SPARC

Stratosphere-troposphere Processes And their Role in Climate

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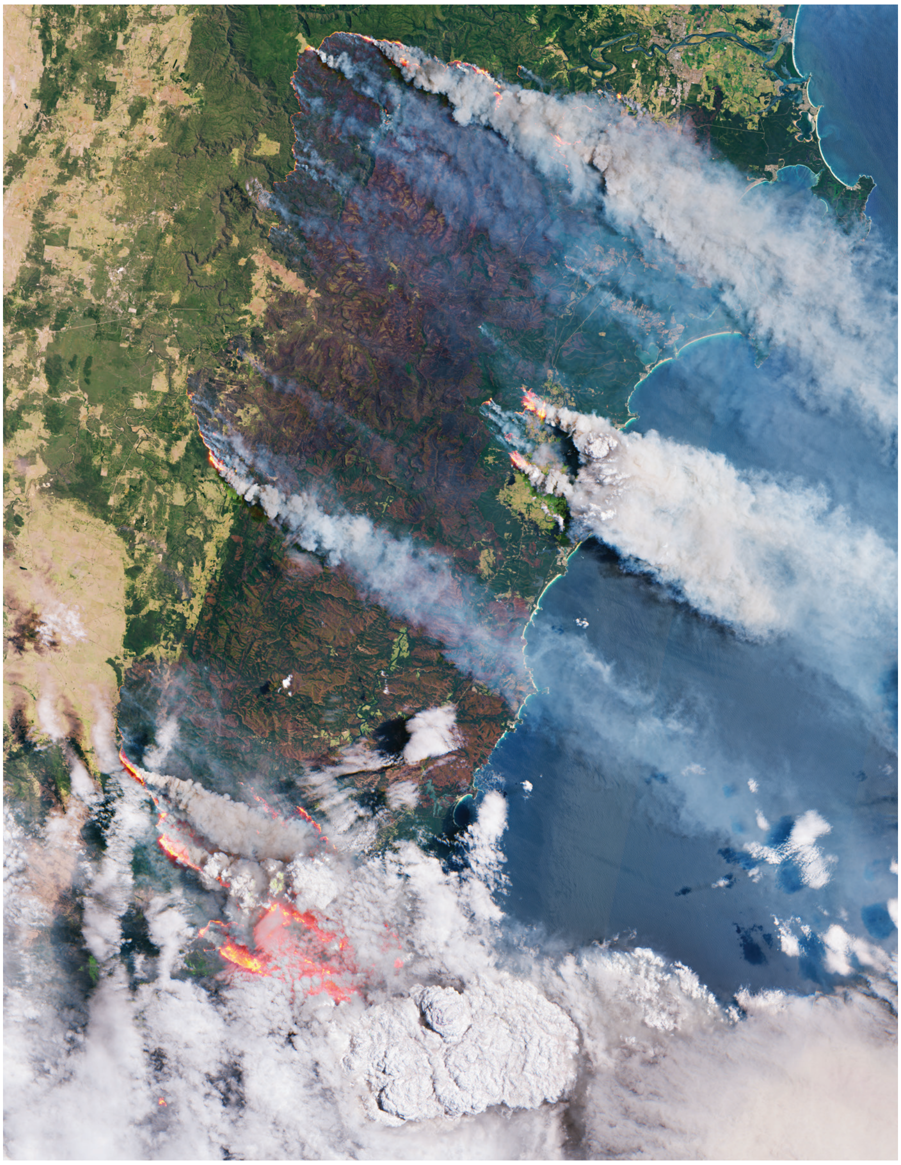

Satellite view on ferocious bushfires south of Nowra, Australia. Smoke vanes, flames, and burn scars recorded by a Sentinel-2 satellite on 31 December 2019. The hot, dry, and windy conditions were influenced by the Sudden Stratospheric Warming, occuring in austral spring (see report on page 10). Increasing the understanding of and ability to predict extreme events is part of the work many SPARC scientists undertake and discuss during their workshops (see report on page 33). The stratosphere plays an important role in predictability, as documented by SPARC scientists in a community paper summarized on page 14.

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World Meteorological Organization

United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

International Science Council

The 27th SPARC Scientific Steering Group Meeting

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The 27th SPARC Scientific Steering Group (SSG) meeting took place in Boulder, Colorado, USA from December 4th to 6th, prior to the AGU fall meeting in San Francisco. It was hosted by the National Center for Atmospheric Research (NCAR) at the Table Mesa Laboratory, and focused on the development of a new SPARC implementation plan for the upcoming 5 years (2021-2025).

Owing to the strategic focus of the meeting, the agenda included considerable time for discussion rounds and break-out sessions. Latest SPARC activity achievements were summarized in three sessions following SPARC's current research themes: "Atmospheric dynamics and predictability", "Chemistry and Climate", and "Long-term observation records for climate understanding". The meeting was also attended by a number of SPARC activity leads and liaisons from partner projects and agencies, who provided valuable input to the strategic discussions (Figure 1). On the last day, the World Climate Research Programme (WCRP) chair Detlef Stammer provided his perspective on WCRP and the envisaged route to realize its Implementation Plan.

SPARC updates and overview talks

The current SPARC co-chairs **Neil Harris** and **Judith Perlwitz** opened the SSG meeting and informed the community that they requested the Joint Steering Committee of WCRP to confirm the SSG member **Seok-Woo Son** as a third co-chair.

In his SPARC Office update, **Hans Volkert** announced that DLR has agreed to extend the position of Science coordinator **Mareike Kenntner** for three more years, which secures the office hosting at DLR-IPA until 2023. Since Hans is to retire from DLR in August 2020, Mareike is prepared to take over the task as office director. Another scientist will be hired to support her as science coordinator. During the past year, accomplishments include the publication of SPARC report No. 9 (LOTUS report), the coordination of 11 SPARC workshops, and assisting WCRP in the preparation of the climate science week at the AGU fall meeting. It is planned to advance the SPARC website by facilitating links to important research publications, assessment reports, webinars and glossaries. It will serve as a resource for early career scientists who are new to SPARC-related research topics. SSG member **Gufran Beig** extended an invitation for SSG-28 to be held in autumn 2020 at the Indian Institute of Tropical Meteorology (IITM) in Pune, India. At this venue SSG-18 had taken place in February 2011 (cf. Newsletter no. 37). The final decision including dates is scheduled for March 2020.

The local host, **Yaga Richter**, gave a brief overview of SPARC-related research at NCAR. She described a model intercomparison study about the future projections of the quasi-biennial oscillation (QBO) and research findings on running and analyzing subseasonal-to-seasonal (S2S) forecasts. The S2S project revealed in particular that the influence of model resolution in the stratosphere tends to be rather model specific, and the models with a coarsely resolved stratosphere often perform quite well. She also introduced a new NCAR Earth-System model, which is running subseasonal forecasts in real time.

Two presentations of a more general nature *(i)* summarized the discussions at the DynVar/SNAP meeting in October about possible practices to reduce the carbon footprint of conferences (**Andrew Charlton-Perez** and **Elena Saggioro**; see report on page 40) and *(ii)* addressed the 2019 Southern Hemisphere polar stratospheric warming and ongoing surface impacts (**Harry Hendon**, see report on page 10).

WCRP update

Boram Lee (via remote link) gave the update on WCRP. She pointed out that the World Meteorological Organisation (WMO) is also undergoing changes.

Figure 1: *Majority of participants at SSG-27 in the afternoon of 4 Dec. 2019 at the NCAR Mesa Laboratory main entrance.*

01 *Frédéric VITART, INT;* **02** *Joan ALEXANDER, US;* **03** *Donald WUEBBLES (SSG), US;* **04** *John McCORMACK, US;* **05** *Shigeo YODEN, JP;* **06** *Marvin GELLER, US;* **07** *Hans SCHLAGER, DE;* **08** *Gufranullah BEIG (SSG), IN;* **09** *Beatriz BALINO, NO;* **10** *Marilyn RAPHAEL, US;* **11** *Andrea STEINER, AT;* **12** *Larry THOMASON, US;* **13** *Takeshi HORINOUCHI (SSG), JP;* **14** *Nathaniel LIVESEY (SSG), US;* **15** *Neil HARRIS (SSG co-chair), UK;* **16** *Amy BUTLER, US;* **17** *Mareike KENNTNER, DE;* **18** *Harry HENDON (SSG), AU;* **19** *Stefanie KREMSER, NZ;* **20** *Scott OSPREY, UK;* **21** *Hauke SCHMIDT (SSG), DE;* **22** *Judith PERLWITZ (SSG co-chair), US;* **23** *Martine DE MAZIÈRE, BE;* **24** *Irina PETROPAVLOVSKIKH, US;* **25** *Karen ROSENLOF (SSG), US;* **26** *Hans VOLKERT, DE;* **27** *Wen CHEN (SSG), CN;* **28** *Megan MELAMED, US;* **29** *Yaga RICHTER, US;* **30** *Seok-Woo SON (SSG), KR;* **31** *Masatomo FUJIWARA, JP.*

photo: Stephanie Shearer; annotation: Hans Volkert.

From January 2020, its structure consists of three pillars, one of which is "Science and Innovation". It is led by Jürg Luterbacher, and comprises the WCRP, the World Weather Research Programme (WWRP), and the Atmospheric Environment Research (AER) Division.

Currently WCRP moves forward with developing its new implementation plan, after the basic structure and general direction were decided during the Joint Steering Committee meeting last May (Figure 2). As a next step the key science questions are to be defined which WCRP plans to tackled during the next decade. A dedicated workshop is planned for the end of February in Hamburg to finalize high-level science questions. In parallel, WCRP is assessing its current structure through task teams on modelling, data and regional activities. The updated structure is to be discussed at an "Elements and Structure" workshop in March or April 2020. A consolidated version of the implementation plan is envisioned to be ready for approval by the JSC-41 meeting in Sydney in May 2020. It will contain the high-level science questions, the elements of the new WCRP, the collaboration landscape and interfaces to partners, the governance and a financial plan. Following the JSC-41, the document is to be approved by the sponsors, and the final version will be released. A transition phase to the new WCRP structure is envisioned to start in April 2021. It was stressed that the SPARC community should develop scientific priorities that could become integrated in the WCRP agenda for the next 10 years.

Boram announced that she is leaving her current position within the Joint Planning Staff (JPS) and will move to a different position within WMO. The SPARC community represented at the meeting expressed their sincere gratitude for Boram's dedicated and cooperative work-style over many years.

WCRP chair **Detlef Stammer** described current plans for WMO, WCRP and the way forward with WCRP's new implementation plan. He stressed that WCRP needs to enhance its strength in order to be able to provide guidance to stakeholders on relevant topics, while taking into account, however, that WCRP is a research programme and not a weather forecast activity. He further emphasized that formulating the key science questions will be crucial as WCRP continues to be a scientific enterprise. The credible integration of social science aspects would provide additional strength. Detlef commented that the number of questions is growing for which the WCRP community is asked to provide convincing answers. He also reminded the community that the complexity of WCRP's structure was criticized repeatedly by reviewers and that WCRP was struggling to financially sustain all working groups and core projects. The Grand Challenges are scheduled to end in the coming years. The number of core projects may change in the new structure. Any transition has to be undertaken in agreement with the sponsors of the existing project offices.

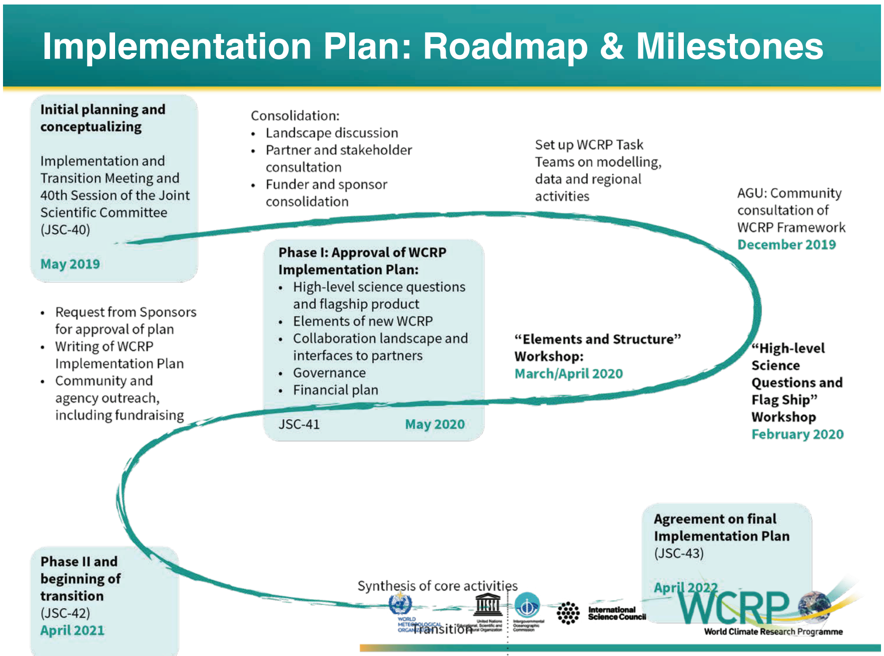

Figure 2: *Roadmap and milestones for the finalization of the WCRP Implementation Plan.*

Annalisa Bracco (via remote link) summarized the structure of the WCRP core project "Climate and Ocean – Variability, Predictability, and Change" (CLIVAR) with oceanography as a main discipline and the various large ocean basins as regional foci. A natural regional cooperation with the CLIVAR-GEWEX Monsoon Panel was reported. Storm track analyses in south-eastern Asia are regarded as an important issue within the CMIP6 efforts. CLIVAR is also much interested in atmospheric composition when tackling carbon fluxes into the ocean.

Beatriz Balino introduced CORA, the Coordination Office for WCRP Regional Activities, which became operational in 2019 and is engaged in the current WCRP task team on regional activities. Three regions of high scientific and societal relevance were identified as the Arctic (Greenland ice sheet), the Andes and the Himalayas (Third Pole).

Discussion session on "Atmospheric dynamics and predictability"

Twelve of the current 18 SPARC activities contributed to this theme. A number of achievements and developments were reported, summarized by the session leads **Amy Butler** and **Seok-Woo Son** at the beginning of the session. Time was also provided for updates from partner projects, namely the "Sub-seasonal to Seasonal prediction project" (S2S; **Frederic Vitart**), the "Polar Climate Predictability Initiative" (PCPI; **Marilyn Raphael**), the "Working Group on Numerical Experimentation" (WGNE; **Julio Bacmeister**), and the "World Weather Research Programme" (WWRP; **Judith Berner**). Each partner project was briefly introduced, results were presented with relevance for SPARC topics under discussion, and expectations were stated regarding possible cooperation with SPARC.

Activity progress and achievements

The *Data Assimilation Working Group (DAWG)* is aiming at 'Dynamical Reanalyses' for which a work plan was developed during a working group meeting held at the University of Colorado/LASP in September 2019 (see report on page 28). 94 scientists participated in the joint workshop of the *Dynamics and Variability (DynVar)* and the *Assessing predictability (SNAP)* activities in Madrid in October 2019 (see report on page 33). DynVar reported that within the DynVarMIP project of CMIP6 dynamical diagnostics are becoming available and three community papers are in preparation.

SNAP acknowledged the special effort by Daniela Domeisen to coordinate two community papers on predictability of the stratosphere and stratosphere-troposphere coupling on S2S timescales. A summary of these papers can be found on page 14.

Research within the *Fine Scale Atmospheric Processes and Structures (FISAPS)* activity showed that reanalyses indicate increasing wind-shear over the North Atlantic (Lee *et al.*, 2019), consistent with climate model projections. The *Gravity Waves* activity received support from the International Space Science Institute (ISSI) to form an international team examining the topic "New Quantitative Constraints on Orographic Gravity Wave Stress and Drag: Satisfying emerging needs in seasonal to sub-seasonal and climate prediction" with a first meeting held in Bern, Switzerland in April 2019. Progress was also reported from the *Observed Composition Trends and Variability in the Upper Troposphere and Lower Stratosphere (OCTAV-UTLS)* activity, with a new update of the JETPAC (JEt and Tropopause Products for Analyses and Characterization) algorithm to analyze multiple satellite-, ground-based and airborne in-situ ozone records in various dynamical coordinates. Furthermore, ozone datasets were remapped in the UTLS for an evaluation and ranking regarding coordinate-dependent reduced UTLS ozone variability.

The *Quasi-biennial Oscillation Initiative (QBOi)* contributed six publications on QBO modelling intercomparison to a special section of the Quarterly Journal of the Royal Meteorological Society in addition to a final publication of previous modelling studies (Butchart *et al.*, 2018). The new *Stratospheric And Tropospheric Influences On Tropical Convective Systems (SATIO-TCS)* activity coordinated its work during a number of meetings and workshops during the past year. The *Solar Influences for SPARC (SOLARIS-HEPPA)* activity fostered evidence that solar variability is indeed a source of decadal climate predictability (Kushnir *et al.*, 2019). Progress was also made on the challenging subject of how to separate solar-induced dynamical signals from internal climate variability as was reported during a working group meeting in Granada, Spain (see report on page 30). The *SPARC Reanalysis Intercomparison Project (S-RIP)* is on track towards a successful completion as report chapter manuscripts were submitted in November 2019. The SPARC Office is currently handling the review, and plans to finalize and publish the full report during 2020.

Future plans

In parallel to shaping the WCRP implementation plan and defining a new SPARC strategy, SPARC activities expressed concrete plans for future studies. These include a systematic reanalysis intercomparison in the upper stratosphere/lower mesosphere (*DAWG*) and dynamic diagnostic output for CMIP6 (*DynVarMIP*). *DynVar* will place emphases on the troposphere and extremes, while continuing to consider stratosphere dynamics and stratosphere-troposphere coupling. *FISAPS* envisages orchestrated efforts to document and understand fine-scale structures in the vicinity of the tropopause as well as dissipative processes and their treatment in global models.

The *Gravity Waves* activity plans to advance efforts regarding their study on orographic gravity wave stress and drag, also through a joint workshop with the Pan-GASS project on surface drag and momentum transport. Mechanisms controlling the relation of ozone with dynamical coordinate variables are to steer future work of the *OCTAV-UTLS* activity, while *QBOi* will concentrate on QBO-influences for seasonal to decadal prediction. In 2020, a dedicated workshop is planned to commemorate the 60th anniversary of QBO's discovery, including the composition of a review publication. SATIO-TCS will concentrate on the downward influence of the stratosphere with regard to tropical convection. They also plan two review publications and have scheduled a workshop in February 2020. *SNAP* plans an additional community paper on stratosphere-troposphere coupling biases in S2S prediction systems, while working on further understanding stratospheric influence on tropospheric predictability on S2S timescales. Finally, the research interest of the *SOLARIS-HEPPA* activity will lie on extracting solar-induced dynamical signals and their influence on decadal climate predictability.

Future science questions

The various activity reports contain a number of promising topics for future research, *e.g.*, the quantification of different classes of uncertainties in both reanalyses and prediction, specific improvements in current simulation models, modification of general circulation structures (*e.g.* Brewer-Dobson circulation, QBO) in a changing climate, and regional aspects of global climate change.

The discussions in the break-out groups revealed further topics of interest (summarized by **Scott Osprey**). These included:

- systematic stratosphere errors/uncertainties/biases impacting forecasts and forecasting skill,
- assessing resolution and resolution dependent processes for alleviating stratosphere biases,
- space weather impacts on composition in mesospheric and stratospheric levels,
- tropospheric impacts of stratospheric extremes, *e.g.* sudden warmings, volcanic eruptions,
- tropospheric dynamical extremes and compound events, *e.g.* blocking and stalled Rossby waves,
- tropical stratospheric impact on atmospheric rivers and possible precipitation extremes,
- climate change effects on weather and regional circulations (recognizing the opportunity to establish and strengthen links to the WWRP).

During the plenary discussion the following additional topics were mentioned: the systematic use of the novel AEOLUS wind data, envisaged longer lead times for S2S-simulations, and the role of ozone with regard to thermodynamic/circulation feedbacks in model simulations.

Discussion session on "Chemistry and Climate"

This session addressed eight of the SPARC activities. It was introduced by **Don Wuebbles** and **Gufran Beig**, who provided a grand overview starting from the WCRP's implementation plan structure via fundamental physical and chemical processes to a list of emerging issues. The session also included presentations from the International Global Atmospheric Chemistry Project (IGAC; **Megan Melamed**) and the Network for the Detection of Atmospheric Composition Change (NDACC; **Martine De Mazière**).

Activity progress and achievements

The *Atmospheric Composition and the Asian Monsoon (ACAM)* activity held its 4th workshop following the 3rd training school in Kuala Lumpur with a total of 154 scientists from 22 countries in attendance (see report on page 19). Another training school was held by the *Chemistry-Climate Model initiative (CCMi)* in Hong Kong in August (see report on page 22). CCMi has juxtaposed advantages and disadvantages of applying CCM-nudging to reanalysis data, published in various papers in the ACP/AMT/ESSD/GMD special issue. The *Atmospheric Temperature Trends (ATC)* activity produced two publications; one addressed the signal-to-noise ratio in temperature trends and time of emergence (Santer *et al.*, 2019), while the other determined the dynamical contribution to temperature trends in the lower stratosphere (Fu *et al.*, 2019). A 'Chemical Reanalysis' theme was newly established by the *Data Assimilation Working Group (DAWG)* with the goal to evaluate and intercompare different chemical reanalysis datasets in order to tackle issues such as the estimation of instrument bias, data homogenization and bias correction among different datasets for the purpose of trend estimation.

An assessment of change in ozone distribution within the upper troposphere / lower stratosphere (UTLS) region was carried out by the *OCTAV-UTLS* activity, which used their JETPAC algorithm to evaluate changes in jet-strength and tropopause-heights. The *Polar Stratospheric Cloud (PSC)* activity compiled the state of polar stratospheric cloud science in the draft of a review article. Improved process understanding of solar-chemistry interactions became a central objective of the *Solar Influences for SPARC (SOLARIS-HEPPA)* activity, which is preparing an overview publication on this topic. Data from the Stratospheric and upper tropospheric processes for better climate predictions (StratoClim) campaign were evaluated within the *Stratospheric Sulfur and its Role in Climate (SSiRC)* activity; it also developed an initiative, termed VolRes, to facilitate cooperation between experimentalists and modellers immediately after major volcanic eruptions.

Future plans

ACAM intends to support the Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP) field campaign in Japan, to coordinate model simulations in cooperation with Aerosol Comparison between Observations and Models (AeroCom) and *CCMi*, and to further analyse and publish StratoClim data. *DAWG* will work to further develop the new Chemical Reanalysis theme and reach out to other SPARC activities with demands for data assimilation.

Transport barriers and stratosphere-troposphere exchange are to be examined by *OCTAV-UTLS*, where topics such as mixing processes across dynamical barriers, relationships of ozone to natural modes of variability (*i.e.* QBO, ENSO), and climate impacts on long-term changes in UTLS composition are of particular relevance.

SSiRC sets out to determine constraints for the pathways of stratospheric aerosol and its precursors by investigating various radiative effects. The *PSC* activity is to come to a close during 2020 after the publication of the review article and a summary to be published in the SPARC newsletter.

Future science questions

The activity reports listed future research topics as, *e.g.*, the interrelation of aerosol-cloud-effects and radiative forcing, a systematic quantification of uncertainties in reanalyses, and thorough investigation of different coupling mechanisms across the UTLS-layer.

The break-out group discussions revealed further topics of interest (summarized by **Hans Schlager**), including:

- the role of intense convection and lightning induced NOx,
- investigation of aerosol-cloud interaction (including secondary organic aerosol),
- monitoring emission change following measures to mitigate climate change.

The plenary discussion revealed that the spatial extent of future SPARC activities needs to be agreed upon, *i.e.* whether or not processes at mesospheric and thermospheric levels should be considered to determine their impact on the stratosphere.

Discussion session on "Long-term records for climate understanding"

Achievements and developments from six relevant activities were reported, summarized by the session leads **Nathaniel Livesey** and **Andrea Steiner**. Partner presentations included an overview of activities at the Japanese Space Agency (JAXA, **Masatomo Fujiwara** on behalf of **Makoto Suzuki**) and the WCRP Data Advisory Panel (WDAC, **Susann Tegtmeier**).

Activity progress and achievements

The SPARC/IO3C/GAW Report on *Long-term Ozone Trends and Uncertainties in the Stratosphere, (LOTUS)* was published as SPARC Report No. 9. It was prepared by the members of the LOTUS activity, and underwent scientific review organized by the SPARC Office. Essential parts had provided timely input to chapter 3 of the WMO/UNEP Ozone Assessment 2018. The activity started its next phase with foci on stratospheric ozone trend models, its own multiple linear regression trend model, and a comparative homogenization of ozone records. The *Atmospheric Temperature Changes and Their Drivers (ATC)* activity is preparing a community paper about an update on atmospheric trends from observations that is providing valuable input to chapter 2 of the IPCC sixth Assessment Report. The *Water Vapour Assessment II (WAVAS II)* activity prepared consistent water vapour datasets from satellite observations, which are publicly available and carry a digital object identifier (DOI) number.

The *Stratospheric Sulfur and its Role in Climate (SSiRC)* activity has completed its work on revising key aerosol datasets, and started the second phase termed Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP). Analyses and comparisons of long-term datasets (ground-based as well as from commercial aircraft) were carried out by the *OCTAV-UTLS* activity, using their JETPAC algorithm. The activity also assessed reduction of uncertainties in dynamical coordinates through trend analyses on Aura MLS records. Meanwhile, the *Towards Unified Error Reporting (TUNER)* activity has developed a framework unifying error reporting approaches of a range of remote measurement techniques, observing wavelengths, target parameters, as well as retrieval approaches. A fundamental paper (von Clarmann *et al.*, 2019) was submitted to the TUNER special issue in Atmospheric Measurement Techniques.

Future plans

The collection and archival of updated ozone records will be one future activity of *LOTUS*, while participants also want to study regional trends especially in polar regions, coherence of stratospheric/tropospheric/ total column ozone and trend model optimisation.

LOTUS will hold a joint TRENDS workshop with the *ATC* activity, which will also finalize their contributions to IPCC AR6 and their community papers. Scientific focus will be on the uncertainty of observations, analysis of CMIP6 warming trends and attribution studies.

SSiRC has defined three questions that they want to answer in their future work: (i) How does ultra-fine ash influence the volcanic sulphate radiative forcing? (ii) How do anthropogenic emissions of aerosol precursors affect stratospheric aerosol variability? And (iii) How does the tropospheric sulfur cycle respond to climate change and how does that affect stratospheric aerosol? *CCMi* plans to assess the science coming out of CMIP6 Aerosol Chemistry Model Intercomparison Project (*AerChemMIP*), and to organize simulations to support the 2022 Ozone Assessment.

A paper aimed at explaining the updated JETPAC output products and showcasing some of the dynamical coordinates selected to reduce ozone variability in the UTLS is planned by *OCTAV-UTLS*. *TUNER* plans a paper aimed at data users and will work on the quantification of the impacts of spatio/temporal variability on "coincidence based" validation studies.The *WAVAS II* activity will end during 2020, but hopes that research questions related to stratospheric water vapour will be incorporated into other SPARC activities. *S-RIP* will focus on finalising its SPARC report (number 10), and intends to start a Phase 2 in 2022.

Future science questions

Future science questions within this theme focus on improved understanding of the uncertainties in observations and reanalysis, and of composition changes in a changing climate. A number of activities pointed out the need to improve climate models' representation of natural variability. Attribution of extreme events and climate variability (How do long-term changes alter atmospheric weather patterns and trigger atmospheric extremes, regional response and surface impacts?) were also identified as an important topic for the future, along with the idea to exploit long-term climate data records for gaining fundamental understanding of short-term climate variability and long-term climate trends from the troposphere to the mesosphere and their causes.

The question was asked, whether SPARC can help to monitor and measure progress towards international targets, and to address societal challenges, low carbon transitions, as well as geoengineering impacts on atmospheric composition. SPARC could define the observing system needed to address those topics, and assess whether current and planned observing systems meet those needs.

Nathaniel Livesey summarized the following discussion, in which further activities were mentioned, such as sustaining and increasing observation and modelling interactions (looking for suitable cross-sections between activities, following the example of S-RIP). Furthermore, improved reanalyses leading to the need for more exact measurements and analyses were mentioned. Full resolution data is often available, but not provided, as it is often cut to the needs of operational agencies. Again, the plenum discussed possible SPARC work to identify critical needs for sustained and new measurements, and agreed that it would be good to hear what operational agencies use or plan to use, however, keeping in mind that data for fundamental research might have to meet different needs. It was mentioned, that a paper on looming gaps was submitted but not welcome in chosen journals.

SPARC Strategy discussions

Neil Harris started the strategic discussion on SPARC's new Implementation Plan 2021-2025, with a retrospective on the challenges and conditions that the SPARC community faced during development of its current strategic plan. He also illustrated that SPARC has been very productive and suggested that it will be useful to produce a brief achievement report to summarize SPARC's success.

A few conditions for the key science questions of SPARC's new strategic plan for 2021-2025 were addressed. The key questions should build on information and identified gaps of recent assessment reports including IPCC's 1.5°C and Land Use special reports, or the WMO/UNEP ozone report. Identified key questions should also contribute to the four science objectives stated in the WCRP strategic plan:

(1) Understanding Earth System processes,

(2) Variability, Predictability and prediction

(3) Climate change projections and ESM feedbacks, and

(4) Bridging climate science and society, managing climate risks.

Lively strategic discussions continued in two breakout sessions and subsequent synthesis. The overarching key science questions that could be included in WCRP's Implementation plan are first formulated:

1. How can prediction of weather and climate-related extreme events on sub-seasonal to decadal timescales be improved?
2. How will climate change on interannual to centennial timescales?
3. How and why is atmospheric composition changing over time and what are the impacts?

Then, all participants formulated a list of SPARC specific research topics and questions that would address the overarching questions together and identified the potential partners that SPARC would work with.

Input from SPARC activity reports, and feedback during discussions

There is an understanding that SPARC should continue to lead the focus on the "atmosphere" aspect in climate research with its balance between observations and modelling and its balance between dynamics and chemistry. Suggestions were made to extend to the mesosphere-lower thermosphere region in cases where an important role in the climate system exists.

The SPARC community expressed support for fundamental research, arguing against using poorly understood aspects of model simulations for impact studies. They want to retain focus on basic science issues that underpin climate modelling, such as process-level understanding to improve physics in models for timescales from long-range weather to climate. At the same time, they support the need to improve capacity building activities and to put more emphasis on fostering engagement with society.

SPARC's role in infrastructure aspects (*i.e.* the role of SPARC data centre, archiving model data and observational records) was brought up, along with a strongly expressed need for continued long-term measurements and global observations, driven by a concern about the availability of satellite datasets in the future. Observational data with high vertical resolution are needed to be available in the future. SPARC could formulate what observing systems are needed for climate research.

SPARC activities expressed willingness and need of increased interaction among activities (*e.g.* joint webinars or workshops), still valuing the current diverse portfolio of SPARC activities. They value of the bottom-up approach to answering science questions was strongly promoted, acknowledging that SPARC works well through a combination of match-making and ground-up initiatives – a practice that should be continued.

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The 2019 Antarctic sudden stratospheric warming

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Forecast of a rare stratospheric event

In late August 2019, operational forecast centres began to predict a very strong and potentially record stratospheric warming event over Antarctica to develop in the upcoming austral spring. Thanks to the advent of stratosphere resolving seasonal predictions, the warming was predicted both to be abrupt and long-lived. For instance, about 10-30% of ensemble forecast members from the Australian Bureau of Meteorology, European Centre for Medium-Range Weather Forecasts, Japanese Meteorological Agency and the UK Met Office forecast systems that were initialized on 1-3 September 2019 suggested a sudden reversal of the stratospheric polar vortex westerly winds at 10 hPa to occur sometime between mid-September and mid-October while all forecast members predicted a substantially weakened vortex to persist through November (Figure 3). Were this wind reversal to have occurred, it would have been only the 2[nd] ever observed major sudden stratospheric warming (SSW) in the Southern Hemisphere (SH) after that of 2002 since observations began in the 1950s. In addition to predicting the increased chance of a SSW and the associated strong weakening of the polar stratospheric vortex into early spring, a strong swing toward the negative polarity of the Southern Annular Mode (SAM) was predicted at the surface for October and November (**http://poama.bom.gov.au/access-s1/bom/**). Based on evaluation of hindcasts initialized during the past 20-30 years, skill to predict variations of the Antarctic polar vortex during austral spring and its downward coupling to the surface is very high for forecasts initialized from 1 August onward (e.g. Domeisen *et al.*, 2019; Seviour *et al.*, 2014; Byrne, Shepherd, and Polichtchouk, 2019). Researchers and forecasters thus promptly acted on these predictions by announcing the possibility of a rare and possibly record stratospheric warming event over Antarctica in spring 2019 with impacts at the surface as a result, and a swing to negative SAM to extend through early austral summer (e.g. Hendon *et al.*, 2019). So how did this stratospheric warming unfold?

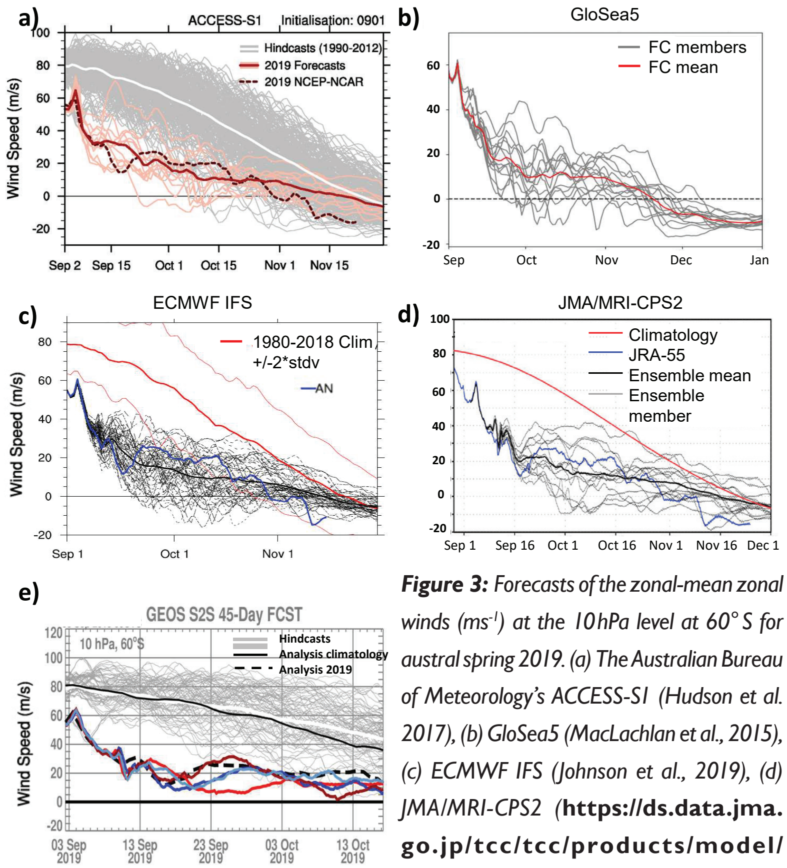

Figure 3: *Forecasts of the zonal-mean zonal winds (ms*$^{-1}$*) at the 10 hPa level at 60° S for austral spring 2019. (a) The Australian Bureau of Meteorology's ACCESS-S1 (Hudson et al. 2017), (b) GloSea5 (MacLachlan et al., 2015), (c) ECMWF IFS (Johnson et al., 2019), (d) JMA/MRI-CPS2 (***https://ds.data.jma.go.jp/tcc/tcc/products/model/outline/cps2_description.html***), and (e) NASA GEOS-S2S (***https://gmao.gsfc.nasa.gov/cgi-bin/products/climateforecasts/geos5/S2S_2/index.cgi***). Forecasts were initialised in early September 2019. The thick solid curves in the midst of respective thin curves displayed in (a)-(d) indicate ensemble mean forecasts. The dotted curves in (a) and (e) indicate NCEP-NCAR (Kalnay et al., 1996) and MERRA-2 (Gelaro et al., 2017) reanalyses, respectively, and the thick blue curve in (c) indicates ECMWF operational analysis. The grey curves with the thick white curve in (a) and (e) display all members of hindcasts with their mean (i.e. ensemble mean climatology) initialized in early September. The thick red curve in (c) and (d) displays the climatology of the hindcasts initialized in early September.*

The stratospheric polar vortex weakening and warming in austral spring 2019

Beginning on 25 August 2019, the Antarctic stratospheric polar vortex abruptly weakened and warmed. According to the NASA Ozone Watch (**https://ozonewatch.gsfc.nasa.gov/**), the stratospheric jet at 10 hPa and 60° S suddenly slowed from about 90 ms^{-1} to 10 ms^{-1} from August 25 to September 17 (Figure 4a), and the Antarctic polar cap average temperature at 30 hPa increased by 35 K from 194 K during the same period (Figure 4b). For this time of the year, this weakening and warming were unprecedented in the mid-to-upper stratosphere during the 40-year observational record of the satellite era, therefore setting all-time records for September. This extraordinary weakening of the polar vortex occurred in association with record strong low-frequency upward wave forcing from the troposphere, as indicated by the record strong poleward heat flux at the 100 hPa level (Figure 4c). The ozone hole that had appeared earlier than usual in late August grew to an area over 15 million km^2 by September 1, but then fell on an area of 8 million km^2 by September 17 (Figure 4d). The zonal-mean zonal winds at 10 hPa and 60° S, however, never fully reversed, and so the conditions for a major SSW were not met (Butler *et al.*, 2015). Nonetheless, the strong weakening and warming of the mid-upper stratospheric vortex persisted through the end of November. At the 10 hPa level, the vortex finally broke down on 30 October, which was the 2nd earliest vortex breakdown date (Butler and Gerber, 2018) since 1979, following the record set in 1988 (27 October).

Although the warming in 2019 did not meet the criterion of a major SSW (*i.e.* a reversal of the zonal-mean zonal winds at 60° S and 10 hPa), the sustained magnitude of the wind and temperature changes during early spring were comparable to those of 2002 (Figure 4a). Perhaps the only reason that the 2019 event did not achieve a major SSW status was that it started substantially earlier in the seasonal cycle when the polar vortex was still very strong and cold, compared to the 2002 major SSW when the vortex was more favourably pre-conditioned for a warming.

Apart from the unprecedented early development of this sudden stratospheric vortex weakening and warming, this event was also unusual for its delayed downward coupling to the surface. Compared to 2002 whose anomalous stratospheric signal "dripped" down to the surface almost immediately, resulting in record strong negative SAM during October 2002, the strong stratospheric anomalies in 2019 did not penetrate downward to the surface until the 3rd week of October.

Tropospheric conditions in austral spring 2019

A plausible cause for the lack of downward coupling from the onset of the event in late-August up through mid-October was the co-occurrence of a very strong positive Indian Ocean Dipole mode (IOD; Saji, *et al.*, 1999) (**http://www.bom.gov.au/climate/**; Figure 5a). The positive phase of the IOD is characterized by anomalous sea surface cooling off Java-Sumatra in the tropical eastern Indian Ocean (0-10° S, 90-110° E) concurrent with anomalous sea surface warming of the tropical western Indian Ocean (10° S-10° N, 50-70° E) (Saji *et al.,* 1999). The IOD is a source of Rossby wave trains that propagates poleward and eastward into the South Pacific (Cai *et al.,* 2011), where it can affect storm activity (Ashok *et al.,* 2007) and thus rainfall across southern and eastern portions of Australia and even Antarctic sea ice (Wang *et al.*, 2019). The IOD, therefore, serves as an important source of predictability of the SH monthly and seasonal climate over tropical eastern Africa, the Indian continent, Indonesia and Australia (*e.g.* Ashok, Guan, and Yamagata, 2001; Marchant, Mumbi, Behera, and Yamagata, 2007; White, Hudson, and Alves, 2013) and the Antarctic sea-ice extent (Nuncio and Yuan, 2015).

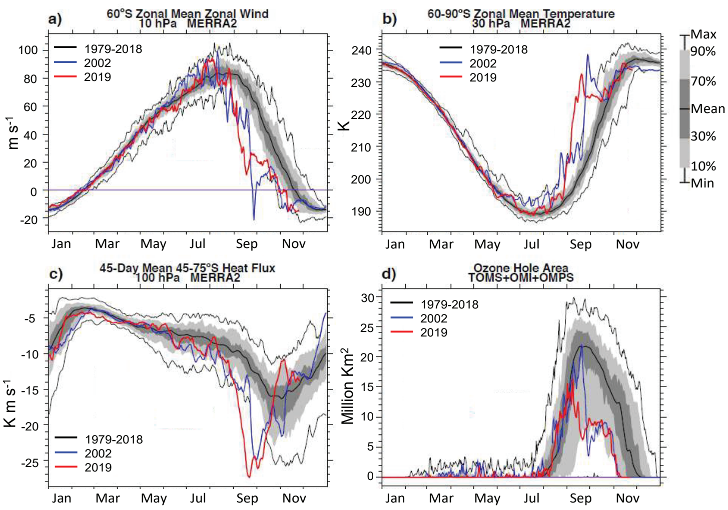

Figure 4: *Observed conditions of the Antarctic polar vortex in 2019 (red curves) compared to those in 2002 (blue curves) and those of climatology (black curves). (a) Zonal-mean zonal wind at the 10 hPa level at 60° S; (b) polar cap temperature averaged over 60-90° S at the 30 hPa level; (c) 45-day mean heat flux averaged over 45-75°S at the 100 hPa level; and (d) Antarctic ozone hole area. The unit is shown on the left of the Y-axis. Plots and data are available from the NASA Ozone Watch site (**https://ozonewatch.gsfc.nasa.gov/SH.html**).*

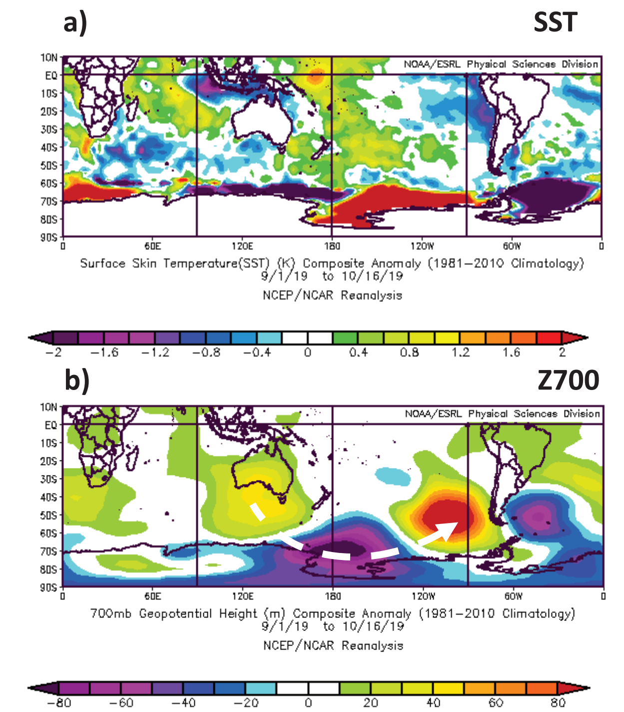

***Figure 5:** (a) Surface skin temperature (K) and (b) 700 mb geopotential height (m) anomalies averaged over the period of 1 September to 16 October 2019 relative to the climatology of 1981-2010. Plots were generated using the graphical user interface portal of NOAA Physical Science Division* **https://www.esrl.noaa.gov/psd/data/composites/day/** *with the NCEP-NCAR Reanalysis set.*

The observed tropospheric circulation anomalies from September to mid-October 2019 show a clear signature of the IOD with a well-defined Rossby wave train that arcs poleward and eastward into the South Pacific (Figure 5b). It appears to be associated with lower than normal heights over the polar cap, which would oppose the tendency of the stratospheric warming to produce higher than normal heights. Further study is required to determine whether the IOD simply acted to interfere with the tropospheric signal being produced by the stratospheric warming or whether there was a dynamical interaction between the anomalous circulation produced by the IOD and the downward coupling process in the polar vortex.

Since late October until the end of December, the stratospheric vortex weakening has robustly coupled down to the surface, promoting the predicted strong and persistent negative SAM (Figure 6a,b). This negative SAM was a key driver of climate anomalies across the SH, including promotion of wet conditions in western Tasmania, the southern part of the South Island of New Zealand, Patagonia and southeast South America, while promoting hot and dry conditions and wild fires in eastern Australia (Gillett *et al.*, 2006; Lim *et al*,. 2018, 2019; Garreaud, 2018) (Figure 6c,d).

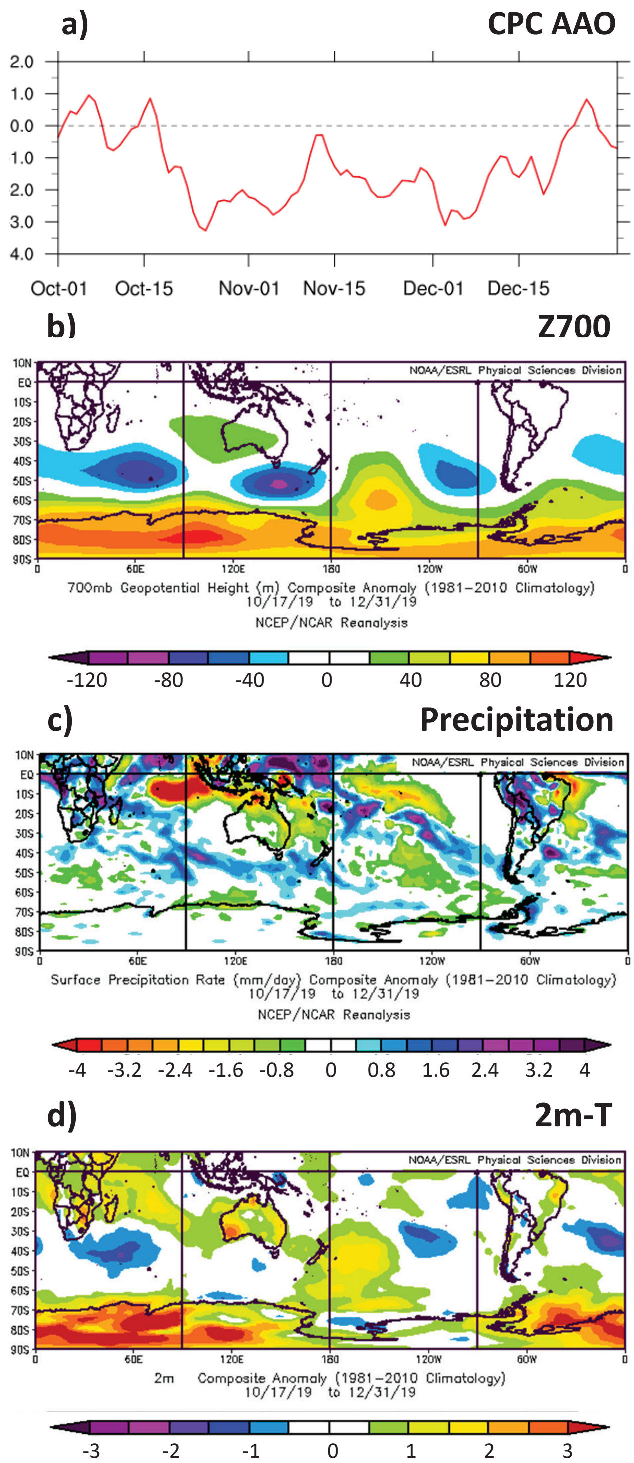

***Figure 6:** (a) NOAA CPC daily Antarctic Oscillation index for October to December 2019, (b) 700 mb geopotential height (m), (c) precipitation rate (mm day^{-1}) and (d) 2m air temperature (°C) anomalies averaged over the period of 17 October to 31 December 2019 relative to the respective climatology of 1981-2010. Maps were generated using the graphical user interface portal of NOAA Physical Science Division* **https://www.esrl.noaa.gov/psd/data/composites/day/** *with the NCEP-NCAR Reanalysis set.*

Concluding remarks

Although a full-blown major SSW did not occur in 2019, a sustained warming and weakening for spring, which was of record strength during September, was well predicted starting from late August.

Together with an improved understanding and appreciation of the long-lived impacts of anomalous weakening of the Antarctic polar vortex on surface climate, especially the increased chances of extreme conditions, including the increased risk of fire weather danger and extreme precipitation events, the stratospheric polar vortex is a promising source of enhanced predictive skill for climate across much of the SH.

From the research perspective, this 2019 stratospheric warming event and its forecasts motivate some interesting questions to be explored:

- What was the source of the record strong upward wave forcing from the troposphere that initiated the event?
- Was there any preconditioning such as anomalous meridional shifts of the upper stratospheric jet earlier in the winter that enabled this large warming?
- What was the role played by the IOD and other tropical SST anomalies both for the onset of the event and for the delayed downward coupling to the surface?
- Why was a SSW predicted by some of the ensemble members? Were there any precursors or distinctive dynamical features in the ensemble members that predicted a SSW?

Comparative case studies on the 2002 and 2019 events may also reveal some clues on the conditions needed for the occurrence of the rare southern SSW.

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The role of the stratosphere in sub-seasonal to seasonal prediction

Scientific report for the Stratospheric Network for the Assessment of Predictability (SNAP)

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A recent effort by the SNAP community (led by co-chairs Amy Butler and Andrew Charlton-Perez) is the assessment of prediction skill on sub-seasonal to seasonal (S2S) timescales with regards to the stratosphere. In particular, SNAP has performed an intercomparison of the prediction systems in the S2S database, led by Daniela Domeisen. The assessment has been published in the special issue of Journal of Geophysical Research – Atmospheres on "Bridging Weather and Climate: Subseasonal-to-Seasonal (S2S) Prediction" as a two-part paper (full references can be foundbelow). The goal of these two studies is to bring together stratospheric scientists working with the S2S database and to together provide a state-of-the-art assessment of predictability in the stratosphere (Part 1) and stratosphere – troposphere coupling (Part 2). The following sections provide a summary of the findings of both studies. In addition to the results described here, a range of additional publications have been written over the past two years relating to this study, using the same models and focusing on particular parts of stratospheric predictability, as indicated below.

Introduction

The stratosphere is known to contribute significant predictability to surface weather and climate in winter and spring on sub-seasonal to seasonal timescales. The recent availability of model databases on S2S timescales, some of which include stratospheric data, allows for the assessment of predictability related to the stratosphere. Our studies assessed skill across all models from the S2S project database that make stratospheric data available. In particular, we compare the predictability of the troposphere to the stratosphere, since the stratosphere generally exhibits longer memory and would therefore be expected to have a higher predictability. We also analyse the signal-to-noise ratio of the stratosphere on sub-seasonal timescales, which has so far not been assessed. We assess the predictability of stratospheric extreme events, including early winter vortex weakenings, sudden stratospheric warming (SSW) events, *i.e.* reversals of the polar vortex in midwinter, strong vortex events, extreme negative heat flux events, and final warmings marking the end of winter in the stratosphere for both hemispheres. These events have different characteristics in terms of their mechanism and evolution, and hence might be expected to exhibit differences in terms of predictability. In addition to an evaluation of the stratosphere, we investigate precursors to SSW events in the extratropical troposphere and in the tropical troposphere and stratosphere.

This article summarizes the findings presented in the two SNAP community papers published in:

Domeisen, D.I.V., A.H. Butler, A.J. Charlton-Perez, B. Ayarzagüena, M.P. Baldwin, E. Dunn-Sigouin, J.C. Furtado, C.I. Garfinkel, P. Hitchcock, A.Yu. Karpechko, H. Kim, J. Knight, A.L. Lang, E.-P. Lim, A. Marshall, G. Roff, C. Schwartz, I.R. Simpson, S.-W. Son, M. Taguchi, 2019: The role of the stratosphere in subseasonal to seasonal prediction. Part 1: Predictability of the stratosphere, *Journal of Geophysical Research: Atmospheres*, **124**. https://doi.org/10.1029/2019JD030920.

Domeisen, D.I.V., A.H. Butler, A.J. Charlton-Perez, B. Ayarzagüena, M.P. Baldwin, E. Dunn-Sigouin, J.C. Furtado, C.I. Garfinkel, P. Hitchcock, A.Yu. Karpechko, H. Kim, J. Knight, A.L. Lang, E.-P. Lim, A. Marshall, G. Roff, C. Schwartz, I.R. Simpson, S.-W. Son, M. Taguchi, 2019: The role of the stratosphere in subseasonal to seasonal prediction. Part 2: Predictability arising from stratosphere - troposphere coupling, *Journal of Geophysical Research: Atmospheres*, **124**. https://doi.org/10.1029/2019JD030923.

SNAP activity webpage: www.sparc-climate.org/activities/assessing-predictability/

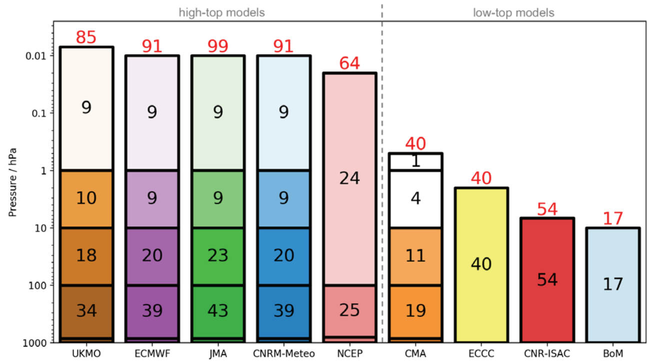

Figure 7: *Schematic representation of model vertical resolution for all S2S prediction systems used in this study. Each block represents the pressure range indicated on the y-axis. The number of model levels in each range is shown numerically. The shading in each box is proportional to the average level spacing [in kilometers] in that region of the atmosphere. The red number at the top of each bar shows the total number of levels in each model. The dashed line indicates the separation between high- and low-top models.*

To consider the influence of the stratosphere on tropospheric predictability, we assess the observed surface amplification of the tropospheric response to stratospheric signals in the multi-model data, as well as lower stratosphere and surface predictability after extreme strong and weak vortex events.

Data and Methods

We use the following prediction systems from the S2S database (Vitart *et al.,* 2017): UKMO, ECMWF, JMA, CNRM-Meteo, NCEP, CMA, ECCC, CNR-ISAC, and BoM. Figure 7 provides a summary of the models in terms of their respective numbers of levels per pressure range. According to this distribution, the models were classified into two categories (high- and low-top models), as indicated in the figure. The model data is compared to ERA-Interim reanalysis in order to assess skill.

Results

As a first step, the assessment of the predictability of the stratosphere versus the troposphere shows that in the Northern Hemisphere, the winter stratosphere is more predictable than its summer counterpart, and the stratosphere tends to exhibit higher predictability as compared to the troposphere for all seasons and for both hemispheres (Figure 8). Interestingly, high-top models tend to exhibit higher predictability as compared to low-top models for both the stratosphere and the troposphere, though no causality is implied, as models with a well-resolved stratosphere may also be equipped to make skillful tropospheric predictions due to typically greater model resolution and complexity, even if no downward impact of the stratosphere is present in the model.

As a next step, the predictability of extreme stratospheric events is investigated. Final warmings at the end of winter tend to be more predictable at sub-seasonal lead times as compared to their midwinter counterparts (Figure 9), *i.e.* sudden stratospheric warming (SSW) events. However, the false alarm ratio for final warmings is also significantly higher, as final warmings by definition happen every year. For SSW events, early winter weak vortex events, and extreme heat flux events, predictability decreases considerably after just a few days for all models. These differences in predictability can likely be explained by the more radiative nature of final warming events, especially late final warming events (Butler *et al.,* 2019), while wave dynamics are responsible for all midwinter events as well as early final warmings, except strong vortex events, where a lack of wave driving is responsible for the event.

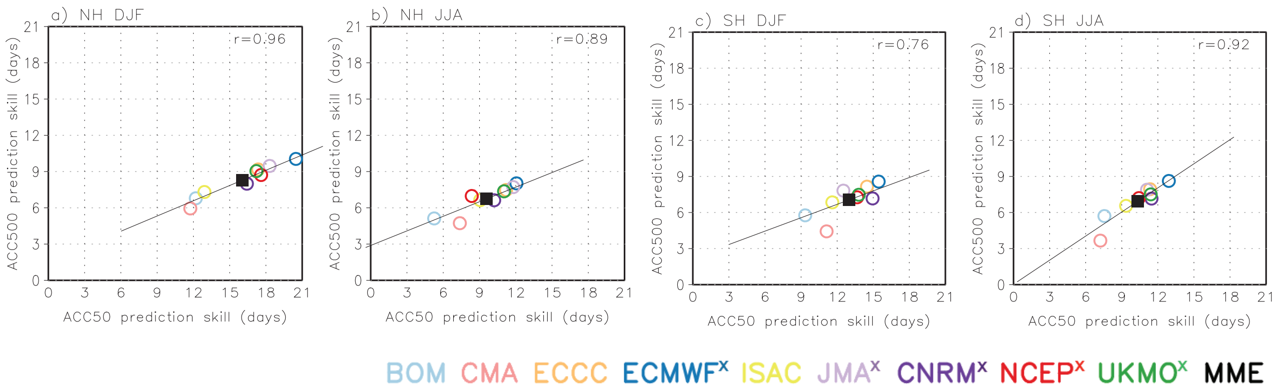

Figure 8: *Scatter plot showing the predictability limit (the day for which the anomaly correlation coefficient (ACC; see Domeisen, et al., 2019a; crosses 0.6) of geopotential height (a-b) north of 30° N and (c-d) south of 30° S for each model at 50 hPa vs. 500 hPa for DJF (a), c)) and JJA (b), d)). The average for all prediction systems is shown as the black square. A linear fit to the data points is shown as the solid line. The correlation coefficient between the prediction skill at 50 hPa and 500 hPa is indicated in the upper-right corner of each panel. '×' indicates high-top models.*

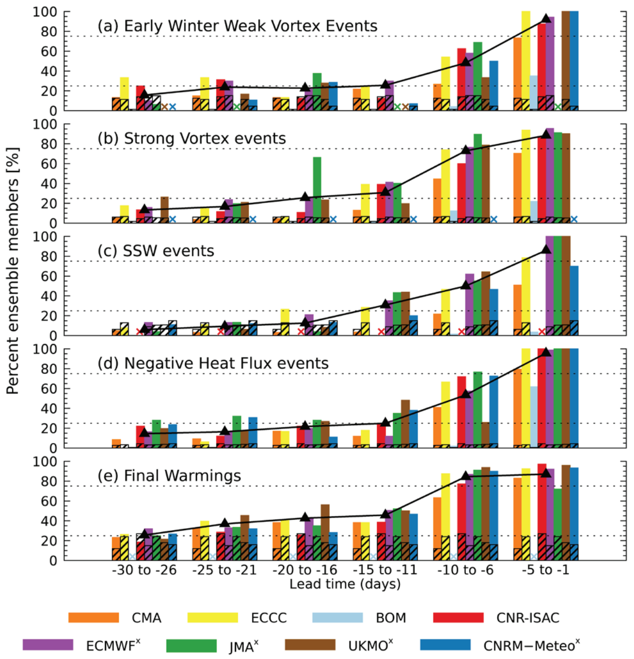

Figure 9: *The average across all events of the percentage of ensemble members as a function of lead time [days] that detect the event within ±3 days of the observed event for (a) early stratospheric warming events, (b) strong polar vortex events, (c) SSW events, (d) negative heat flux events, and (e) final warming events. The black line shows the multi-model mean based on 5 prediction systems (CMA, ECCC, ECMWF, JMA, and UKMO). Dotted lines show where 25 % and 75 % of ensemble members detect the event. '×' marks the high-top models in the legend. Where a prediction system was not used for the analysis or where there were not enough available ensemble members (at least 10 members were required for a given lead time range) is marked by an × in the color of the prediction system. Patterned black bars give the "false alarm rate" (events that were predicted but not detected at the given lead times).*

SSW events, on average over all events, tend to not be predictable for any model beyond the two-week timescale, while final warming and strong vortex events exhibit some predictability beyond three weeks. In addition, final warmings in the Southern Hemisphere exhibit higher predictability as compared to the Northern Hemisphere. Interestingly, for SSW events, displacement events tend to be more predictable than split events, as already indicated by Taguchi (2018) for a smaller set of events.

Although stratospheric extreme events are most often not predictable beyond deterministic lead times, there exist teleconnections and remote forcings that allow for a probabilistic prediction of the frequency and occurrence of these events (Figure 10). For example, tropical phenomena such as the Quasi-Biennial Oscillation (QBO), the Madden-Julian Oscillation (MJO), and El Nino Southern Oscillation (ENSO) can add probabilistic predictability for the polar vortex by weakening the vortex in early winter for easterly QBO, El Nino, or MJO phases 5 and 6, with respect to their respective counterparts. More information on the ENSO teleconnection in S2S models can be found in Garfinkel *et al.* (2019), and on the QBO teleconnection in Garfinkel *et al.* (2018). These teleconnections are found to be present mainly in several of the high-top models. The QBO has not only an extratropical influence via the Holton-Tan mechanism but can also influence tropical convection and the predictability of the MJO (Lim *et al.*, 2019).

In addition to tropical phenomena, precursors have been identified in the extratropical troposphere, especially a deepened Aleutian low in the North Pacific and higher geopotential heights over Eurasia. While most models are able to reproduce the deepened Aleutian low, fewer models fully represent the anomalies over Eurasia, which have recently been found to be a crucial precursor to SSW events (Peings, 2019; White *et al.*, 2018).

Once extreme events occur in the stratosphere, they can be associated with significant downward impacts on S2S timescales (Figure 11).

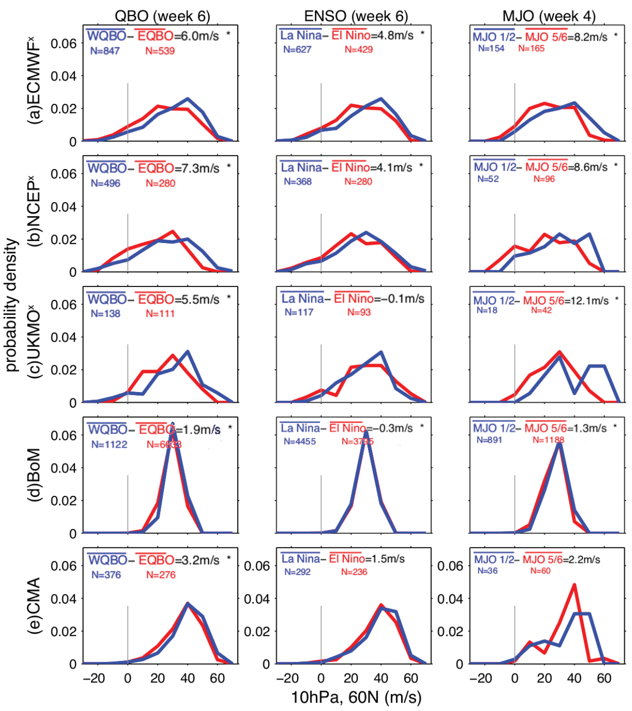

Figure 10: *Probability density of zonal mean zonal wind at 10hPa, 60°N for hindcasts initialized in November and December. Red (blue) lines indicate hindcasts initialized during (left) eQBO (wQBO), (center) El Nino (La Nina) conditions, and (right) MJO phases 5/6 (1/2). All histograms are normalized for comparison. No smoothing is applied. The vertical line indicates zero zonal wind speed. Each panel indicates the difference in the means [ms⁻¹] between the considered phases (top left corner). * indicates values that differ significantly from zero [p < 0.05] as given by a Students t-test. High-top models are indicated by an ×. N indicates the sample size for each category.*

During weeks 3-4 after the occurrence of a weak or strong vortex event, surface temperature anomalies of several degrees C are found, with a focus on Eurasia and eastern Canada. In particular, cold (warm) anomalies dominate northern Eurasia after weak (strong) vortex events, while opposite anomalies are observed further south. These responses are well reproduced in the models, though the multi-model mean response is slightly too weak.

It is not straight forward to be able to say that an overall well-represented multi-model mean response at the surface will indeed lead to increased predictability. Predictability remains difficult to assess, and it is found that especially over Europe, skill often decreases after extreme vortex events, while over Russia, the USA, and the Middle East predictability increases. The limited predictability over Europe is likely linked to Europe being at the node between cold anomalies in the north and warm anomalies in the south after weak vortex events – this transition is not always correctly simulated. In addition, it is found that the small sampling of SSW events in the model database are not sufficient to get good statistics on predictability.

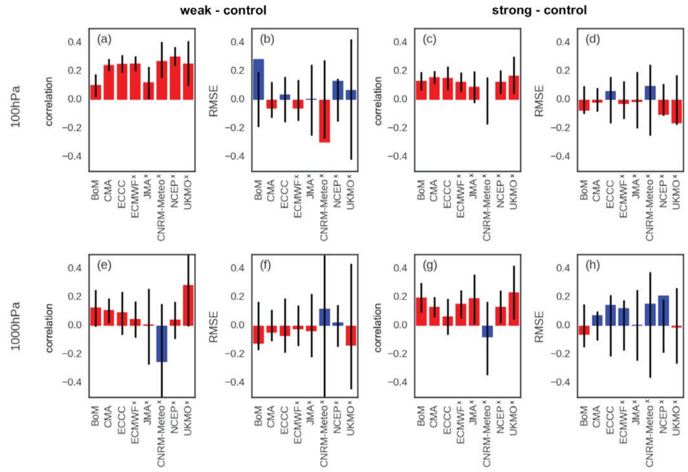

Figure 12: *Differences in skill for forecasts initialized during weak (a,b,e,f) and strong vortex (c,d,g,h) for the NAM index at 100 hPa (top) and 1000 hPa (bottom) for the correlation coefficient (a,c,e,g) and RMSE (b,d,f,h). Where the difference represents an improvement (degradation) in skill the bar is plotted in red (blue). Confidence intervals ($p < 0.05$, estimated from a 10,000 bootstrap sample with replacement) are shown in black lines. All metrics are calculated for the average NAM for weeks 3 and 4. Note that for this analysis, model data was not available for CNR-ISAC and so this model is not included. '×' indicates high-top models.*

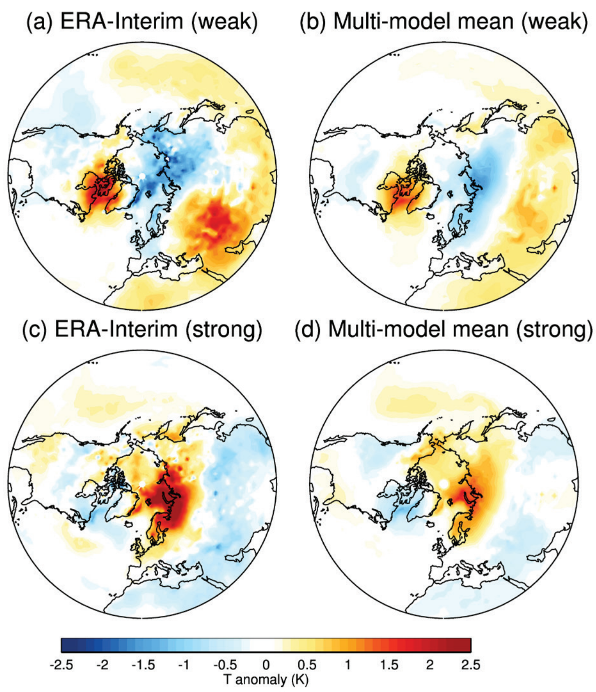

Figure 11: *Composite 2m temperature anomalies (K) for weeks 3-4 for (top) weak vortex states and (bottom) strong vortex states. (b)/(d) show the multi-model mean for forecasts initialized during weak/strong vortex states. (a)/(c) shows the equivalent anomalies for ERA-interim where each date present in the multi-model mean in (b)/(d) has been given an equivalent weighting.*

In order to be more independent of the exact representation of the cold and warm anomalies, and to account for model biases, the changes in predictability in the Northern Annular Mode (NAM) index are also investigated (Figure 12). It now becomes clear that predictability is increased after weak vortex events, and to a lesser degree (with larger error bars), for strong vortex events. This increased predictability is more significant in the lower stratosphere than at the surface, as tropospheric processes can obscure the signal.

Conclusions

In summary, the stratosphere exhibits predictability on a range of different timescales. While on average, it is more predictable than the troposphere, this predictability is limited to deterministic timescales before wave-driven stratospheric extreme events such as sudden stratospheric warmings. Hence, it is challenging to forecast the stratosphere on subseasonal timescales, though predictability in general is higher than in the troposphere, and it is higher before radiatively-driven events as compared to wave-driven events.

Remote teleconnections from the MJO, ENSO, and the QBO can have a significant effect on the polar vortex and could improve probabilistic forecasts of the stratosphere on S2S and longer timescales if simulated correctly.

Several of the high-top models reproduce these teleconnections, inducing a weakening of the vortex during easterly QBO, El Nino, or MJO phases 5 and 6.

The stratosphere can also contribute to surface S2S predictability in certain regions of the Northern Hemisphere for up to several weeks after strong or weak vortex events. The surface temperature signal after strong and weak vortex events is well reproduced and leads to increased predictability in large parts of the Northern Hemisphere.

To conclude, the stratosphere can contribute significantly to S2S prediction, and it is therefore worthwhile including a well-resolved stratosphere in prediction systems. Providing stratospheric data for model prediction databases allows for a better assessment of the contributions of the stratosphere to S2S prediction. We look forward to future collaboration with the S2S community to better understand stratospheric predictability and stratosphere-troposphere coupling on this timescale. If there are scientists not currently involved in SNAP who would like to be involved in future studies, please contact either of the SNAP co-chairs.

The SPARC Network on Assessment of Predictability (SNAP) project seeks to answer several outstanding questions about stratospheric predictability and its tropospheric impact. SNAP's scientific goals include: (i) assessing current skill in forecasting the extra-tropical stratosphere; (ii) investigating the extent to which accurate forecasts of the stratosphere contribute to improved tropospheric predictability; and (iii) understanding the partitioning of any gains in predictability with a well resolved stratosphere between improvements in the estimation of initial conditions and improvements in forecast skills. The central aim of SNAP is to design and organise a new intercomparison of stratospheric forecasts. This will also leave a legacy of datasets to be used by a broad community of researchers.

Find out more at: **www.sparc-climate.org/activities/assessing-predictability/**

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The fourth Workshop and third Training School of ACAM

Hans Schlager[1], Mian Chin[2], Mohd Talib Latif[3], Fatimah Ahamad[3], Ritesh Gautam[4], Federico Fierli[5], and Bhupesh Adhikary[6]

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Date:
24-28 June 2019

Number Of Participants: **153**

Scientific organising Commitee:
Hans Schlager, Mian Chin, James Crawford, Laura Pan, Hiroshi Tanimoto, Michelle Santee, Jianchun Bian, Gabi Stiller, Chang-Keun Song, Klaus Gottschaldt, Jonathon Wright, Ritesh Gautam, Federico Fierli, Buhpesh Adhikary.

Local Organising Committee:
Mohd Talib Latif, Fatimah Ahamad, Abdus Salam, Xuemei Wang, Manish Naja, Suresh Babu, Didin Agustin Permadi, Puji Lestari, Masatomo Fujiwara, Sachiko Hayashida, Prabir Patra, Chang-Keun Song, Rokjin Park, Ohnmar Tin Hliang, Maheswar Rupakheti, Muhammad Fahim Khokar, Liya Yu, Worradorn Phairuang, Kim Oanh, To Thi Hien.

Host Institution:
Universiti Kebangsaan Malaysia, Bangi, Malaysia

Workshop Webage:
http://www.ukm.my/acam/

Activitiy webpage:
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 which has important regional and global impacts. The aim is to build strong international collaborations for ACAM science, and to promote early career scientists and students in the monsoon region.

The ACAM activity was initiated in 2013 and focuses on the interplay between emissions, monsoon dynamics and atmospheric composition. The objective is to understand the impacts from local to global scales including air quality, aerosol-cloud interaction, convective transport of pollutants, and effects on the composition of the upper troposphere and lower stratosphere. Integrated studies are important to quantify the impact of the monsoon system, including in-situ and remote sensing observations as well as modeling from regional to global scales. ACAM promotes the establishment of international collaborations bringing together diverse expertise and resources as well as capacity building in the monsoon region through workshops and training schools.

Following the first ACAM workshop in Kathmandu, Nepal, 2013, and the ACAM workshops and training schools in Bangkok, Thailand, 2015, and Guangzhou, China, 2017, the present workshop and training school in Bangi, Malaysia again provided an excellent opportunity for ACAM scientists to highlight and discuss their research results and for students and early career scientists to learn about ACAM related science and to get familiar with corresponding datasets in small projects conducted during the training school.

Workshop

The fourth ACAM Workshop was held on 26-28 June 2019 at the Universiti Kebangsaan Malaysia (UKM) in Bangi, Malaysia, including 153 participants from 22 countries/regions. Scientific presentations and discussions covered a broad range of topics including emissions and air quality in the monsoon region, deep convection coupled to surface emissions, transport pathways of pollutants into the stratosphere, Asian tropopause aerosol layer (ATAL), and monsoon-climate interactions. An understanding and accurate representation of the monsoon system in global chemistry-climate models is critical to predicting climate change. The workshop program was structured according to the four ACAM themes:

1. Emissions and air quality in the Asian monsoon region,
2. Aerosols, clouds, and their interactions with the Asian monsoon,
3. Impact of monsoon convection on chemistry,
4. Response of the upper troposphere and lower stratosphere to the Asian Monsoon.

Sponsors:

The workshop included 50 oral and 90 poster presentations. About 30 percent of the oral presentations were given by early career scientists. All posters were also introduced in rounds of 1-minute oral presentations. After an introductory presentation to the workshop by **Hans Schlager** (DLR, Oberpfaffenhofen, Germany), each session began with invited talks. Concerning emissions and air quality in Asia, **Tao Wang** (Uni. Hong Kong) presented tropospheric ozone trends in subtropical Asia, **Nguyen Thi Kim Oanh** (AIT, Bangkok, Thailand) described the role of crop residue burning for air quality in the monsoon region, and **Maheswar Rupakheti** (IASS, Potsdam, Germany) presented mitigation measures of air pollution in the Himalayan region. Aerosol-induced changes in convective cloud systems were discussed by **Chandan Sarangi** (PNNL, Richland, USA). **Hartwig Harder** (MPI-C, Mainz, Germany) presented aircraft measurements and results of simulations with a global chemistry model related to the OMO campaign in the Asian monsoon region. **Pengfei Yu** (NOAA, Boulder; USA and Uni. Jinan, Guangzhou, China) discussed modeling of stratospheric aerosols. Results from the recent StratoClim aircraft campaign in the center of the Asian summer monsoon anticyclone were presented by **Stephan Borrmann** (MPI-C, Mainz, Germany) and **Michael Höpfner** (KIT-IMK, Karlsruhe, Germany). Contributed presentations covered results from recent balloon campaigns (SWOP and BATAL) as well as modeling results on the coupling of local emissions with regional and global composition. Also, satellite retrievals of atmospheric composition over the Asian monsoon region were presented. In addition, plans for upcoming field campaigns related to ACAM were reported, e.g. the ACCLIP campaign in 2020. Most of the oral and poster presentations are available on the ACAM website **https://www2.acom.ucar.edu/acam**.

The workshop also included break-out meetings of the three ACAM working groups:

1. "Observations and Data Sharing" which aims to identify ACAM-relevant datasets, organize data sharing, and encourage future coordinated observations,
2. "Modeling and Analysis" with the objective to foster interactions between the global and regional modeling communities and to organize ACAM-related modeling,
3. "Training School" which is focusing on the development of future training opportunities for early career scientists on observations and modeling.

In the working group meetings the focus of the discussions was on the best way to promote collaborations in the field of ACAM science, e.g. partnership with other modeling communities (e.g. CCMI, AEROCAM) and sharing of data from recent ACAM-related field campaigns.

Figure 13: *Participants of the fourth ACAM Workshop in the Pusat Siwazah Lecture Hall of the Universiti Kebangsaan Malaysia.*

Also, the discussions during the working group meetings and poster sessions allowed the scientists to initiate collaborations with international partners. Scientists and students who are interested to join the ACAM activity and working groups can send a subscription request via the ACAM website.

Training School

The third ACAM Training School took place on 24-25 June 2019 at the Universiti Kebangsaan Malaysia (UKM) preceding the ACAM Workshop. It included 37 early career scientists, postdocs, and graduate students from 15 countries. The focus of this training school was on "Satellite Observations and Analysis of Atmospheric Chemistry and Aerosols in the Asian Monsoon region". The school included lectures, computer-based tutorials, and small student projects. Latest satellite and reanalysis datasets on atmospheric composition were used with focus on the monsoon region. Lectures at the school were given by **Ilse Aben** (SRON, Netherlands), **Bhupesh Adhikary** (ICIMOD, Nepal), **Silvia Bucci** (LMD, France), **Federico Fierli** (EUMETSAT, EU), **Ritesh Gautam** (EDF, USA), **Laura Pan** (NCAR, USA), **Amit Pandit** (NASA Langley, USA) and **Mark Parrington** (ECMWF, UK). The training school participants had also the opportunity to attend the ACAM workshop to learn more about ACAM related science.

One emphasis of the school was the live demonstration of satellite datasets and open source platforms/scripts for reading, visualization, and analysis of the data (*e.g.* Google Earth Engine and Python scripts). The various satellite datasets included TROPOMI (CO, NO_2 and SO_2 products), GOME (NO_2), MODIS (aerosol), CALIPSO (vertical aerosol profile). In addition the Copernicus Atmospheric Monitoring Service was introduced (CAMS trace gas products). A live webinar was conducted prior to the school providing an overview about the format of the school and the multi-sensor satellite data products to be used. Also specific information about the datasets and analysis platforms were made available to the students prior to the school on EUMETSAT's e-learning platform.

After the science lectures on the first day, the participants worked in groups to perform small projects focusing on the analysis of NO_2 pollution hotspots in the monsoon region. Urban and fire emissions were analysed using TROPOMI and GOME trace gas data, as well as MODIS and CALIPSO data on dust and smoke. Satellite data were compared with model results using the CAMS platform. The school concluded with group presentations of the participants summarizing their findings and experience with the data and tools.

This was the first ACAM training school that included practical work in groups besides the science lectures. This new concept for the ACAM school was very well received by the participants.

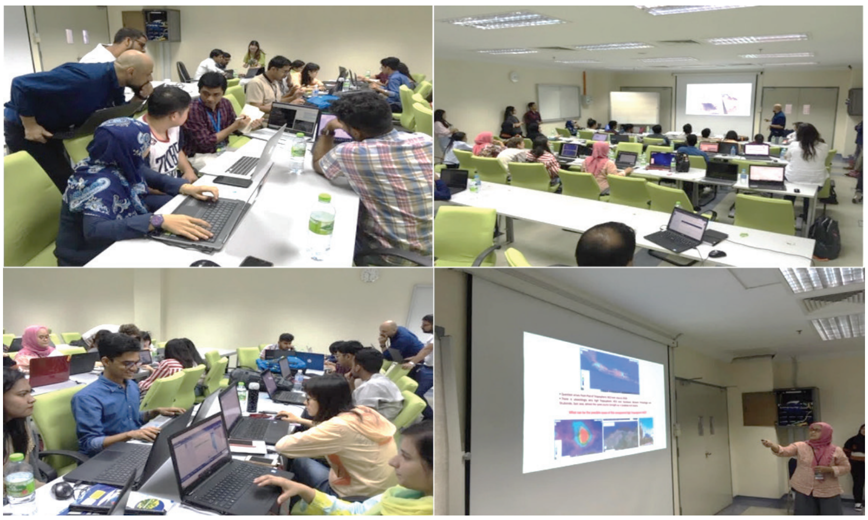

Figure 14: *Students and early career scientists at the third ACAM Training School.*

IGAC/SPARC CCMi summer school and workshop

David Plummer[1], Tatsuya Nagashima[2], and Michaela Hegglin[3], Amos Tai[4], Thomas Birner[5], Andrew Gettelman[6], Béatrice Josse[7], Jean-Francois Lamarque[6], Olaf Morgenstern[8], Gunnar Myhre[9], Clara Orbe[10], Seok-Woo Son[11], and Paul J. Young[12]

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Date:
4-9 August 2019

Number Of Participants:
Summer school: **16** Early Career Scientists
Workshop: **>70**

Organisers:
David Plummer (Environment and Climate Change Canada); Tatsuya Nagashima (National Institute for Environmental Studies, Japan); Michaela Hegglin (Univ. of Reading, UK).

Local host:
Prof. Amos Tai (Earth System Science Programme)

Host Institution:
The Chinese University of Hong Kong (CUHK), Institute of Environment, Energy and Sustainability

Workshop webpage:
http://www.cuhk.edu.hk/sci/essc/tgabi/CCMI-WS/ccmi_2019_hongkong_welcome.html

Sponsors:

香港中文大學 The Chinese University of Hong Kong

香港中文大學環境、能源及可持續發展研究所 Institute of Environment, Energy and Sustainability, CUHK

Earth System Science Programme, Faculty of Science · The Chinese University of Hong Kong

IGAC; futurearth research for global sustainability; SPARC Stratosphere-troposphere Processes And their Role in Climate; WCRP World Climate Research Programme

Activitiy webpage:
www.sparc-climate.org/activities/ccm-initiative/
http://blogs.reading.ac.uk/ccmi/

The IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) 2019 Science Workshop was held August 7-9, 2019 in Hong Kong, hosted by Amos Tai and his research group at the Chinese University of Hong Kong (CUHK). More than 70 scientists and students from 18 different countries participated in the workshop, which consisted of keynote, invited and contributed presentations, two very lively poster sessions, and break-out group discussions to advance the planning for Phase Two of CCMI.

The workshop covered a wide variety of research themes. These reflected the on-going analysis of multi-model results from the first phase of CCMI (Eyring *et al.*, in SPARC newsletter No 40, 2013; available at: **www.sparc-climate.org/publications/newsletter/**), in-depth process-based analyses of single models, as well as regionally-important topics - particularly by groups in south and east Asia who were well represented at the workshop. Analysis of the CCMI-1 simulations covered the stratosphere, investigating model simulated trends of ozone in the lower stratosphere and the dynamical influence of stratospheric ozone changes on the troposphere, for example; it also covered the troposphere via, among others, investigations into the diversity of hydroxyl radical concentrations across the CCMI models. Analysis of single model studies included the effects of land use and land cover changes on surface ozone, the ability of models to reproduce observed long-term changes in surface ozone, as well as the possible effects of continued emissions of CFC-11 on the future evolution of stratospheric ozone. Reflecting the importance of aerosols in heavily populated areas, a number of modelling studies were presented estimating the effects of aerosols on regional climates in South America and southern Africa, and the Asian monsoon. A number of studies were also presented to better characterize the distribution, seasonal cycle and sources of particulate matter, reflecting the growth of in-situ measurements sampling different regions of the world.

In addition to contributed presentations, the workshop featured two keynote presentations. The first was given by **Dr. Becky Alexander** from the University of Washington, who presented isotopic constraints on the ratio of O_3:HO_x from ice cores and how global chemistry models are unable to reproduce the derived changes in the ratio during the Last Glacial Maximum.

The modelled response of the ratio, driven by the expected decreases in temperature-dependent emissions, was opposite to that derived from the ice core proxies, suggesting other factors not currently accounted for in the models are important. **Dr. Jason West** from the University of North Carolina presented the second keynote presentation, giving an overview of developing efforts to improve estimates of the impact of air pollution on human mortality, including within the Global Burden of Disease project. Dr. West highlighted recent work to revise hazard ratio functions and new work to fuse global observations of pollutant concentrations and models to improve estimates of health impacts. A number of invited speakers also presented the activities and future plans of research initiatives related to areas explored by CCMI, including the Tropospheric Ozone Assessment Report (TOAR; **Dr. Martin Schultz**), Atmospheric Composition and the Asian Monsoon (ACAM; **Dr. Mian Chin**) and Solar Influences on Climate (SOLARIS-HEPPA, **Dr. Eugene Rozanov**).

Time during the workshop was also devoted to break-out group discussions to better define the scientific goals of a second phase of CCMI. An online discussion of the scientific questions that should motivate a CCMI-2, and the model experiments and outputs required to address them, had been on-going in the lead up to the workshop and can be found here[1]. While discussions of the scientific focus of CCMI-2 continues, we are moving ahead defining experiments to provide input for the 2022 WMO/UNEP Ozone Assessment and more information on this activity can be found here[2]. If you wish to be involved with either of these efforts please do not hesitate to contact one of the CCMI co-chairs, Tatsuya Nagashima or David Plummer.

The IGAC/SPARC Chemistry Climate Model Initiative (CCMI) summer school 'Earth System Modelling and Observations to Study Earth in a Changing Climate'[3]

In advance of their Science Workshop, the CCMI activity held a summer school on the campus of the Chinese University of Hong Kong focused on atmospheric chemistry as a component of the Earth System and the representation of processes in numerical models.

Figure 15: *CCMI 2019 Science Workshop Participants.*

[1] **https://docs.google.com/document/d/1UbEPCqgIskoDZfHKfjzaGKljzBgRRdjeaapnfM_vPCE/edit?usp=sharing**

[2] **https://blogs.reading.ac.uk/ccmi/ccmi-phase-two/**

[3] as published on the SPARC webpage, available at: **www.sparc-climate.org/meetings/ccmi-summer-school-in-hong-kong-2019/**

Figure 16: *Impressions from the CCMi summer school: Seok-Woo Son presenting (left), and Hong Kong skyline (right).*

From the 4th to the 6th of August 2019, 16 early career scientists from eight different countries (across four continents) gathered on the Chinese University of Hong Kong (CUHK) campus to improve their understanding of the representation of atmospheric chemistry and atmosphere-biosphere interactions in Earth System Models.

The course was a mixture of lectures, covering a broad range of topics relevant to the field of chemistry-climate interactions, and practical exercises. Lectures focused on the representation of physical and chemical processes in numerical models (David Plummer), an introduction to the chemistry and circulation of the stratosphere (Michaela Hegglin), the chemistry and associated processes controlling tropospheric composition (Tatsuya Nagashima), as well as chemistry-climate and stratosphere-troposphere dynamical coupling (Seok-Woo Son) and approaches to modelling the role of the biosphere in the Earth System (Amos Tai). Practical exercises had the participants playing with simple one-dimensional advection codes to explore the limitations of solving differential equations discretized in space and time and investigating the complexities of comparing model output from the CCMI phase 1 data archive with station data from the Tropospheric Ozone Assessment Report (TOAR) ozone database. A highlight of the practical exercises was the chance to work with the Terrestrial Ecosystem Model in R (TEMIR) developed by Prof. Tai's group at CUHK to simulate the response of a forest canopy to increasing concentrations of CO_2 and to investigate how this modifies the relationship between evapotranspiration and photosynthesis.

While the turbulent political situation in Hong Kong made for an interesting backdrop to the summer school, and a general strike on the second day meant a very late start for everyone, participants were enthusiastic about the opportunity to be exposed to a broad variety of topics in chemistry-climate interactions and the chance to meet colleagues from around the world.

The organisers would like to express their deep gratitude to Future Earth's IGAC and WCRP/SPARC for sponsoring the summer school, as well as to the Institute of Environment, Energy and Sustainability at CUHK for providing additional generous funding. The event was followed by the 2019 IGAC/SPARC CCMI Science Workshop, which provided the early career scientists with a great opportunity to get a taste of the most recent development in the research field of chemistry-climate interactions and to discuss their own research with researchers around the world.

The organisers would like to express their deep gratitude to Institute of Environment, Energy and Sustainability at CUHK for their generous financial support of the workshop, as well as Future Earth's IGAC and WCRP/SPARC for additional support.

Figure 17: *Participants of the CCMi summer school in Hong Kong, August 2019.*

Update on: Towards Unified Error Reporting (TUNER)

Thomas von Clarmann[1], Nathaniel J. Livesey[2], and Doug Degenstin[3]

[1]Institute of Meteorology and Climate Research / ASF, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany; [2]NASA JPL, Pasadena, CA, USA; [3]College of Arts and Science , Univ. of Saskatchewan, Canada.

Dates:

1 - 5 April 2019 (ISSI Team meeting)

10 - 12 September 2019

Organisers:

Thomas von Clarmann (KIT, Germany), Nathaniel J. Livesey (NASA JPL, USA), and Doug Degenstein (Univ. of Saskatchewan, Canada).

Host Institution:

ISSI, Berne, Switzerland

Finnish Meteorological Institute, Helsinki, Finland

Activitiy webpage:

www.sparc-climate.org/activities/tuner/

Sponsors:

The SPARC Activity "Towards Unified Error Reporting" (TUNER) was launched to develop a framework for reporting error estimates for atmospheric temperature and composition measurements from space in a consistent and inter-comparable manner. Along with this, a similarly consistent and inter-comparable framework for the characterization of spatial resolution and content of a priori information of the remotely sensed data is needed. Such a framework is needed, as quantitative work with remotely sensed data, *e.g.*, data assimilation, data merging, time series analysis, testing of hypotheses *etc.*, depends largely on the adequate characterization of the data. Currently, multiple retrieval methods are used by the different instrument groups, with various approaches to error estimation and reporting applied. Resulting errors are not always inter-comparable. Some kinds of uncertainties are sometimes not reported at all. The different altitude resolutions and the different content of prior information in the data products are particular problems. To tackle these problems, the TUNER team has had three meetings of the full team (in Saskatoon, 15 June 2017; Karlsruhe, 4-7 December, 2018; and Helsinki,10 - 12 September, 2019). Beyond these, a subset of the team formed an "International Team" to meet two times (4-7 December, 2017; and 1-5 April, 2019) at the International Space Science Institute in Berne. The recent team meeting in Helsinki coincided with the achievement of a milestone, namely the submission of a team paper laying down the theoretical framework of retrieval and error estimation and providing recommendations on how unified error reporting should be approached (von Clarmann *et al.*, 2019).

Figure 18: *Participants of the TUNER workshop in Helsinki, September 2019.*

This paper is currently under review and accessible in the discussion forum of the journal Atmospheric Measurement Techniques, where the TUNER articles are collected in a dedicated special issue.

Before developing recommendation on error reporting, first some criteria were compiled to judge when error reporting can be considered as adequate. The following conditions of adequacy were agreed:

1. The error estimates shall be intercomparable among different instruments and/or error estimation schemes. This requires a common language and a common understanding which is instrument-independent.
2. Error estimates should be empirically validatable by comparison of different measurement systems measuring the same state variable. We consider error estimates as empirically adequate if differences between measurements can be fully explained by error bars, natural variability in the case of less than perfect collocations, different resolution in time and space, and different amounts of a priori information.
3. The estimated errors should be independent of the vertical grid. That is to say, correct propagation of errors onto another grid should render the same error estimates as direct evaluation of the errors on the new grid.
4. The error budget should be useable without detailed technical knowledge of the instrument or retrieval technique.
5. The error analysis shall be traceable in a sense that all ingoing assumptions are documented.
6. The data volume associated with this error reporting shall be reasonable. This is important, because involved covariance matrices and averaging kernels exceed the data volume of the data themselves by orders of magnitude.

Along these conditions of adequacy, we have formulated the following recommendations for unified error reporting:

1. A clearly defined language should be used.
2. Every effort should be made to make the error budget as complete as possible in the sense that all sizeable sources of uncertainty are included relevant for the instrument and retrieval scheme under assessment.
3. Substantive contributions from each relevant error component should be reported separately.
4. The meaning of the reported error estimates should be made clear. The user must be informed whether these refer to one or two sigmas or to 95 % or 99 % confidence limits or whatever other convention is in use.
5. If representative error budgets are reported, it should be stated if errors are additive or relative (percentage) to allow re-scaling to the actual profile.
6. For each error component it should be made clear whether it contributes to the random or to the systematic error.
7. For each error component correlations in various domains (time, space, species, *etc.*) shall be described.
8. Known systematic dependencies of errors on time, latitude, or other parameters should be reported.
9. Ingoing assumed uncertainties used for the error propagation should be reported.
10. If a priori information is used, it should be reported.
11. Data and errors should be reported in terms of a vertical profile of potential error in geophysical parameter, regardless in which space (*e.g.*, log(vmr), empirical orthogonal functions *etc.*) the retrieval has been performed.
12. Averaging kernels should be reported.
13. If the averaging kernels do not refer to the state variable but to a function of it (*e.g.*, log(vmr)), this must be stated.
14. If mean averaging kernels are reported instead of all individual averaging kernels, the correlation profile between the averaging kernels and the profiles should be reported.
15. If the smoothing error is reported, it should not be reported as part of the total error estimate but separately.
16. To keep the data volume of the data characterization within reasonable limits, it is often advisable to restrict oneself to a limited number of representative cases.
17. If reporting of full covariance matrices for all error components exceeds the data volume considered as reasonable, correlation matrices can be reported instead.

18. Error reporting is adequate if the error estimates can be validated by comparison of measurements. The random error estimation is adequate if it explains the variance of the differences between instruments. The systematic error estimation is adequate if it explains the bias between independent measurement systems.

The discussion of these recommendations has been finalized during the Helsinki meeting, and the recommendations have been published in von Clarmann *et al.* (2019).

The second major topic of discussion of the Helsinki workshop was the outline of another team paper which is targeted at data users (the first being mainly aimed to data providers). This paper will take a tutorial approach, walking the reader through representative scientific analyses based on observations whose uncertainties are reported in the TUNER framework. The focus will be on the proper mapping of uncertainties in the observations into uncertainty on derived geophysical quantities. Examples include computing a total column abundance from a vertically resolved profile, computing total stratospheric chlorine based on profile observations of multiple chlorine species, and computing long-term trends from timeseries of individual regional average. This paper is part of a consolidated effort by the TUNER team to guide instrument scientists towards compliance with as many TUNER recommendations as are possible.

Papers submitted to the TUNER Special Issue by individual team members cover the following topics: The Harmonization and comparison of vertically resolved atmospheric state observations (Keppens *et al.,* 2019); the application of mean averaging kernels to mean trace gas distributions (von Clarmann and Glatthor, 2019); an exemplary level-1 error budget for MIPAS on Envisat (Kleinert *et al.,* 2018); and two studies where a detailed level-2 error analysis is demonstrated (Borger *et al.*, 2018; Garcia *et al.*, 2018).

Further activities within TUNER which were discussed in Helsinki included (a) Markov chain Monte Carlo uncertainty estimation; (b) uncertainty quantification approaches for OCO-2 CO_2 measurements; (c) promotion of the TUNER recommendations within the community of instrument scientists; and (d) OMPS-LP error estimation.

Acknowledgements

The authors would like to thank SPARC for travel support and Viktoria Sofieva for hosting the meeting at FMI in Helsinki.

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The 14th SPARC Data Assimilation Working Group Workshop

John McCormack[1], Sean Davis[2], Quentin Errera[3], V. Lynn Harvey[4]

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Date:
11 - 12 September 2019

Number Of Participants: 14

Organisers:
John McCormack (Naval Research Laboratory, USA), Sean Davis (NOAA ESRL, USA), and Lynn Harvey (LASP, USA).

Host Institution:
Laboratory for Atmospheric and Space Physics (LASP), University of Colorado, Boulder, CO, USA

Workshop Webpage:
http://lasp.colorado.edu/home/2019-sparc-data-assimilation-working-group-meeting

Sponsors:

Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

World Climate Research Programme

Activitiy webpage:
http://www.sparc-climate.org/activities/data-assimilation

The 14th SPARC Data Assimilation Working Group (DAWG) workshop was held at the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) in Boulder, Colorado on 11 - 12 September 2019. The overarching goal of DAWG is to coordinate state-of-the-art data assimilation research to address climate issues on a range of timescales. Based on input from the community at the 2018 General Assembly in Kyoto, DAWG established three themes to address this goal: chemical reanalysis (led by Sean Davis); dynamical reanalysis (led by John McCormack), and research supporting future limb sounder development (led by Quentin Errera and Susann Tegtmeier). The focus of this workshop was to establish work plans for each theme and identify specific outcomes that will contribute to both the overarching DAWG goal as well as broader SPARC-related objectives.

The workshop consisted of a series of plenary sessions during the first day along with smaller breakout sessions among individual themes, followed by a series of group discussions on the second day. For this workshop, only the chemical and dynamical reanalysis themes were discussed. A summary of these sessions and discussions is presented below. For information on DAWG, see **www.sparc-climate.org/activities/data-assimilation**. More information about this workshop, including presentations, can be found at **http://lasp.colorado.edu/home/2019-sparc-data-assimilation-working-group-meeting**.

Introductory session

The workshop began with an overview of the new DAWG implementation plan given by **Quentin Errera**, emphasizing the desired outcomes of DAWG to produce peer-reviewed publications and to improve collaborations with other SPARC activities. This was followed by an introduction to the chemical reanalysis theme by **Sean Davis**, who described existing chemical reanalysis systems at five different operational centers and outlined a work plan to conduct an inter-comparison between these and other systems modelled on the successful S-RIP project. In particular, this theme will expand on the reanalysis of stratospheric ozone and water vapor in relation to Chapter 4 of the S-RIP report (Davis *et al.*, 2017).

This was followed by several presentations describing specific chemical reanalysis systems. **Quentin Errera** began with a presentation on BRAM2 (BASCOE Reanalysis of Aura MLS version 2).

He described the details of this chemical reanalysis system, the data availability, and ongoing validation efforts with independent data sets. Next, **Kazuyuki Miyazaki** presented results from decadal multi-constituent chemical reanalyses with the MIROC-Chem and GEOS-CHEM systems and described a multi-model framework for improving the quality of chemical reanalyses through better identification of systematic model biases. This was followed by a presentation on constituent records, harmonization, and trends given by **Krzysztof Wargan** describing the StratChem project. This session concluded with a presentation by **Thierry Leblanc** on long-term ground-based records from lidar observations and their relevance to both chemical and dynamical reanalysis themes.

Dynamical and Chemical Reanalysis

The session on dynamical reanalysis began with a description of the theme goals and potential research topics by **John McCormack**. Next, **Lynn Harvey** provided an overview of results from Chapter 11 of the S-RIP report on the upper stratosphere and lower mesosphere, which could serve as a model for future DAWG activities related to the dynamical reanalyses theme. This was followed by a presentation on whole atmosphere data assimilation and modelling with the WACCMX+DART system by **Nick Pedatella**. Continuing on this theme, **Dai Koshin** described JAGUAR+LETKF, an ensemble-based Kalman filter data assimilation system for the whole neutral atmosphere. Next, **Ruth Lieberman** described the extension of the GEOS system up to 100 km altitude for improved representation of mesospheric and lower thermospheric (MLT) dynamics. The session concluded with a presentation by **Valery Yudin** on the vertical extension of NOAA models into the MLT region, specifically the FV3GFS-80km and GSM-WAM systems, and the need for the assimilation of wind measurements from both ground-based and space-based platforms.

The second day of the workshop began with three presentations relevant to both themes. First, **Kaoru Sato** described recent findings on the relationship between the Brewer-Dobson circulation and the effects of gravity waves based on inter-comparisons using 4 different reanalysis data sets and discussed consistency with the findings from the KANTO project. This was followed by a presentation from **Xinzhao Chu** on the derivation of gravity wave drag characteristics from ground-based lidar observations. Finally, an overview of dynamical and constituent fields produced with the NAVGEM-HA system was presented by **John McCormack**.

Outlook

The workshop concluded with presentations from the theme leaders summarizing key findings based on discussions both within the individual breakout sessions and among the entire group. For the chemical reanalysis theme, it was determined that an inter-comparison among different chemical reanalyses patterned after S-RIP should be undertaken. The initial steps needed to be taken are to identify key diagnostic quantities and to establish a time frame for the inter-comparison. For the dynamical reanalysis theme, it was determined that an inter-comparison of data assimilation and modeling systems extending into the MLT would help to quantify the value added by whole atmosphere approaches to climate questions. Both chemical and dynamical reanalysis themes identified validation with independent ground-based data sets such as lidar and radar profilers as a highly valuable resource that should be incorporated into each theme's work plan. Finally, the workshop discussions identified the following key science issues that DAWG will help address: improved understanding of the Brewer-Dobson circulation in a changing climate; seasonal prediction of dynamical and photochemical processes in the polar stratosphere affecting stratospheric ozone, and development of methods to better quantify uncertainties in reanalyses to aid continued monitoring and climate model validation. These discussions identified other ongoing SPARC activities (e.g., CCMI, QBOi, Gravity Waves, LOTUS, and OCTAV-UTLS) that align with these key issues, with which DAWG could potentially partner through joint workshops.

In the near future, plans will be made to follow-up via regular teleconferences and occasional webinars among the entire DAWG group and among participants in each individual theme to begin the implementation of these work plans and to keep all members informed of progress. The date and location for the next workshop, to include all three themes, will be decided at a future date.

Acknowledgments:

Many thanks to Lynn Harvey and LASP for hosting this workshop, and to WCRP/SPARC for providing travel support. The first author's participation in this workshop was supported by the Chief of Naval Research.

Report on the SOLARIS-HEPPA Working Group Meeting

Bernd Funke[1] **and Katja Matthes**[2,3]

[1] Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain (**bernd@iaa.es**); [2] GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany; [3] Univ. Kiel, Germany.

Date:
18 - 19 September 2019

Number Of Participants: 17

Organisers:
Bernd Funke (Instituto de Astrofísica de Andalucía, Spain), Katja Matthes (GEOMAR Helmholtz Centre for Ocean Research, Germany).

Host Institution:
Instituto de Astrofísica de Andalucía (CSIC), Granada, Spain

Workshop webpage:
https://solarisheppa.geomar.de/granada2019

Sponsors:

Activitiy webpage:
http://solarisheppa.geomar.de/solarisheppa/

The 2019 SOLARIS-HEPPA Working Group meeting was held at the Institute of Astrophysics of Andalusia (CSIC) in Granada, Spain on 18-19 September 2019. The meeting focused on the results of the five working groups (see **http://solarisheppa.geomar.de/workinggroups**), which have been defined to coordinate the analysis of the impact of solar variability by irradiance and energetic particles on the atmosphere and climate in simulations of the Chemistry-Climate Model Intercomparison (CCMI) project (WG1-3), to assess and improve statistical analysis methods in support of the latter (WG4), and to compare atmospheric impacts due to mid-energy electron (MEE) precipitation in models and observations (WG5). A mayor objective of the meeting was to collect relevant results for publication in an overview paper and to coordinate targeted publications on specific topics related to the different working groups. The agenda allowed for ample discussion time after talks. Participants represented 9 countries (USA, Norway, Spain, Finland, United Kingdom, Germany, Japan, Switzerland, Greece).

Tropical and mid-latitude stratospheric ozone and temperature responses (WG1&3)

Klairie Tourpali analysed the solar cycle signal in total and vertically resolved ozone from REFC1 and RFC2 simulations (*c.f.* Figure 19). While the signals mostly agree in REFC1 simulations from models that explicitly consider UV variability, larger deviations occur in REFC2 simulations. These could be attributed to different solar forcing specifications, deviating from the recommended solar cycle in various models. Overall, solar responses of total ozone in REFC1SD simulations roughly match the observations at low latitudes. **Markus Kunze** found a coherent stratospheric temperature response in the tropics and mid-latitudes among those REFC2 simulations that explicitly consider the solar cycle, with a tendency for a slightly reduced response in the future (2010 - 2100) period. A similar behaviour was also observed for stratospheric ozone responses.

Polar chemical and dynamical responses: the role of UV, energetic particles, and internal variability (WG1&4)

A large fraction of the meeting was dedicated to the analysis of polar stratospheric responses to solar forcing in chemical and dynamical fields from REFC2 simulations, hereby differentiating between solar UV and energetic particle precipitation (EPP) induced impacts (the latter restricted to simulations from those models considering EPP).

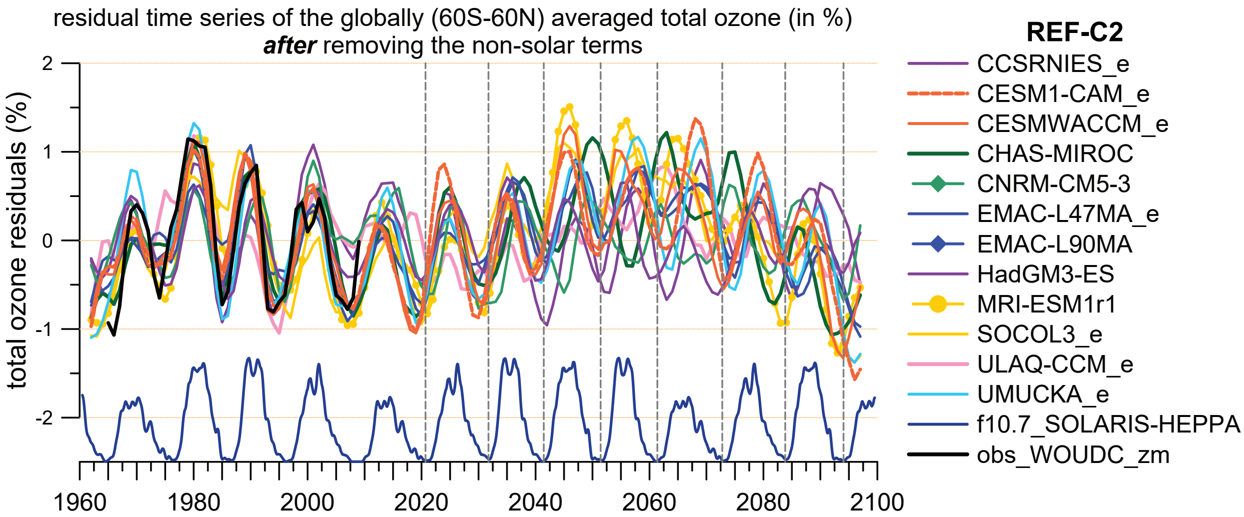

***Figure 19:** Residual time series of globally averaged total ozone (60S-60N) from CCMI REF-C2 simulations after subtraction of the non-solar component of a multi-linear regression model. Observed total ozone from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) is also shown for 1960-2010. The solar cycle progression (in terms of normalized F10.7 solar radio flux) compliant with the CCMI solar forcing recommendations is included in the figure for reference. Figure credit: Klairie Tourpali.*

The challenges are twofold: Firstly, the analysis – based on multi-linear regression (MLR) – has to account for amplified internal variability during polar winter, and secondly, cross-correlations of solar irradiance and particle-related variability, both driven by the solar cycle, introduce additional complexity in the analysis of model simulations that include particle impacts. The critical assessment of regression methods, predictor choice, and new approaches accounting for non-linear modulations (e.g., by the QBO) as done within WG4 is therefore particularly important. **Ales Kuchar** revised different statistical methods to determine the relative importance of individual predictors and explored the use of solar signal filtered annular mode predictors to account for the dominant internal variability in dynamical fields in order to increase explained variance. **Alessandro Damiani** inspected time series residuals from MLR analysis of ozone fields from EPP-accounting models with different combinations of predictors for solar UV, energetic electron effects and solar proton events (SPEs). Only the combined use of all solar predictors enabled a significant reduction of the residuals, thus demonstrating the feasibility to separate solar UV and particle responses. On the other hand, **Markus Kunze** encountered non-negligible aliasing effects between diagnosed NOy responses to UV variability and SPEs, calling for further efforts to improve the currently used SPE predictors. **Bernd Funke** analysed EPP responses in WACCM REFC2 simulations and found indications for a modulation of the responses by the QBO. Further, an increased chemical signal (NOy enhancements and ozone loss) was detected in the future period (2010-2100) compared to the historical period. These findings motivated the introduction of cross-term predictors in the MLR analysis to account for greenhouse gas and QBO induced modulations of EPP signals.

Solar surface responses (WG2)

Klairie Tourpali provided an overview on the analysis of solar surface signals within working group 2, primarily addressing the quantification of Northern Hemisphere regional impacts and the identification of the responsible dynamical mechanisms for signal propagation. Particular emphasis is given to the representation of ocean coupling across the CCMI models. **Stergios Misios** demonstrated a solar surface impact in precipitation and sea surface temperature/surface temperatures/sea level pressure in the Western Pacific in PCRMIP simulations without stratospheric forcing. There is evidence that these signals are mostly produced by the direct effect of total solar irradiance variability.

Stratospheric signals in observations and specified dynamics simulations (WG3)

Arseniy Karakgodin summarized recent progress of working group 3. Advances have been made in assessing the impact of different reanalysis datasets, used for nudging, on the representation of the dynamical solar cycle response in REFC1SD simulations. Overall, specified dynamics simulation based on ERA-I tend to show a larger tropical temperature response compared to those simulations nudged to JR55 or MERRA reanalysis data.

A comprehensive evaluation of simulated stratospheric ozone responses in comparison with observational analysis, based on most recent climate records, has been initiated. An extension of this activity to stratospheric temperature signals in collaboration with SPARC-ATC (co-lead: Amanda Maycock) has been proposed. Further, simulated carbon monoxide and water vapour responses to the solar cycle in the stratosphere and mesosphere have been compared to satellite datasets from HALOE, MLS, and MIPAS. **Alessandro Damiani** compared simulated and observed NOy ozone evolutions during austral polar winter and demonstrated that observed EPP responses are – at least partly – reproduced by those CCMI models accounting for energetic particles. On the other hand, the comparison to specified dynamics simulations not considering EPP can facilitate the distinction between solar and internally forced responses. **Bernd Funke** assessed decadal variations of EPP-generated polar winter NOy enhancements in WACCM and SOCOL simulations in comparison with MIPAS observations and concluded that the solar cycle modulated variability is significantly underestimated in the simulations by a factor of three. By comparing simulated temperature and nitric oxide distributions in the polar winter mesosphere with satellite observations, **Thomas Reddmann** found indications for model insufficiencies in the representation of polar winter tracer descent.

Mid-energy electron forcing (WG5)

Pekka Verronen provided an overview on current and planned WG5 activities, addressing atmospheric impacts due to mid-energy electron (MEE) precipitation in models and observations. This includes the inter-comparison of existing MEE ionization rate datasets (with a particular emphasis on the CMIP6-recommended data), on the one hand, and the evaluation of model simulation, based on these ionization data, with satellite observations on the other hand. **Joshua Pettit** reported on WACCM-SD simulations of odd nitrogen descent in the 2003 Antarctic winter, using different MEE datasets, in comparison with satellite observations. The results indicate improved agreement for MEE ionization rates that explore the full range of pitch angle distributions of radiation belt electrons. Free-running WACCM simulations with and without MEE were analysed by **Pekka Verronen**, who found clear evidence for chemical MEE impacts in the polar stratosphere. However, the attribution of simulated temperature variations to particle impacts is challenged by the predominance of non-local dynamical heating/cooling, which is difficult to separate from internal variability. On/off ensemble experiments with a free-running WACCM version were also analysed by **Sigmund Guttu**. Results indicate a polar vortex intensification due to MEE in mid-winter, being strongest in the Northern Hemisphere. On the other hand, the Southern Hemisphere polar vortex tends to weaken in late winter due to reduced poleward ozone transport and an associated reduction in longwave cooling. The study also indicates positive Northern Annular Mode (NAM) and negative Southern Annular Mode (SAM) anomalies when considering MEE.

Acknowledgements

We would like to thank WCRP/ SPARC for providing travel support for three early career scientists.

Figure 20: *Participants of the SOLARIS-HEPPA Working Group meeting.*

Joint DynVarMIP/CMIP6 and SPARC DynVar & SNAP Workshop: Atmospheric Circulation in a Changing Climate

Alexey Karpechko[1], Amy Butler[2,3], Natalia Calvo[4], Andrew Charlton-Perez[5], Daniela Domeisen[6], Edwin Gerber[7], Elisa Manzini[8], and Alison Ming[9]

[1]Finnish Meteorological Institute, Helsinki, Finland; [2] Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA; [3] NOAA, ESRL, Chemical Science Devision, Boulder, CO, USA; [4] Univ. Complutense, Madrid, Spain; [5] Univ. of Reading, UK; [6] Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland; [7] New York Univ., N.Y., USA; [8] Max Planck Institute for Meteorology, Hamburg, Germany; [9] Univ. of Cambridge, UK.

Date:
22-25 October 2019

Number Of Participants: 94

Local Organizing Committee:
Natalia Calvo, Ricardo Garcia-Herrera, David Barriopedro, Marta Abalos, Blanca Ayarzagüena, and Alvaro de la Cámara (Universidad Complutense de Madrid, Spain).

Scientific Organizing Committee
Ed Gerber (New York University, USA), Elisa Manzini (MPI für Meteorologie, Hamburg, DE), Amy Butler (CIRES/University of Colorado and NOAA, Boulder, USA), Natalia Calvo (Universidad Complutense de Madrid, Spain), Andrew Charlton-Perez (University of Reading, UK), Daniela Domeisen (ETH Zürich, CH), and Alexey Karpechko (Finnish Meteorological Institute, Helsinki, FI).

Host Institution:
Universidad Complutense de Madrid, Spain

Sponsors:

Workshop webpage:
www.sparc-climate.org/meetings/workshop-on-atmospheric-circulation-in-a-changing-climate/

A joint DynVarMIP/CMIP6, SPARC/DynVar and SPARC/SNAP Workshop was held on 22-25 October in Madrid, kindly hosted by the Facultad de Ciencias Fisicas - Universidad Complutense de Madrid. We would like to express our sincere thanks to the local committee for excellent organization of the workshop and great hospitality. Support from the International Association of Meteorology and Atmospheric Sciences (IAMAS), the Stratosphere-Troposphere Process and their Role in Climate Project (SPARC) and the Grand Challenge on Near-Term Climate Prediction of the World Climate Research Programme (WCRP), and US National Science Foundation, enabled attendance by over 20 Early Career Scientists.

The workshop was the 5th workshop of the DynVar activity and the 2nd time it was organized jointly with SNAP, highlighting strong synergy between these two SPARC activities. Both DynVar and SNAP focus on dynamics of the stratosphere-troposphere coupled system but address different time scales. The workshop was attended by researchers interested in large-scale atmospheric dynamics, in particular understanding atmospheric circulation response to climate change and the role of atmospheric circulation predictability in sub-seasonal to seasonal (S2S) forecasts. Altogether 94 participants from 17 countries attended the meeting, of which 46% were female (Figure 21).

A primary goal of the workshop was to present and discuss analysis of the new Coupled Model Intercomparison Project Phase 6 (CMIP6) experiments and, specifically, share new results based on additional diagnostics requested by the DynVar Model Intercomparison Project (DynVarMIP; Gerber and Manzini, 2016), an endorsed participant of CMIP6. Changes in atmospheric general circulation have first order effects on regional climate. However, our understanding of the dynamical response of the atmosphere to external forcings behind climate change is poor. Models show various degrees of agreement regarding changes in different aspects of the general circulation – for example they tend to agree on the sign of the Brewer-Dobson circulation response (strengthening) and Hadley cell response (widening) but disagree even on the sign in projections of changes in the stratospheric polar vortex or North Atlantic Oscillation. While part of the inter-model spread is due to inherent variability in the climate system, the spread also includes significant contribution due to model uncertainty (Manzini *et al.*, 2014).

Figure 21: *Participants of the Joint DynVarMIP/CMIP6 and SPARC DynVar & SNAP Workshop: "Atmospheric Circulation in a Changing Climate".*

To address these issues and to better understand and quantify the circulation response to climate change, the SPARC DynVar activity initiated DynVarMIP. Rather than proposing new experiments, DynVarMIP requests additional model output from existing CMIP6 experiments. The workshop in Madrid provided an excellent opportunity to discuss the first results of DynVarMIP.

A second goal of the workshop was to consider the predictability of the atmospheric circulation on subseasonal to seasonal (S2S) timescales (and beyond). The SNAP activity seeks to quantify and understand circulation processes that contribute to predictive skill at S2S timescales. SNAP has recently become part of Phase II of the S2S project (Vitart *et al.*, 2017), a key component of both the World Weather Research Programme (WWRP) and WCRP. Many of the same biases in CMIP6 models are also found in S2S prediction systems, so a joint DynVar & SNAP workshop was a useful way to synergize where further model improvement is needed and where uncertainty remains across timescales.

Following the successful use of Twitter during the previous DynVar meeting, the Madrid workshop was also tweeted live from the account **@WCRP_SPARC**, thanks to Alison Ming. Each talk was tweeted with total number of tweets being 86. The **@WCRP_SPARC** profile was visited 925 times during the workshop and 44 people followed it. About 30 other people in the audience were also engaged with **@WCRP_SPARC** on twitter. These efforts led to great popularity of the workshop on twitter and the workshop tweets appeared 21,800 times in other profiles, an impressive number by any measure!

Overall, the meeting accommodated 57 oral presentations (52% of all speakers were female, and of the invited/keynote speakers 44% were female) and 41 posters. The presentations on Tuesday and Wednesday mostly covered DynVar topics, Friday was dedicated to SNAP, while Thursday had a mixture of DynVar and SNAP presentations. The keynote presentation to the meeting was delivered by **Rolando Garcia**. In his talk, Rolando discussed what we have learned about the middle atmosphere by studying its response to anthropogenic forcing. In particular he attributed the excellent match between observed and simulated stratospheric temperature trends to our improved understanding of radiative transfer and middle atmosphere chemistry. A diverse response of the Quasi-biennial Oscillation (QBO) to climate change across climate models instead demonstrated our incomplete understanding of QBO drivers and the limitation of the current representation of the QBO in models, heavily relying on parametrized processes such as convection and gravity waves. He showed that increasing vertical resolution of the models is a necessary step to progress in improving simulation of QBO, and potentially extratropical dynamics.

CMIP6 and DynVarMIP

New opportunities provided by various experiments of CMIP6 were explored in several talks, and some of these studies made use of DynVarMIP diagnostics, such as age of air, wave flux diagnostics and daily data not always available in previous rounds of CMIP. A multi-model approach proved vital in assessing model abilities to faithfully capture the observed circulation, as well as to understand sources of spread in future projections (e.g. Charlton-Perez *et al.*, 2013; Manzini *et al.*, 2014).

New studies showed potential to shed light on long-standing problems in stratospheric dynamics. Among those is the attempt to reconcile the observed and simulated trends in the age of stratospheric air, the question addressed in a multi-model CMIP6 and CCMI study by **Hella Garny**. Hella showed that when uncertainty in deriving mean age of air from observed tracers is fully considered, then modelled and observed trends become partly overlapping due to both large observational errors and large spread across models. Hella concluded that while discrepancies remain, observations and models can be reconciled. Another question – how the frequency of Sudden Stratospheric Warmings (SSW) will change in a warmer world - was addressed in an invited talk by **Blanca Ayarzagüena**. Blanca found that while SSW frequency shows significant changes in some of the analyzed CMIP6 models, there is no consensus in the sign of these changes even when long data records and extreme forcing (4 times CO_2) are used. The discrepancy calls for additional analysis with more attention to the possible role of model formulation and biases. CMIP6 model biases in simulated SSW frequency were assessed in a poster by **Zheng Wu**.

The DynVarMIP diagnostics from the multi-model CMIP6 data were also used by **Marta Abalos** to confirm projected strengthening of the Brewer-Dobson Circulation in response to global warming. **Elisa Manzini** used CMIP6 models in her poster presentation to analyse projected changes of the Arctic polar night jet and wave forcing. **Kevin Grise** compared Hadley cell widening simulated by CMIP5 and CMIP6 models to conclude that CMIP6 simulate on average larger widening over the historical period. While Southern Hemisphere (SH) widening in response to greenhouse gases emissions is simulated similarly by both datasets, larger differences emerge in the Northern Hemisphere (NH) future response, in particular in June-July-August, where CMIP6 models simulate cell contraction owing to larger climate sensitivity of CMIP6 models. Overall, there was a strong focus on changes in the tropospheric circulation at the workshop, which is somewhat different from previous DynVar meetings.

Multi-model analysis of CMIP6 simulations is expected to continue as more models will submit their outputs. Meanwhile, several more studies presented analyses of single models. These include **Michael Sigmond** (CanESM5), **Natalia Calvo** (WACCM), **Froila M. Palmeiro** (EC-EARTH), **Clare Orbe** (GISS), **Maria Kolennikova**, **Vasilisa Vorobeva** and **Pavel Vargin** (INM CM5). In particular, using simulation from the Polar Amplification Model Intercomparison Project (PAMIP), **Michael Sigmond** demonstrated that in the CanESM5 model the response of the atmosphere to sea ice loss depends on the basic state, which controls planetary wave propagation in the stratosphere. Depending on the basic state, planetary wave propagation shows different sensitivity to sea ice loss, which affect a zonal mean dynamics and the Northern Annular Mode (NAM) response. Sensitivity of the changes to the basic state can be used as an emergent constraint to better quantify future sea ice loss. PAMIP simulations by several models were also analysed in a poster study by **Alexandre Audette** to address changes in atmospheric poleward heat transport. **Natalia Calvo** separately investigated changes in the deep and shallow branches of the Brewer-Dobson circulation and found that more than half of the strengthening of the shallow branch occurs during the first 10 years after an abrupt quadrupling of CO_2. The changes in the deep branch were attributed to both warmer sea surface temperatures (SSTs) and radiative cooling in the stratosphere with equal contribution of both factors. **Clare Orbe** showed that, unlike climate sensitivity, the dynamical sensitivity in GISS models depends on coupling with chemistry, especially in the SH. Similarly, the difference between dynamical and climate sensitivity was explored in a multi-model study by **Tom Wood**, who showed that despite having larger climate sensitivity than CMIP5 models, CMIP6 models do not exhibit larger trends in the Southern Annular Mode (SAM).

Progress in process understanding

In addition to channelling community efforts towards analysis of CMIP6 simulations, DynVar traditionally welcomes exciting studies on large-scale atmospheric circulation ranging from idealized modelling experiments to statistical analysis of observations. A brief look at the topics covered by the presenters of the Madrid workshop provides insight into what currently drives the interests of the research community.

Mechanisms of the stratosphere-troposphere coupling remain an intriguing subject and **Peter Hitchcock** in his invited talk assessed our current level of understanding of which mechanisms are most robust. He concluded that at least two distinct mechanisms need to be involved, to account for the downward influence of the stratospheric signal to the troposphere and the amplification of the signal at the surface.

The role of surface amplification was further emphasized by **Mark Baldwin** who pointed to a significant amplification of the air flow convergence in the lower troposphere towards the Arctic, leading to increased sea level pressure after SSW events. The study by **Ian White** confirmed sensitivity of tropospheric impacts following SSWs to the strength of the lower stratospheric anomaly, while **Philip Rupp** in an idealized model study of baroclinic wave life cycles found that the presence of the stratospheric vortex affected the final state of the cycles with the barotropic jet being located more southward in the case when no stratospheric vortex is present (*i.e.* mimicking SSW situation). Philip also reported on significant sensitivity of the simulated wave life cycles to the vertical resolution of the model. **Alvaro de la Camara** showed that there is a decoupling between lower tropospheric bursts of wave activity and sudden stratospheric warming implying that other factors, like stratospheric vortex geometry and lower-stratospheric dynamics may be more important for SSWs. **Froila Palmeiro** investigated factors affecting heat flux in the lower stratosphere. Polar vortex dynamics was further considered in posters by **Yulia Zyulyaeva**, **Roland Walz**, and **Toshihiko Hirooka**. Studies also looked at other aspects of stratospheric dynamics, including Brewer-Dobson circulation response to increased CO_2 (**Andreas Chrysanthou**), effects of gravity waves on the large-scale circulation (**Roland Eichinger**) and transport (**Petr Sacha**), and stratospheric eddy mixing (**Jezabel Curbelo**).

Owing to its potential societal impacts, widening of the Hadley cell received considerable attention. Idealized model experiments by **Thomas Birner** demonstrated the leading role of eddies in the response of the Hadley cell to global warming. In his study, Thomas used a simplified model to conclude that the Hadley cell expansion under a "4xCO2" scenario is entirely due to changes in eddy forcing. Observed widening of the Hadley cell, discussed also by Kevin Grise (see section on CMIP6 results above), was addressed by **Penelope Maher** who analysed various approaches to quantify it. **Molly Menzel** used CMIP5 models to show that the Hadley cell edge response to global warming is decoupled from that of the subtropical jet response.

Another popular topic, which is relevant to both DynVar and SNAP, is the influence of ENSO on extratropical circulation. **Paloma Trascasa-Castro** and **Israel Weinberger** investigated the linearity of the European climate response to ENSO phases in model experiments. Common in their findings was an increase of SSW frequency during El Nino and a decrease of SSW frequency in La Nina phases, as well as an opposing response of the European climate between the phases. On the other hand, a significant non-linearity of the response to linearly increasing El Nino forcing was reported in another model study by **Bernat Jiménez-Esteve**, implying that the research on this topic is far from being settled. Extratropical influence of ENSO was further discussed in posters by **Maria Kolennikova**, **Bianca Mezzina** and **Eun-Pa Lim**.

Interplay of the QBO and ENSO was investigated in two talks. **Jessica Neu** addressed the role of QBO phase, and its dependence on ENSO/SSTs on transport of stratospheric tracers. Potential alignment of QBO phase with warm ENSO episodes was investigated by **Bo Christiansen**.

While the above studies address tropical forcing of the extratropical circulation, **Sarah Kang** looked at the opposite case. In her invited talk, she discussed sensitivity of the Walker Circulation to extratropical radiative forcing (variations in insolation created *e.g.* by aerosols) and concluded that the Walker circulation may be more sensitive to extratropical radiative forcing than to the tropical one. Stratospheric dynamics and stratosphere-troposphere coupling in the Tropics were addressed in posters by **Cristina Pena**, **Federico Serva**, **Kasturi Shah**, and **Aaron Match**.

The dynamics of atmospheric adjustment to abrupt increase of CO_2 to 4 times with regard to pre-industrial concentration was explored in an invited talk by **Paulo Ceppi** using CMIP5 models. Paolo showed that the adjustment has two distinct timescales – fast (on timescale of 5 - 10 years) and slow (on timescale of ~ 100 years) – both of which were characterized by a specific type of SST warming pattern, which controlled dynamical adjustment by affecting baroclinicity. Most of the changes in the jet stream position took place during the fast adjustment. The exception was the poleward shift of the Pacific jet which took place during the slow phase as a response to emerging El Nino-like type of SST response. Rapid adjustment of the atmosphere was also investigated by **Amanda Maycock** who showed dependence of the adjustment on different types of external forcing, using simulations from the Precipitation Driver Response Model Intercomparison Project (PDMIP). An important message of her talk was that different external forcings have different fingerprints in rapid adjustment, and that this dependence may help to better understand regional climate change.

Seeking to understand increased tropospheric ozone concentrations during the Last Glacial Maximum (LGM) seen in paleoclimate records, **Qiang Fu** looked at the strength of the Brewer-Dobson Circulation during LGM in model simulations. In contrast to an expected BDC strengthening, which would be consistent with more downward ozone transport from the stratosphere, Qiang found a weaker BDC which he attributed to a reduced generation of the orographic gravity waves by a smoother topography of the ice sheets.

Sudden Stratospheric Warmings are an important topic, addressed by both DynVar and SNAP communities. Interesting results regarding SSW forcing were reported by **Lesley Gray** who showed that nudging of their model towards observed troposphere and upper equatorial stratosphere led to a good replication of SSW timing and magnitude. This result implied that improving Semi-annual Oscillation (SAO) climatology in the models may improve forecasting of SSWs. **Hilla Gerstman** found an influence of the Pacific region on the Atlantic storm tracks following SSW events in observations. SSW impacts of the surface climate was investigated in poster studies by **Lars VanGalen** and **Yuli Zhang**.

Several talks addressed specific features of the atmospheric circulation in the SH. An invited talk by **Martin Jucker** was devoted to SH stratosphere-troposphere coupling. Noting methodological difficulties in applying definitions developed for the analysis of more active Arctic stratosphere to SH studies (*i.e.* almost complete absence of the major SSW), he proposed alternative ways to define SH stratospheric events (such as extreme heat flux events) and demonstrated generic similarity of tropospheric impacts between the two hemispheres. An unusual visitor to the SH stratosphere, a strong (but not major by the classical definition) stratospheric warming that occurred in early September 2019 was investigated by **Eun-Pa Lim**. She showed that sub-seasonal forecast models predicted vortex weakening since mid-August, but they overpredicted the downward propagation. The most likely factor that opposed the downward propagation of the signal to the troposphere was the positive phase of the Indian Ocean Dipole. In another SH talk, **Elio Campitelli** analysed observed SH circulation using complex Principal Component Analysis. A storyline approach to present SH climate change was developed in the poster study by **Julia Mindlin**.

Observational uncertainties especially in the middle atmosphere, where in situ measurements are sparse, can negatively affect *e.g.* forecast model initialization. Novel observations and observational networks for the upper atmosphere, such as infrasound systems, high-resolution lidars, and meteor radars, were described in an invited talk by **Elisabeth Blanc**. These data can deliver information on gravity wave properties, provide improved coverage of planetary wave activities, *e.g.* during SSWs, and can be used for tuning parameterisation schemes and evaluation of forecast models.

Extreme events

The Madrid workshop saw a number of studies focused on the dynamics of extreme events, in particular the links between extreme weather, and stationary waves that promote persistent weather patterns and lead to enhanced impacts on long time scales. **Rachel White** showed changes in waveguides associated with stationary waves. These waveguides are well represented in CMIP6 models, giving hope that projected changes may provide useful information on future changes in extreme weather. The role of anomalous propagation of stationary Rossby waves in climate extremes was shown in a poster by **Irina Rudeva**, while **Kai Kornhuber** attributed increased risk of heatwaves to Rossby wave amplification. Changes in quasi-stationary waves in future climate were analysed by **Dor Sandler**. Dynamics of SH extreme events were analysed in a poster by **Ghyslaine Boschat**.

While study of extreme events is hardly a new branch of atmospheric sciences, the shift in analysis from a statistical description to attempting to better understand their underlying dynamical (and physical) processes marks a new step, which may bring about model improvements. Given that the upcoming focus of the DynVar activity will also include the dynamics of extreme events, an increased attendance of the extreme event community to the Madrid workshop is a welcome first step towards the new direction.

SNAP

Ongoing research activities coordinated by SNAP focus on the analysis of the S2S project data set, a unique international effort to share in a near real-time setting sub-seasonal to seasonal forecasts to advance research into predictability (Vitart *et al.*, 2017). Many presentations in Madrid used data from S2S prediction systems to analyse predictability of various dynamical features both in the troposphere and the stratosphere.

In an invited talk **Andrea Lang** combined observations with S2S forecasts to show importance of the extratropical transition of tropical cyclones for early winter stratospheric events. **Amy Butler** used S2S data to study the predictability of final warmings and their surface responses. The above results were put into a wider context for the predictability of a range of stratospheric events in the talk by **Daniela Domeisen**. Further confirmation that stratosphere-resolving models have better predictive skill both in the extratropical stratosphere and the troposphere came from **Hera Kim**'s study. **Jian Rao** showed enhanced predictability (beyond 18 days) of the 2019 SSW. **Jung Choi** showed that more skilful tropospheric forecasts often follow periods of a reduced upward propagation of the planetary waves, and even a partial wave reflection. **Kevin DallaSanta** introduced a Tropical Annular Mode, a tropical analogue to extratropical NAM and SAM, and showed that its predictability is higher than that of extratropical counterparts. Forecasts by S2S models were further analysed in posters by **Craig Long**, **Irina Statnaia**, **Cory Barton**, **Andrew Charlton-Perez**, **Masakazu Taguchi**, **Simon Lee**, and **Eun-Pa Lim**.

SNAP relevant research includes topics beyond analysis of the S2S dataset, such as investigation of teleconnections that give rise to seasonal to interannual predictability. **Nicholas Tyrrell** showed sensitivity of the stratosphere-troposphere coupling following atmospheric forcing by Eurasian snow cover to model biases. **Émilien Jolly** investigated mechanisms of atmospheric response to sea ice loss in an idealized model and found a showering down of planetary waves, leading to more persistent cold spell anomalies in mid-latitudes. **Paolo Ruggieri** analysed sources of seasonal predictability in Copernicus Climate Change Service models and noted little predictability from QBO in these models but a role from ENSO. **Yueyue Yu** demonstrated how combining dynamical forecasts in the stratosphere and a statistical link between stratospheric circulation and surface climate can increase predictability of cold air outbreaks beyond 2 weeks. **Craig Long** overviewed operational sub-seasonal forecasting activities at the NOAA Climate Prediction Center and showed cases when stratospheric information can contribute to improve the forecasts.

Synergy with other SPARC activities

Topics shared between DynVar and other SPARC activities were visibly present at the workshop. Several studies used chemistry-climate models from the Chemistry-Climate Model Initiative (CCMI) to address the role of interactive chemistry for climate response. These studies noted sensitivity to chemistry feedbacks of climate sensitivity and atmospheric dynamics (**Gabriel Chiodo**), of SH circulation trends (**Ioana Ivanciu**) and SH stratospheric dynamics (**Pu Lin**). Pu Lin noticed that a simple linear scheme captures key effects of stratospheric ozone-climate interactions. A poster study by **Juan-Antonio Anel** discussed factors affecting trends in the age of air. Interactions with CCMI need to be continued. Individual contributions of variability in ozone and water vapour to the seasonal cycle of the tropical tropopause temperature were quantified in an idealized modelling study by **Alison Ming**.

SPARC/QBOi focuses on improving the Quasi-Biennial Oscillation representation in climate models and so is a close partner activity of DynVar. The status of QBOi experiments and key papers was overviewed by **Scott Osprey**. QBOi experiments were discussed in posters by **Shingo Watanabe**, **Javier Garcia-Serrano**, and **Naoe Hiroaki**. The SPARC Stratospheric Reanalyses Intercomparison Project activity (S-RIP) was presented in a poster by **Lesley Gray**.

New opportunities

Along with application of improved models, novel experiments and new data sets that all pave the way for progress, the workshop also showed several relatively new routes for advancement. Application of advanced statistical tools (including machine learning) is one of the most actively discussed new opportunities in climate science. In her talk, **Marlene Kretschmer** demonstrated how causal discovery networks, an approach based on graphical models, can be used to test complex mechanisms, such as a multi-step link between the loss of the Arctic sea ice and weakening of the Arctic stratosphere polar vortex. Upon confirming the mechanism, Marlene further proposed to use model biases in the present sea ice to constrain polar vortex response. Specifically, overestimation of the sea ice in current models implies that the simulated weakening of the polar vortex is overestimated in climate models. A similar approach was used by **Elena Saggioro** to quantify stratosphere-troposphere coupling in the SH. A relatively unexplored potential of another statistical approach, Principal Oscillation Patterns (POPs), was demonstrated in presentation by **Aditi Sheshadri**.

Aditi argued that the ability of POPs to represent both spatial and time structures, and to naturally reveal both stratospheric and tropospheric modes can be useful for studies on predictability and climate response.

Models of intermediate complexity fill the gap in model hierarchy between simple conceptual models, which represent only a few processes, and complex climate models, which have too many feedbacks and processes to fully understand mechanisms. Systematic application of model hierarchy can help in our fundamental understanding of the processes controlling behaviour of the climate system and its response to external forcing. Intermediate complexity models were used by **Chaim Garfinkel** to understand biases in simulated stationary waves, by **Ed Gerber** to understand the response of jet streams to climate change, by **Bernat Jiménez-Esteve** to investigate ENSO teleconnections to extratropics, and by **Ian White** to investigate downward coupling. **Nedjelka Zagar** used an intermediate-complexity model to explore scale dependence of biases.

New opportunities also arise due to the improved capacity of computing resources that allow to considerably increase the size of model simulation ensembles. These large ensembles provide unprecedented description of internal variability in the climate system (with the caveat that models are capable of faithfully reproducing the internal variability). Large ensembles were used in poster studies by **Hauke Schmidt** to quantify teleconnections, and by **Elisa Manzini** and **Alexey Karpechko** to describe stratospheric climate change.

Summary and future of SNAP and DynVar

SNAP faces an exciting few years ahead as collaborations with the S2S project continue. A community paper detailing the role of stratosphere-troposphere coupling in S2S prediction systems, led by Daniela Domeisen, has recently been published (see summary on page 14). SNAP co-Chairs Andrew Charlton-Perez and Amy Butler are working to develop new community-led studies and possibly new model experiments that would link SNAP further with QBOi and the SATIO-TCS communities.

With the CMIP6 era just beginning, DynVar research will on the one hand continue to be focused on analysis of the changing atmospheric circulation, a theme included in CMIP6/DynVarMIP. Currently, plans for DynVarMIP community papers are emerging, including three papers, respectively focused on: Sudden Stratospheric Warmings (led by Blanca Ayarzagüena and Andrew Charlton-Perez), changes in the Brewer-Dobson circulation (led by Marta Abalos and Natalia Calvo) and changes in the NH extratropical stratosphere-troposphere circulation (led by Elisa Manzini and Alexey Karpechko). On the other hand, the new DynVar Co-chairs **Daniela Domeisen** and **Alexey Karpechko** will develop the activity to encompass urgent and relevant topics, such as the atmospheric dynamics of extreme events, and strengthen fruitful interactions with other SPARC and WCRP activities and the wider international climate community.

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CO_2 estimates

As a first estimate of the carbon footprint of the meeting, we calculated the total carbon cost of return flights from Madrid to the capital cities of the countries from which participants travelled (since more detailed travel information was not collected) using the ICAO carbon footprint calculator (**https://www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx**). Where we knew that participants attended by rail we calculated the carbon footprint of this travel using the EcoPassenger tool (**http://www.ecopassenger.org/bin/query.exe/en?ld=uic-eco&L=vs_uic&OK#focus**). Note that of course there are significant uncertainties in our estimate, but we think it serves as a useful starting point of discussion. Our estimate does not include any calculation of the carbon cost of food, accommodation and local transportation, but we note the excellent work done by the organising committee in arranging for local food, served largely plastic free. In total, the carbon footprint from travel is estimated to be 45.4 tons eCO_2. Per capita, the meeting carbon footprint was 483 kg eCO_2. For context, a recent (2014) estimate of per capita, annual carbon emissions for Spain is 5 tons eCO_2 (**https://data.worldbank.org/indicator/en.atm.co2e.pc**).

Members of the SPARC community have discussed the carbon footprint of their research activities. One of the elephants in that room certainly is meetings and workshops and in particular, the travel carbon emissions of the meeting participants.

A small group that participated in the SPARC workshop in Madrid have written down their thoughts on how the community could reduce its ecological footprint. These thoughts should be seen as a starting point for discussions, but also for taking action in the SPARC community and beyond. The article particularly addresses workshop organisers and provides some ideas what they should consider when setting up their meeting to reduce the carbon footprint.

We look forward to receiving more ideas from the community and insights from future workshop experiences. This shall lead to a binding guideline for setting up SPARC meetings in the future.

Reducing the carbon footprint of SPARC/WCRP workshops

Elena Saggioro[1], Andrew Charlton-Perez[1], Roland Eichinger[2], and other workshop participants

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During the recent DynVar & SNAP workshop held in Madrid a group of participants met informally to talk about the challenge of organising environmentally sustainable conferences. The discussion was very productive and inspiring, with a wide support for taking practical action on the matter. Both senior scientists and Early Career Researchers expressed a strong wish to actively reduce work-related footprints, mostly generated via the air miles required for travel to conferences. Conferences are important professional occasions and we really value the great support that SPARC in particular provides to the community to help organise them. Yet at the present moment individual scientists are often left alone with a major dilemma around attending meetings because of their awareness of the environmental consequences of doing so.

We note that other communities are taking radical steps to reduce the carbon footprint of conferences (e.g. **[1]**, **[2]**) and that there is growing academic interest in how reductions in flying might be achieved **[3]**. It feels, therefore, somewhat strange that the WCRP community has not taken a lead in this area.

As individuals, the actions we can take are important but limited. It is therefore at the community level that we need to act. We would like to strongly encourage WCRP projects to think about ways to radically mitigate the environmental impact of their academic collaboration. Here we list our main suggestions for the SPARC community to consider when organising workshops and conferences. New guidelines shaped around the following points should help to lower the footprint of these meetings and, importantly, would align WCRP with the trajectory of it's constituent countries to meet the net-zero targets in the Paris Agreement.

Virtual participation: Challenging questions we should ask ourselves are 'can our conference or workshop happen virtually?' and 'do we all need to meet in person in all occasions?'. To move beyond the present high carbon practice, all workshops should be built around the corner stone of virtual participation. Although there are some encouraging changes at the moment, virtual participation is considered secondary. To make this a viable and enjoyable option, inclusion of remote participants in the informal, discursive part of the conference needs to be considered.

Alternative formats: In the spirit of rethinking and improving our approach, redesigning how conferences are organized could play an important role. One idea, already trialed in the anthropology community is a 'multi-center' approach to global meetings, whereby one center in each continent is set as local hub and streamed or delayed talks are used to allow engagement with the other hubs. A mix of local face-to-face interaction and remote virtual participation would be an interesting option for SPARC to trial. There are many possible positive side-benefits to conferences held in this way including the strengthening of local collaborations, reduce travel time and time away from family and a reduction in costs that promotes inclusion.

Low carbon travel: Travelling by train or buses could be encouraged with a waiver on the conference or workshop fee. Alternatively, arrangements for ticket discounts with train companies are possible. Even coach-pooling has been considered as a cost-effective and low carbon option! This incentive is important as a means of mitigating the currently higher fares for lower carbon alternatives and the, perhaps unrealistically, low cost of flying.

Vegetarian and local food: A simple way to reduce the embedded impact of conferences is to provide a vegetarian menu or a menu that avoids beef and lamb, with seasonally and locally sourced food. Many universities have begun to take this step for their own internal catering **[4]** with significant impacts on their carbon budget.

Waste: Waste and the use of single use items can easily be reduced to zero at conferences and workshops, as was very effectively demonstrated in Madrid. The highest level of recycling standard available in the host country should always be met. Moreover, we suggest avoiding any handing out of conference branded material (e.g. pens or tote bags), as they are unrelated to the success of the meeting and often quickly become waste.

Carbon budget: Accounting for the progress of all our institutions and projects in reducing their emissions is a key step in driving behaviour change. We suggest the establishment of a carbon budget for each WCRP project to be included in the annual report and expressed in terms of absolute and per capita carbon emission, complementing the usual financial budget. Since calculating a total carbon budget is probably unfeasible at the moment, we suggest focusing on the travel carbon budget, which can be easily quantified through well-established carbon calculators (e.g. **[5]**). Each meeting organising committee should compute and report the amount of equivalent CO_2 emitted by travel of participants to the pertaining WCRP project which will be able to compute the yearly total utilized budget. During 2020 the aim should be to collect information in order to establish a carbon baseline and from 2021 on, an updated budget and ambition should be set. Positive competition and sharing of best practices among meetings should help boosting overall progress.

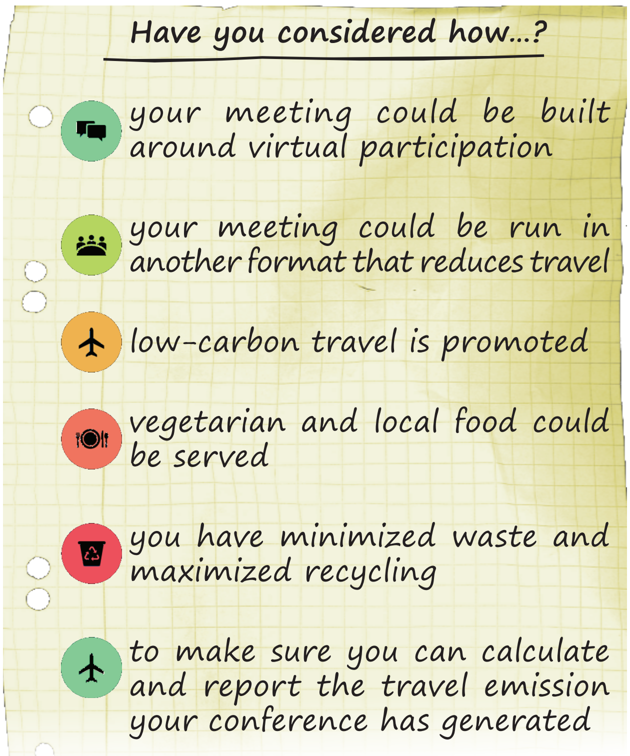

Figure 22: *A check-list for conference and workshop organisers. Please address these questions during the planning stage of your meeting and ask for help from the SPARC office and others in the community if you are unsure about how to reduce the carbon footprint of your meeting.*

The reduction of the environmental footprint of conferences will require considerable effort and strong leadership from WCRP. However, such an endeavor will not be in isolation. A group of academics has recently formulated an open letter addressing the AGU and EGU General Assemblies calling for a reduction of the carbon footprint associated with their annual meetings **[6]**. These efforts are extremely encouraging but we recognize that smaller conferences are numerous and a crucial part of the progress of science. They need to be addressed too.

We welcome any comments and the inclusion of other people and perspectives in the discussion. We particularly welcome collaboration with other institutions working towards the same goal, such as the collective **Labos1point5** in France and note the action already taken by many Universities around the world.

By implementing some of the above ideas as new policies for future workshops, SPARC could help climate scientists maintain their credibility with policy makers and the general public **[7]**. A change in our behavior as international scientific community would send a strong message to the rest of the society and promote true climate action.

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Singapore Upper Air Station visited by SPARC researchers

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Singapore stratospheric zonal wind data are used by SPARC and other scientific research communities to document the Quasi-Biennial Oscillation (QBO; Baldwin *et al.*, 2001; see also a recent historical review by Hamilton, 2018). To describe the QBO, Naujokat (1986) compiled monthly mean equatorial zonal wind data based on radiosonde data from Canton Island (January 1953-August 1967), Gan Island, Maldives (September 1967-December 1975), and Singapore (January 1976-present); this data set, extended to the present using Singapore radiosonde data, is now available at Freie Universität Berlin's website (**www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html**)[1]. During the past few years, various SPARC researchers have visited the Singapore Upper Air Station, and were surprised to find that the station staff were largely unaware of the extensive use of their radiosonde data for scientific research. In turn, the SPARC researchers are unaware of the history and current operational issues of the Singapore Upper Air Station. The purpose of this article is to provide some of this background information and to foster closer collaboration between the SPARC community and Singapore Upper Air Station to ensure that this world-class measurement time series is maintained and to ensure that its scientific value can be maximized. The rest of the article is organized as follows. Sections 1 and 2 present a brief history and current operational challenges, respectively, of the Singapore Upper Air Station. Section 3 presents experiences of various SPARC researchers with the station. Finally, section 4 presents a brief history and production procedures of the Freie Universität Berlin's QBO data set.

Figure 23: *A photograph of the Tai Seng site in Singapore (taken from MSS, 1995). An observer is releasing a weather balloon with attached Vaisala RS80-15N radiosonde (winds from OMEGA global navigation system).*

1. A brief history of the Singapore Upper Air Station

The Malayan meteorological annual reports published in 1952, 1953, and 1956 (MMS, 1946–1957) explain how an upper air observatory was established in Singapore. These reports provide the following detail:

- "Under a Colonial Development and Welfare grant an upper air observatory for combining radar wind and radio sonde ascents was established at the new International Airport at Paya Lebar. This project was designed to assess the value of the establishment of a permanent upper air observatory in Singapore. Regular radar wind ascents, twice daily[2], were commenced in July (1953)."

- Funds for this observatory were actually available from mid-1952 but difficulties in obtaining the equipment and stores from the United Kingdom[3] delayed the commencement of this trial, which aimed to perform research into the upper atmosphere in low latitudes for 3 years. The trial concluded in June 1956.

[1] Note that NOAA/NCEP Climate Prediction Center (CPC) and NOAA Earth System Research Laboratory (ESRL) also provide QBO indices, but they are both based on NCEP/NCAR R-1 reanalysis data. See **www.cpc.ncep.noaa.gov/data/indices/** and **www.esrl.noaa.gov/psd/data/climateindices/list/**

[2] This refers to rawinsonde ascents. Twice daily radiosonde sounding started in October 1983.

[3] Singapore, together with Cocos-Keeling and Christmas islands, was a British Crown Colony from 1946 to 1963.

- In July 1956, the station was established as a permanent feature of the Malayan Meteorological Service and finances were borne entirely by the Malaya territories. Upper air winds were determined twice daily; pressures, temperatures and humidities once daily by using radar techniques for tracking hydrogen filled balloons carrying meteorological instruments.

Radiosonde sounding actually began on 1 August 1954 at 03 UTC (Hassim *et al.*, 2019) at Paya Lebar. It is most probable that this site is identical to the Tai Seng site (1.340° N, 103.888° E; Figure 23) which was used until December 2011 when the station was moved to the current site just across the road due to land developments in the area. The observatory is now co-located with the Centre for Climate Research Singapore (CCRS) at 36 Kim Chuan Road. The current station (Figure 24; 1.34041° N, 103.888° E, 21 m altitude) is located on the top floor of the modern CCRS building. Table 1 summarizes the radiosonde instrument models used since the beginning of the upper air sounding program (see Gaffen, 1993; MO, 1961; BOM, 1976; Nash and Schmidlin, 1987; Nash *et al.*, 2011; Jeannet *et al.*, 2008; and references therein for information on most of these radiosonde models). For radiosonde wind measurements, the radar tracking technique was used up to 1983. The OMEGA global navigation system, using very low frequency (VLF) radio signals, was used between 1984 and September 1997. The Global Positioning System (GPS) has been used since October 1997. In April 1957, the launch time was changed to 00 UTC, and in October 1983, twice daily sounding at 00 UTC and 11 UTC (1040 UTC to be exact) was started (we also referred to the IGRA2 database which will be explained in the next paragraph). Around 2008, helium gas started to be used rather than hydrogen. See also Fong (2012) for some photographs of the Singapore upper air measurements around 2012 or before.

Period	Radiosonde model
Aug 1954 – Oct 1954; Aug 1956 – Mar 1957	Kew Mark 2B[4]
Apr 1957 – 1970	Kew Mark 2B
1971 – Apr 1972	Astor 403, introduced; Kew Mark 2B, still in use
May 1972 – 1975	Astor 403
1976	Astor RS4[5], introduced; Astor 403, still in use
1977	Astor RS4
1978 – 1980	Vaisala RS21-12C, introduced; Astor RS4, still in use
1981 – 1983	Vaisala RS21-12C
1984 – Sep 1997	Vaisala RS80-15N (winds from OMEGA)
Oct 1997 – 2008	Vaisala RS80 (winds from GPS)
2009 – Dec 2011	Vaisala RS92
Dec 2011 – 2015	Graw DFM-09
2015 – present	Vaisala RS41SG

***Table 1:** Radiosonde models used at Singapore Upper Air Station. Updated from Hassim et al., 2019. (We also referred to Gaffen (1993)).*

***Figure 24:** The current Upper Air Station within the 4-story building sharing with the Centre for Climate Research Singapore (CCRS) located at 36 Kim Chuan Road in the central-to-eastern part of Singapore. Top left: The front view of the building; on the top right of this photo, we see the "Launch Platform" where the radiosonde preparation and balloon inflation and launch are conducted. Top right: The inside of the "Launch Platform." (The radiosonde instrument is prepared at the lower level. See Figure 26.) Bottom left: Just before balloon launch, the ceiling is being opened. Bottom middle and right: Just after a balloon launch.*

Figure 25 shows a history of balloon burst pressures and associated altitudes at Singapore, using the minimum pressure point of each temperature profile as extracted from the Integrated Global Radiosonde Archive (IGRA) Version 2 (IGRA2) database (**https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00975**), with the ID "SNM00048698" for the Singapore station.

[4] Based on Gaffen (1993).

[5] This is most probably the one usually called as the "Philips RS4" (Nash and Schmidlin, 1987; Gaffen, 1993).

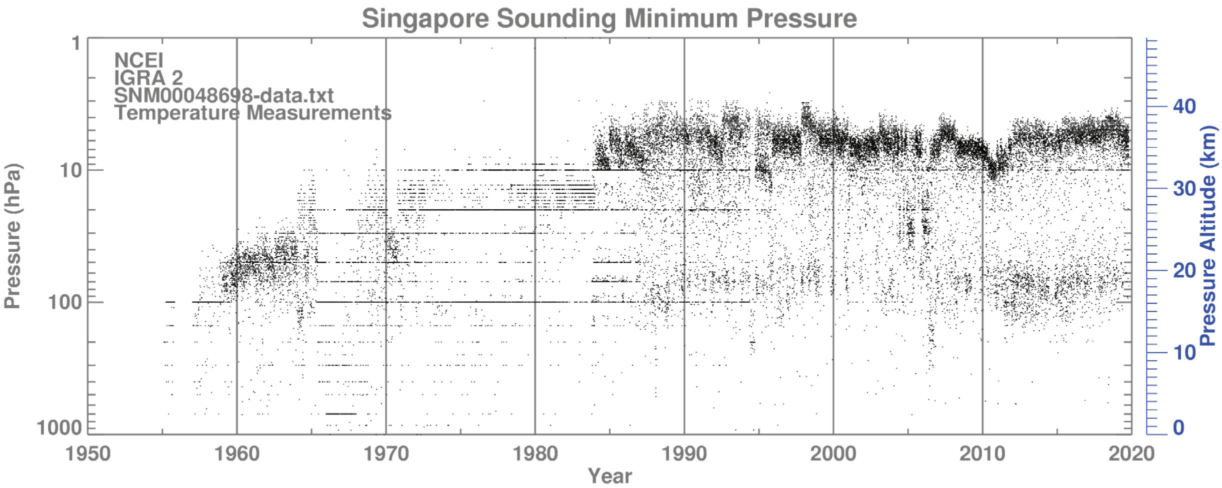

Figure 25: *The minimum pressure reached by each radiosonde flight (i.e., temperature profile), showing the approximate balloon burst point, based on historical flight data extracted from the IGRA2 database. See text for the details.*

Temperature data are used to filter out lower tropospheric wind measurements that were conducted not at the Upper Air Station but at the Changi Airport meteorological station using pilot balloons with a theodolite and using a wind profiler (the latter was in operation after October 2013). The horizontal "lines of points" correspond to the mandatory (or standard) pressure levels; they are probably due to the fact that the reporting through the Global Telecommunication System (GTS) of the World Meteorological Organization (WMO) was made only at these levels. An alternative version of Figure 25, with the maximum "height" point of each "wind" profile based on the same IGRA2 data, can be found in Figure 2 of Hassim *et al*. (2019).

2. Operational Challenges at the Singapore Upper Air Station

As seen in Figure 25, the Singapore Upper Air Station faces difficulties in regularly attaining the burst pressure of 10 hPa or better, especially during the evening ascents where the typical premature balloon bursts rate is more than 30 %. In the presence of significant low cloud cover, or after widespread heavy rains, the premature bursts rate can be more than 40 %. The very cold tropopause could be one of the causes of this balloon behaviour. As the Arctic site Ny-Alesund has faced similar challenges (cold tropopause and premature bursts), and subsequently improved balloon performance by pre-heating the balloons and treating them in a bath mixture of diesel, kerosene and engine oil, it has been suggested to test similar solutions at the Singapore station. However, due to its unique location within an office building, there are concerns over smell and fire safety. The Singapore station will therefore explore alternative options, such as spraying the surface of the balloon with a thin layer of oil, and pre-heating the balloons in a water bath.

Another solution to the early balloon burst problem that has been proposed by the Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN; **https://www.gruan.org**; see also the next section) community is to use the so-called double balloon flight configuration with a larger balloon inside a smaller "sacrificial" balloon. The Singapore station did trials with double layer balloons (1000 g inner, 350 g outer) which did not result in improvement in burst heights under challenging weather conditions. The Singapore station will explore different configurations of double balloons.

Singapore is a heavily urbanized island, and air traffic over Singapore is congested. Over the last few years there have been several radiosonde landings over mainland Singapore, including the airport, which resulted in disruptions. While the conventional radiosonde releases have been a long standing arrangement, there are challenges in securing approvals for new types of soundings (such as multiple-payload soundings).

3. SPARC researchers' experiences at Singapore Upper Air Station

Greg Bodeker visited the Singapore Upper Air Station on 19 January 2015 and again on 28 July 2015.

His visit was in his capacity as co-chair of GRUAN with the goal of eventually establishing Singapore as a GRUAN site. The three main objectives of GRUAN are to provide long-term high-quality climate records of vertical profiles of selected Essential Climate Variables (ECVs), to constrain and calibrate data from more spatially comprehensive global networks, and to fully characterize the properties of the atmospheric column. GRUAN is described in more detail in Bodeker *et al.* (2016). Given the importance of the Singapore upper-air soundings, it was imperative that its long-term continuity was assured and that establishing Singapore as a GRUAN site would foster that long-term continuity. After his first visit to the Singapore station, Bodeker sent a list of 122 papers that mentioned the use of the Singapore upper-air data as a measure of the value of these data to the community researching different aspects of the QBO.

Lawrence Coy, Paul Newman, Scott Osprey, Qing Liang, Rich Eckman, and Ralf Tuomi visited the station on 8 August 2017 (Figure 26) while attending the 14th annual Asia Oceania Geosciences Society (AOGS) meeting in Singapore. During the AOGS meeting, there was a special session on "The Quasi-Biennial Oscillation and its Role in the Climate System" (**http://www.asiaoceania.org/aogs2017/public.asp?page=spec_lectures.htm**). This session (10 August 2017) featured talks by Lawrence Coy on "Quasi-Disruptions of the QBO: Tropical Wave Activity of 1987-88 and 2010-11 Compared to the 2015-16 NH Winter", Paul A. Newman on "The 2015-16 Disrupted Quasi-biennial Oscillation's Impact on Stratospheric Trace Gases", Scott Osprey on "The Representation of the QBO and its Effects in Modern Climate Models", and Seok-Woo Son on "QBO Modulation of the Interannual Variability of the Madden-Julian Oscillation". Naturally, the attendees wanted to see the station that was so prominently featured in all of these talks. Prompted by the 2015-16 disruption of the QBO (Newman *et al.*, 2016; Osprey *et al.* 2016) and by the visit, Newman and Coy developed a website to highlight a number of QBO features, including winds, phase, temperature, water vapor, and ozone from a variety of observational systems (**https://acd-ext.gsfc.nasa.gov/Data_services/met/qbo/qbo.html**). For this website, the twice daily profiles of Singapore sounding data are taken through the WMO GTS, and bad or missing data are filled with MERRA-2 reanalysis winds (Gelaro *et al.*, 2017) to create monthly means.

Masatomo Fujiwara visited the Singapore Upper Air Station on 23 May 2019 during the GRUAN 11th Implementation and Coordination Meeting (ICM-11; GCOS, 2019), as a GRUAN working group member and a co-chair of the GRUAN task team on radiosondes. The station was certified as a GRUAN site in early 2019.

Figure 26: *SPARC researchers discuss with the station staff at the Upper Air Station radiosonde preparation area of the CCRS building on 8 August 2017. From left to right: Ralf Tuomi (Imperial College London, UK), Paul A. Newman, operation staff Dahlan Samubari, Scott Osprey (University of Oxford, UK), and Lesley Choo.*

Before the visit, based on the information from Greg Bodeker described above, Fujiwara communicated with James Anstey and decided to bring two "gifts" for the radiosonde operators. One is the world famous textbook on meteorological dynamics, "An introduction to dynamic meteorology" written by the late Professor James R. Holton (Holton and Hakim, 2013); its Figure 12.15 (p. 433) uses historical Singapore data and shows time-height cross section of equatorial zonal wind, describing the QBO, as an update from Naujokat (1986). The other is the SPARC Newsletter No. 45 that includes an article by Anstey et al. (2015), as a showcase of recent research activities on the QBO. At the station, with these presents, Fujiwara briefly explained the QBO and its global impacts to the radiosonde operators (Figure 27), emphasizing that their daily work has significant importance on the global climate research community.

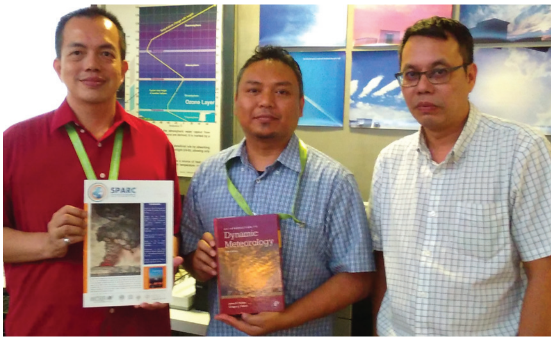

Figure 27: *Radiosonde operation staffs (from left to right: Lam Tuck Wai, Dahlan Samubari, Mohd Shahril Fuad) of the Singapore Upper Air Station holding SPARC Newsletter No. 45 and James R. Holton's textbook "Dynamical Meteorology" (5th edition) on 23 May 2019.*

4. Freie Universität Berlin's QBO data set

With the increasing number of radiosonde soundings in the framework of the International Geophysical Year (IGY) 1957/58 the Institute of Meteorology at the Freie Universität Berlin (FUB) began in 1957 to produce daily maps of the stratosphere for the Northern Hemisphere based on radiosonde soundings. In the scope of this work, Barbara Naujokat of the Stratospheric Research group started to build up the FUB QBO data set. For the early years (January 1953 – August 1967) soundings from Canton Island (3°S, 172°W) were used, followed later by soundings from Gan Island (Maldives 1°S, 73°E; September 1967 – December 1975), and finally from Singapore (1°N, 104°E; January 1976 – present) (Naujokat, 1986; Labitzke and van Loon, 1999). Until today, the FUB QBO time series is updated regularly using the technique of Naujokat (1986). The monthly QBO time series is based on the Singapore radiosonde soundings (Station ID 48698), as they are distributed via the WMO GTS. FUB receives the GTS radiosonde data via Germany's National Meteorological Service (DWD). All available soundings for 00 and 12 UTC[6] are used, decoded and error checked. The wind direction and speed for the mandatory pressure levels 100, 70, 50, 30, 20, and 10 hPa (if available) are directly taken from the sounding. In addition to these main pressure levels, significant level data for the stratosphere, encoded in part D of the GTS data, are incorporated in the FUB QBO data set. Significant levels are defined by the air pressures where the vertical temperature gradient changes sign. Using the wind direction and speed of the significant levels thus enhances the vertical resolution of the QBO. The wind direction and speed in knots are then converted to the zonal and meridional wind components. As the data on significant levels are on non-mandatory pressure levels which change from sounding to sounding, interpolation to a set of standard pressure levels is required. The interpolation to the final pressure levels 100, 90, 80, 70, 60, 50, 45, 40, 35, 30, 25, 20, 15, 12, and 10 hPa is linear in p^{R_d/c_p}, with R_d the specific gas constant for dry air, c_p the specific heat capacity of dry air at constant pressure, and $R_d/c_p = 0.286$. The interpolated data are lastly averaged over all soundings available for each month, to get the final monthly mean wind data, as published in Naujokat (1986). The FUB QBO data set is widely used for different applications, for example to specify the QBO winds in models, and can be downloaded from **https://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/index.html**.

In this article, we have presented both operational and research aspects of the Singapore upper air measurements focusing on the QBO.

6 As explained in section 1, the latter time is actually 11 UTC, or 1040 UTC to be exact.

We strongly hope that this short article will foster and stimulate closer collaboration between research and operational communities. Such a collaboration is a key to ensure long-term continuity of climate monitoring which is sometimes at risk for various reasons in various parts of the world.

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