheric Ozone: Recent Observations, Current Understanding, and Future Evolution". She discussed ten important research questions, from how volcanic eruptions affect polar ozone, to how polar ozone is expected to develop in the

Sponsors:

National Institute of Environmental Research

National Institute of Meteorological Sciences

IUGG

IAMAS International Association of Meteorology and Atmospheric Sciences

NASA

SPARC Stratosphere-troposphere Processes And their Role in Climate

WORLD METEOROLOGICAL ORGANIZATION

KOPRI Korea Polar Research Institute

future. The second keynote by **Neil Harris** (Cranfield University, UK) was titled: "Understanding Changes in Tropical and Mid-latitude Stratospheric Ozone". Using the long-term total column ozone record collected at Arosa in Switzerland as the underlying thread, he summarised a wide spread of ozone research topics, starting from health studies in the 1920s to our current understanding of the processes. The presentation covered findings related to ozone changes and variability, with a special focus on scientific achievements from the recent decades. In addition to the keynote presentations, 90 abstracts were submitted to Session A. Nineteen presentations were 5-minute talks separated into three oral sessions. 71 abstracts were summarized in 2-minute eLightning talks and were available for online viewing as posters. The presentations covered a wide range of topics, including descriptions and analysis of ground-based and satellite-based measurements in different regions of the world, modelling studies, trend analyses, studies of specific polar vortex years or events, intercomparisons of different observations and model simulations, and introduction of new and improved methodologies of ozone observations.

Several presentations (**D.H. Ahn et al; A. Lecouffe et al.; H. Lee et al.; G. Liu et al.; A. Pazmino et al.; R. Roy et al.,; M.J. Schwartz et al.; Zuev et al.**) dealt with the exceptional Antarctic winter of 2019, when a stratospheric warming caused smaller ozone hole over Antarctica compared to other years since 2000. Shortly thereafter, the Arctic experienced a very cold winter in 2020 with a strong and long-lasting polar vortex, resulting in record spring ozone loss. This exceptional event, its impacts on the Northern Hemisphere mid-latitudes, and retrospective simulations of ozone changes under the "world avoided" scenarios (i.e. due to enactment of the 1987 Montreal Protocol, **C. Wilka et al.**), were discussed in several presentations (**W. Feng et al., J.-U- Grooß et al., U. Raffalski et al., I. Tristcher et al.; P. Vargin et al.; I. Wohltmann et al**.). Many presentations were dedicated to observational record updates and comparisons of different datasets: ozone depleting substances (e.g. BrO, OClO) (e.g. **R. Querel et al.**); Very Short Lived Halogens (**E. Bednarz et al.; L. McBride et al.; R. Salawitch et al.**), ground-based measurements from Antarctica (**L. Gomez-Martin et al.; S. Kim et al.; H. Lee et al.**); ground-based and satellite-based measurement comparisons from Southern Brazil (**G. Carbajal-Benitez; L. Vaz Peres et al.**), analyses of Brewer and Pandora measurements from Canada (**X. Zhao et al.**), analyses of ozone profiles from different observing systems in Korea (**S. Eun-Ji.; D. Shin et al.**), or the Southern Hemisphere Additional Ozonesondes (SHADOZ) network in the tropics (**M. da Silva Ferreira et al.; A. Thomposn et al.**). One study investigated the stability and homogeneity of satellite- and ground-based measurement systems (**D. Hubert et al.**).

Sponsors:

KOREA TOURISM ORGANIZATION

DAEJEON METROPOLITAN CITY

DIMÉ
대전마케팅공사
Daejeon International Marketing Enterprise

InterMet
International Met Systems

IO3C International Ozone Commission

YONSEI UNIVERSITY 1885 연세대학교

Many studies reported trends in ozone analysing different ground-based and satellite-based measurements with different results depending on the period and the region analysed (**H. Bencherif et al.; L. Bernet et al.; S. Davis et al.; J. Kryscin et al.; E. Maillard-Barras et al.; V. Sofieva et al.; C. Vigouroux et al.; C. Wespes et al.**) A key focus in these studies was to update our knowledge of regions in the atmosphere where ozone recovery is now detectable (**N. Azouz et al.; M. Weber et al.**). New longitudinally resolved ozone datasets, for example, provide a better picture of regional ozone changes (**M. Koledewy-Egbers et al.; V. Sofieva et al.**). A number of presentations (**K. Bognar et al.; M. Chipperfield et al.; S. Dietmüller et al.; A. Inness et al.; A. Karagodin et al.; J. Y. Li et al.; H. Nakamura et al.; M. Weimer et al.**) discussed global ozone modelling in different model simulations, especially from the WCRP Coupled Model Intercomparison Project (CMIP6, CCMI , **Keeble et al.**). Other studies looked into the impacts on the ozone distribution coming from stratospheric dynamics (**A. Chrysantou et al.; F. Hasebe et al.; M. MDiallo et al.**) from the. Quasi-biannual Oscillation (QBO, **L. Oman et al.; J. Seo et al.; Y. Yamashita et al.**) , the Asian Summer Monsoon (**L. Pan et al; M. Santee et al.**), the extreme 2020 Australian wildfires (**S. Strahan et al.**), or from varations in the lowermost stratosphere (**W. Ball et al.; L. Millan et al.; H. Ryu et al.**).

B. Ozone Depleting Substances, Sources, Sinks, and Budgets

Session B on ozone depleting substances and their replacements started with a keynote presentation by **Sunyoung Park**, who highlighted the importance of regional emission estimates derived from measurements made at the Gosan station, Jeju Island, South Korea. Data from this station have been important for understanding unexpected changes in emissions of a range of ozone depleting substances (ODSs) and hydroflurocarbons (HFCs) in recent years, such as trichlorofluoromethane (CFC-11) and trifluoromethane (HFC-23). **Professor Park** highlighted these results and demonstrated that a substantial portion of the recent unexpected global emission changes can be attributed to eastern China. Results for related gases were also highlighted as they provide insights into the causes of the unexpected emission changes on regional and global scales.

The oral presentations continued the discussion of the magnitude and distribution of unexpected emission changes for CFC-11 (**M. Lickley et al.; S. Montzka et al.; L. Hu et al.**), other chlorofluorocarbons (CFCs, **M. Lickley et al.**), and methyl bromide (CH_3Br, **H. Choi et al.**). The two final oral presentations of that session discussed recent trends for atmospheric abundances of HFCs relative to previous projections (**G. Velders et al.**), and a new metric for assessing ozone recovery based on cumulative ozone depletion (**J. Pyle et al.**).

Presentations during the poster session expanded the discussion of themes touched on in the oral presentations. **L. Westerm** discussed global atmospheric abundance trends of the ODSs 1,1-dichloro-1-fluoroethane (HCFC-141b), and **M. Nicewonger** discussed the causes of atmospheric abundance variability measured for CH3Br. Furthermore, recent advances in spectroscopic measurements that have enabled atmospheric abundances of HFC-23 and chlorodifluoromethane (HCFC-22) to be determined over long periods were presented by **H. Nakajima**. Oceanic influences on lifetimes and inferred emissions of CFCs and HFCs were discussed by **P. Wang.** A new index was proposed by **S. Reimann** for communicating HFC atmospheric changes and climate impacts, and revisions to calculating ozone depletion potentials for short-lived gases were discussed by **D. Wuebble**s. Presentations by **M. Jesswein**, **M. Rotermund** and **I. Murata** focused on shorter-term variability in inorganic chlorine, inorganic bromine, hydrochloric acid (HCl) and hydrogen fluoride (HF) related to different atmospheric conditions in recent years. Other presentations by **G. Dreyfus, G. Wetzel, J. Jia** and **T. Brown** included a suggested a method for offsetting the adverse environmental impacts of unexpected production of ozone-depleting gases; the determination of UTLS abundances of hydrocarbons, HCOOH, and peroxyacetyl nitrate; modelled and measured ozone depletion in the Arctic induced by solar proton events; and the quantification of current and near-future impacts of rocket launches on the stratosphere.

C. Tropospheric Ozone scienc

Session C was composed of 33 presentations representing the research activities from 16 countries. The session's keynote presentation "Ozone Pollution and Research Programs in China: An Overview", was given by **Prof. Yuanhang Zhang** of Peking University (China). His presentation drew attention to deteriorating surface ozone pollution over China in recent years, which is mainly caused by high loading and slow reduction of Volatile Organic Compounds (VOCs). Ozone mitigation practices in China have led to a regionally integrated multi-pollutant control strategy with short-term priority to VOCs and long-term priority to Nitrogen Oxides (NOx). The contributed presentations covered major topics of tropospheric ozone research, including trends (**Liu et al.; Zieme et al.**) and variabilities of tropospheric ozone on local, regional, and global scales (**Hubert, et al.; Soulie et al.; Mayer et al.**). Further topics highlighted the impacts of local emissions on ozone pollution (**Oak et al.**), the effects of the COVID-19 pandemic on tropospheric ozone (**Steinbrecht et al.**), the role of stratospheric transport on free tropospheric ozone (**Chouza et al.; Ma et al.**), and recent advances in ozone chemistry modelling (**Sudo and Matsuda**). The presentations showed that there is increasing availability of tropospheric ozone records, enabled by the growing list of ozone-observing satellites (including OMI, MLS, GOME, SCIAMACHY, GOME-2, OMPS and TROPOMI). Both tropospheric ozone products produced by combining nadir and limb viewing observations and the reanalysis products assimilating satellite data provide rich information for analysing tropospheric ozone behaviour including stratosphere-troposphere-exchange, and for evaluating CCMs. Discussions during the Q/A session reflect the interest in the community for these products. A wide range of analyses were presented using airborne, balloon-borne, ground-based, and research vessel-based ozone measurements, many combined with meteorological measurements. Results show that these diverse modes of observations play an important role in process studies and modelling tropospheric ozone.

D. Ozone, Climate, and Meteorology

This session covered the impacts of climate change on atmospheric ozone, evolution of large-scale circulation, radiative forcing of ozone, and the impacts of ozone changes on surface climate and meteorology. It also covered a recent hot topic, the impact of the large-scale Australian wildfire events in late 2019 to early 2020 on the composition of the lower stratosphere in the Southern Hemisphere.

In the oral session, 10 presentations, including the keynote talk by **Amanda C. Maycock**, provided an overview of the numerous impacts of tropospheric and stratospheric ozone variability and its

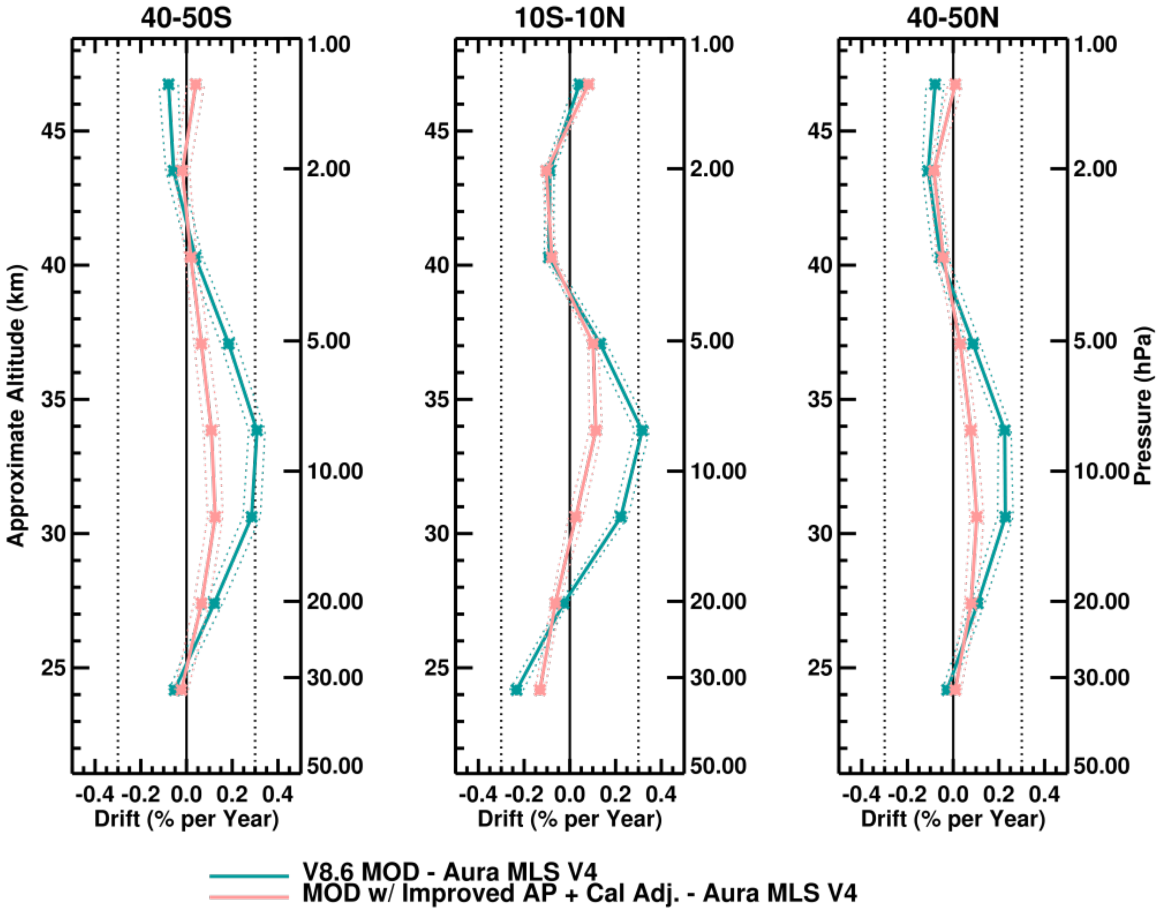


Figure 13: *Relative drift (in % per year) between the SBUV Merged Ozone Dataset (MOD) and Aura Microwave Limb Sounder for the period 2004-2018 shown for three wide latitude zones. Green lines represent relative drifts in the MOD record based on version 8.6 SBUV data. Pink lines are for the MOD with the improved climatology and updated cross-calibrations, demonstrating increased stability of the updated MOD record. The new advanced climatology (Frith et al., 2020; Ziemke et al., 2021) is used in evaluation of the relative offsets between pairs of overlapping Solar Backscattered UltraViolet (SBUV) instruments. The instrument bias corrections improve consistency of the NASA's historical merged ozone record.*

trends on global and regional climates as synthesized in the IPCC Sixth Assessment Report and the WMO/UNEP 2022 Scientific Assessment of Ozone Depletion. The need for interactive stratospheric ozone in climate models, in comparison with prescribed ozone, was shown and discussed by four presenters: **Feng Li** for Southern Hemisphere troposphere in austral spring; **Marina Friedel** for Northern Hemisphere surface climate focusing on springtime Arctic ozone depletion; **Pu Lin** for global stratospheric temperature trends in response to ozone depletion; and finally, **Olaf Morgenstern** for Southern Annular Mode using CMIP6 models with and without stratospheric chemistry. Using reanalyses for past decades, CMIP5, and CMIP6 models for 1950-2100, **Peter von der Gathen** showed a statistically significant increase in the local maxima of PSC formation potential within the Northern Hemisphere polar vortex. **Gabriel Chiodo** investigated the radiative impacts of ozone-depleting substances focusing on the period with the largest growth of atmospheric ODS abundances (1955-2000) and found their unique contributions to climate change including warming of the lowermost tropical stratosphere. The final three talks were on the impacts of the Australian wildfire events on the stratosphere: **Michelle L. Santee** showed Microwave Limb Sounder (MLS) measurements of various relevant species including biomass-burning products in the Southern Hemisphere stratosphere; **Sergey Khaykin** analyzed satellite aerosol and other data, showing a massive injection of absorbing aerosols into the stratosphere that created a self-maintained anticyclone, or smoke-charged vortex that persisted for three months and ascended to 35 km altitude, while **William J. Randel** also analyzed various satellite data, pointing out that the polar ozone depletion, temperature, and polar vortex evolution broadly resembled the effects of the Calbuco volcanic eruption in 2015.

The poster session continued and expanded the science discussion of session D's theme of ozone, climate, and meteorology using both atmospheric observations and climate models. Overall, 33 posters were presented. These summarized a broad range of science studies from the regional scale to the global scale; including observations that defined the importance of continuing long-term monitoring networks, improved sensitivity, and validation, along with the use of observations in the evaluation of model results. Modeling and observational studies tested our understanding of key chemical processes in both the troposphere and stratosphere.

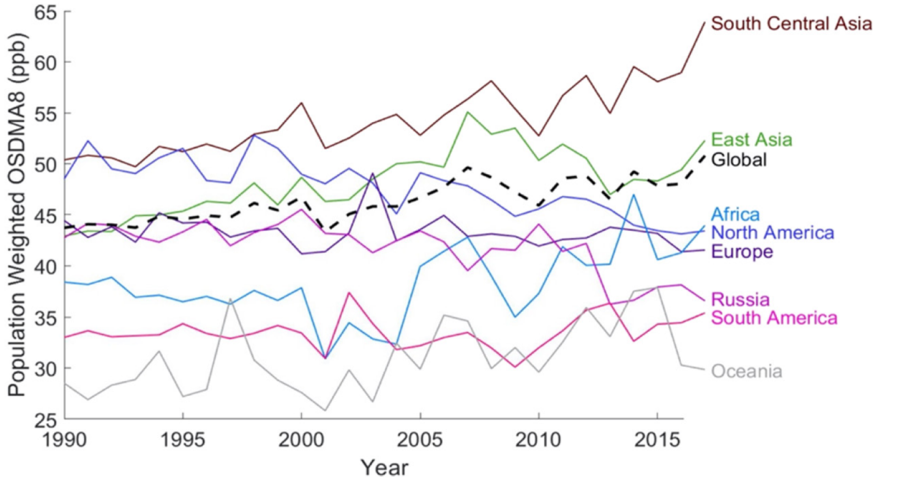


Figure 14: *Ozone trends regionally averaged for 1990-2017 period. The metric is population weighted OSDMA8 (ozone season daily maximum 8-hour mixing ratio). All trends have a p-value less than 0.05, except for Europe and South America (Fig. 5b in DeLang et al, 2021)*

E. Ozone Monitoring and Measurement Techniques

This session had the most abstract submissions and had to be split into several sessions. It started with the keynote talk by **Natalya Kramarova** (NASA Goddard) giving a historic overview of the stratospheric ozone products based on the satellite remote sensing techniques. She concentrated on the SBUV and OMPS UV instruments and discussed recent advances made in separation of instrumental artifacts and natural variability signals (see Figure 13) that are embedded in the long-term combined ozone records used for trend analyses. The topic of satellite validations using ground-based observations included discussion of the needs for NOAA's operational ozone products (presented by **L. Flynn et al.**), offered a first look at the GEMS satellite ozone products validation (by **A. Keppens et al.** and by **K. Baek et al.**), and voiced concerns with the gaps and inconsistencies between ground-based datasets (**T. Verhoelst et al.**). The session also addressed new homogenized satellite products with a focus on tropospheric ozone trends (by **A. Keppens**), enhancement in ozone profile retrievals by combining UV and IR observations (by **N. Mettig et al.**), machine learning techniques (by **D. Loyola et al.** and by **S. Dhomse et al**.), and the use of satellite records to fill in the gaps of the long-term ground-based ozone records (by **L. Zhang et al.**). The advances in stability and consistency of the ground-based and satellite-based records were demonstrated in several oral and multiple poster presentations that discussed results of homogenization of ozonesonde records (**R. Van Malderen et al.**), new version of Pandora total ozone record using climatological effective temperature (**M. Tiefengraber et al.**), coherence between the Umkehr and overpass satellite ozone records (**I. Petropavlovskikh et al**.), transition of the surface ozone networks to the new ozone cross-sections (**P. Brewer et al.**), impacts of the time response in ozonesonde cells on ozone vertical biases (**H. Vömel et al.**), and attribution of the "drop-off" in ozonesonde records to manufacturing changes (**R. Stauffer et al.**). Updated assessment of the Brewer reference triad performance (from 1999 to 2019) and the first comprehensive assessment of the Double Brewer reference triad were shown (**X. Zhao et al.**) compared to ground-based and satellite measurements. The oral session also paid a tribute to 25 years of recurrent and sustained experiments to assure data quality in ozonesonde records (**H. Smit et al.**). Several presentations introduced new satellite instrument concepts, including the Infrared Tomography Explorer (**B.-M. Sinnhuber et al.**) and the Community Microwave Limb Sounder (**N. Livesey et al.**) for continuing and expanding the capability of global observations of atmospheric composition change. Sixty poster presentations gave a detailed overview of the status and achievements of the ground-based, in-situ, aircraft and satellite networks, introduced new and enhanced calibration techniques (the Eubrewnet activities were featured in several posters). Posters also discussed reprocessing of satellite and ground-based data in order to improve the accuracy and consistency of observed ozone records across different techniques, with a significant number focussed on homognenization of ozonesonde observations. Further posters introduced improvements to old measurement approaches along with proposed new ones (e.g., SAGE IV) for tracking ozone, CFCs and atmospheric tracers needed to verify stratospheric ozone recovery and for understanding of causes of changes in tropospheric ozone. Common interest of the tropospheric and stratospheric ozone research communities was satisfied with new information in terms of monitoring and technological development.

F. Environmental and human health effects of atmospheric ozone and UV

The focus of this session was on the influence of atmospheric ozone and UV radiation on public health, agricultural crop yield, ecosystem service impacts, and material degradation. A keynote by **Prof. Jason West** provided evidence from mapping global ground-level ozone concentrations for the period between 1990 and 2017 (see Figure 14) in support of health impact assessment. Further talks covered surface UV radiation and its contribution to the increase of melanoma incidence in Europe over a period of 20 years (**A. Czerwinska et al.**), the temporal variability of solar UV radiation in Brazil (**G. Reis et al.**) and a comparison of the temporal variability of erythemal UV-B dose measurements (**S. F. Leon-Luis et al.**, presented by **A. Redondas**). A projection of total ozone and DNA weighted UV radiation changes in the future, exploring the influence of greenhouse gases in the atmosphere, was presented by **K. Eleftheratos**. **S. Falk** introduced a characterisation of subarctic biomes for land surface modelling of ozone pollution and climate risk and I. Fountoulakis highlighted findings from a satellite-based UV and visible climatology for biological and agricultural applications for Greece and Cyprus. Poster presentations covered the estimation of UV Indices and biological dose rates, as well as the application of various models to achieve this for South Korea (**H. Lee et al., J. Kim et al.**), and changes in the Aura OMI Total column and UV Index over Indonesia, linking these to regional cloud cover (**N. Komala et al.**). Discussions of the tropospheric

***Figure 15:** Participantsof the Quadrennial Osone Symposium 2021*

ozone impacts on forests in Delhi, India (**P. Saxena et al.**) and the relationship between ozone and cardiorespiratory mortality for different age groups in a region in Greece (**L. Dimitriadou et al.**) were followed by an introduction of the SOUVENIR project (SOlar UV Extensive Network for Information and Reporting, DOI:10.13140/RG.2.2.18274.04802), a network for solar UV measurements (**G. Fasano et al.**). **C. Gonzalez** presented a comparison of measurement results of global UV spectral irradiance, while **K. Cizkova** focused on modelling of spectral UV radiation at the Marambio base on the Antarctic Peninsula. The variation of stratospheric ozone concentrations and genotoxic effects of solar UV radiation in southern Brazil (**B. C. Borin et al.**) and further work on the climatology of the UV index, as well the behaviour of the index during events influenced by the Antarctic Ozone Hole over southern Brazil was presented by **B. C. Lopes**.

Links to Sessions

Session A

http://qos2021.yonsei.ac.kr/download/program/1.QOS2021_Program_SUN1.pdf

http://qos2021.yonsei.ac.kr/download/program/2.QOS2021_Program_MON1.pdf

Session B

http://qos2021.yonsei.ac.kr/download/program/6.QOS2021_Program_TUE2.pdf

http://qos2021.yonsei.ac.kr/download/program/7.QOS2021_Program_TUE3.pdf

Session C

http://qos2021.yonsei.ac.kr/download/program/8.QOS2021_Program_WED1.pdf

Session D

http://qos2021.yonsei.ac.kr/download/program/9.QOS2021_Program_WED2.pdf
http://qos2021.yonsei.ac.kr/download/program/12.QOS2021_Program_THU3.pdf

Session E

http://qos2021.yonsei.ac.kr/download/program/10.QOS2021_Program_THU1.pdf

http://qos2021.yonsei.ac.kr/download/program/11.QOS2021_Program_THU2.pdf

http://qos2021.yonsei.ac.kr/download/program/13.QOS2021_Program_FRI1.pdf

http://qos2021.yonsei.ac.kr/download/program/16.QOS2021_Program_SAT1.pdf

http://qos2021.yonsei.ac.kr/download/program/17.QOS2021_Program_SAT2.pdf

Session F

http://qos2021.yonsei.ac.kr/download/program/14.QOS2021_Program_FRI2.pdf

http://qos2021.yonsei.ac.kr/download/program/18.QOS2021_Program_SAT3.pdf

References

Marissa N. DeLang, Jacob S. Becker, Kai-Lan Chang, Marc L. Serre, Owen R. Cooper, Martin G. Schultz, Sabine Schröder, Xiao Lu, Lin Zhang, Makoto Deushi, Beatrice Josse, Christoph A. Keller, Jean-François Lamarque, Meiyun Lin, Junhua Liu, Virginie Marécal, Sarah A. Strode, Kengo Sudo, Simone Tilmes, Li Zhang, Stephanie E. Cleland, Elyssa L. Collins, Michael Brauer, and J. Jason West, Mapping Yearly Fine Resolution Global Surface Ozone through the Bayesian Maximum Entropy Data Fusion of Observations and Model Output for 1990–2017, *Environmental Science & Technology* 2021 55 (8), 4389-4398, DOI: 10.1021/acs.est.0c07742

Frith, S. M., Bhartia, P. K., Oman, L. D., Kramarova, N. A., McPeters, R. D., and Labow, G. J.: Model-based climatology of diurnal variability in stratospheric ozone as a data analysis tool, *Atmos. Meas. Tech.*, 13, 2733–2749.

Ziemke, J. R., Labow, G. J., Kramarova, N. A., McPeters, R. D., Bhartia, P. K., Oman, L. D., Frith, S. M., and Haffner, D. P.: A global ozone profile climatology for satellite retrieval algorithms based on Aura MLS measurements and the MERRA-2 GMI simulation, *Atmos. Meas. Tech.*, 14, 6407–6418.

Kramarova, N. A., J. R. Ziemke, L.-K. Huang, J. R. Herman, K. Wargan, C. J. Seftor, G. J. Labow, and L. D. Oman. 2021. Evaluation of Version 3 Total and Tropospheric Ozone Columns From Earth Polychromatic Imaging Camera on Deep Space Climate Observatory for Studying Regional Scale Ozone Variations. *Frontiers in Remote Sensing* 2 [10.3389/frsen.2021.734071]

SPARC meetings

08 - 10 February 2022
Workshop on Understanding and Modeling Complex Risks in Coupled Human-Environment Systems,
Online

28 March - 01 April 2022
SPARC Gravity Wave Symposium
Frankfurt, Germany
(postponed from 2020)

17 - 19 May 2022
3rd International Workshop on Stratospheric Sulfur and its Role in Climate (SSiRC)
Leeds, UK
(postponed from 2020)

30 May - 3 June 2022
11th International Workshop on Long-Term Changes and Trends in the Atmosphere (TRENDS 2020)
FMI, Helsinki, Finaland
(postponed from 2020)

8 - 10 June 2022
HEPPA-SOLARIS Workshop and SOLARIS-HEPPA WG meeting
Bergen, Norway

16 - 24 July 2022
COSPAR 2022 - 44th Scientific Assembly
Athens, Greece

04 - 08 July 2022
QBO@60 – Celebrating 60 years of discovery within the tropical stratosphere
UK Met Office, Exeter, UK
(postponed from July 2020)

24 - 28 October 2022
7th SPARC General Assembly
China, U.K., and U.S.A.

SPARC related meetings

08 - 09 April 2022
4th ECRA General Assembly
Brussels, Belgium

23 - 27 May 2022
EGU 2022
Viena, Austria

23 - 27 May 2022
Living Planet Symposium 2022
Bonn, Germany

17 - 19 October 2022
2nd Climate Observation Conference
Darmstadt, Germany

Find more meetings at: www.sparc-climate.org/meetings

Publication details

Editing
Sabrina Zechlau & Stefanie Kremser
Design & layout
Brigitte Ziegele & Sabrina Zechlau
Distribution & print (on demand)
DLR - IPA, Oberpfaffenhofen

ISSN 1245-4680

SPARC Office

Director
Mareike Heckl

Project Manager
Sabrina Zechlau

Office Manager
Brigitte Ziegele

Contact
SPARC Office
c/o Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
Institut für Physik der Atmosphäre
Münchener Str. 20
D-82234 Oberpfaffenhofen, Germany
email: *office@sparc-climate.org*